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Identify factors which influence operations management framework of lean manufacturing production strategies in implementing batch flow vs single piece-flow

A Dissertation submitted for the

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed .....RHall..... (candidate)

Date ……10th April 2023.....

STATEMENT 1

This work is the result of my own investigations, except where otherwise stated.

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Abstract

IMI-C have strong brand awareness across multiple industrial sectors. To retain IMI-C's market position, the organisation is exploring adapting its production strategy to achieve the rising customer demands for reduced product lead times whilst remaining strategically competitive in product costings.

IMI-C conducted an operations management research project, focusing on the philosophy of Lean manufacturing (LM) to measure if product costings and processing times could be reduced through the implementation of Single Piece Flow (SPF) production.

A literature review identified the theory of SPF as a critical tool within the LM toolbox to help reduce costs and lead times. This has promoted IMI-C to explore the theory of SPF to address its current global challenges. A batch reduction study was designed to be conducted across three of IMI-C's high-volume production lines, The ICO, ICoS and IFR lines. Each production line contains multiple manufacturing process steps and a different level of customer demand.

The study began with the ICO production line, which saw an entire batch of products timed through the manufacturing cycle. The batch quantity was lessened 10%, and a repetition of the study was conducted until the final batch quantity became 1 individual component, achieving SPF.
The data collected during the studies were as follows, batch size, manufacturing step, processing time and the first pass yield of each batch run documented for the study. The studies were replicated across IMI-C's ICoS and IFR production lines under the same conditions.

The results from the data were then statistically analysed using the Person coefficient correlation methodology, which determined a strong positive correlation between batch quantities vs production times. Identifying that as a batch quantity decreases, the physical time to produce an individual component also decreases, as reviewed during the literature review process. Resulting in lower production costs and higher capacity availability.

The study also identified a negative correlation between batch sizes and first-pass yield (FPY). As batch sizes increase, the FPY reduces, showing that IMI-C's current production method negatively impacts the organisation.

The causation for the correlation discovered during this report was not explored within the scope of work. Future work would be to determine the causation further and replicate the batch reduction study in other business areas to identify if SPF could be implemented across all IMI-C production facilities. This would work towards creating a competitive advantage through operations management and allow IMI-C to remain market leaders across their multi-industrial sectors.

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1.0 Introduction

IMI Critical (IMI-C) specialises in high-pressure engineering systems. The organisation is currently part of the IMI-PLC family on the FTSE 250. The IMI-C site in Poole generates the highest revenue of all UK IMI sites. Annual turnover has grown over the last four years from £19million in 2018 to an on-target of £25million for year-end 2022. Forecasted sales for 2023 and 2024 predict 15% year on year growth increase from the business entering new markets with its existing products. IMI-C directly employs more than two hundred employees. The organisation has a combination of the following manufacturing capabilities:

- Twenty-eight CNC machines to support IMI-C in producing standard products alongside new project development programmes and research and development.

- Twelve standard assembly production lines produce over three hundred industry-leading products using its strong brand awareness within different industrial sectors.

- A customer-focused projects team who works with customers to create bespoke industrial solutions and drive innovation.

IMI-C operates across the following highly regulated markets:

- Petrochemical
- Nuclear Power
- Nuclear Marine Defence
- Life sciences

Due to the extremely high customer demand across multiple standard products, IMI-C is reassessing its production facility operations management strategy. The rise in demand from new customer growth across its standard product range is driving higher production costs due to the following reasons:

- Increased batch sizes, there is a significant increase in rejected products from the production lines.
- Storing excessive stock to meet demand creates further issues when an obsolete product occurs due to engineering product updates.
- Extra production shifts and increased overtime to meet customer demand.

This puts IMI-C at risk of increasing its product cost prices to cover the additional expense caused by its operations management style, potentially putting IMI-C in an exposed position of being superseded by current and advancing competition.

This exposure has forced IMI-C to review how it assess operations management within the business in particular it’s production model. From an operations management point of view to reduce production costs whilst creating extra production capacity to manufacture the rising demand for its products.

This project will focus on three standard production lines identified:

1. ICO - current yearly demand as of 2022 is sixty thousand units.
2. ICoS- current yearly demand as of 2022 is thirty thousand units.
3. IFR - current yearly demand as of 2022 is twelve thousand units

IMI-C launched the above products between 2000-2004. At the time of implementation, demand for the product was below ten thousand units a year for ICO, ICoS and IFR. Once the products became market-established and high repeat orders from different customers occurred, IMI-C implemented dedicated production lines for each product family in 2006.

2.0 Business Justification For The Project

IMI-C plans to enter the Asia-Pacifc market (APAC) in 2024 as part of its strategic market expansion. Sales forecasts predict an increase of 25% across the ICO3S, ICO4S and IFR ranges. These forecasted sales could negatively impact the business due to a lack of available capacity.

One of the biggest challenges facing IMI-C is the strategic growth programme which is entering new markets, such as APAC, alongside high demand in IMI-C's existing markets. The extra growth from existing markets has become a strain on the resources available to the business.

The senior management team (SMT) at IMI-C has identified current resources are unable to maintain increasing demand, even before 2024's APAC market entry.

To achieve organisational sales targets for 2023, IMI-C implemented several interim solutions across the ICO, ICoS and IFR production lines:

- The use of temporary agency staff has increased across all production lines.
- ICO, ICoS and IFR production line employees were offered extra overtime.
- The quality checks between workstations have been removed to reduce assembly production times.
- High dependency on sub-contractor companies being used to help fulfil orders.

The solutions have caused multiple issues at IMI-C. To achieve sales there is an over-reliance of employees working extra hours every week, which is not guaranteed resulting in sales targets not being achieved. This has also caused a further underlying issue between management and the shop floor employees, who now feel they are pressured into working extra hours.

The Quality department team has highlighted an increase in defective products produced across all ICO, ICoS and IFR production lines during 2022. The cause of this is linked to the over-reliance on temporary agency staff deployed with inadequate product training. The reduction in quality checks further exaggerates this situation by removing the safety net barriers to increase throughput.

The interim solution deployed by IMI-C's SMT could potentially be causing long-term damage to the business through its capacity solution. All of the IMI-C products are safety critical and must be highly reliable. The implications of a defective product reaching customers within highly regulated and controlled markets could significantly impact the business reputation, damaging the brand and removing IMI-C as a market leader.

The financial implications associated with extra overtime and the addition of additional temporary agency workers are driving the production costs of the products higher. The question is, how will IMI-C recuperate these higher product costs? IMI-C may have to offset the additional production costs to their end customers reducing market price competitiveness. Or absorb the cost rise within the organisation, reducing gross profit from the extra direct labour and increasing the costs of goods sold. Ultimately impacting IMI-C's bottom line, which is vital to helping the business grow through reinvestment.

The project aims to research how the reduction of product batch sizes of various products impacts the lead time and production cost. From an operations management perspective, this will help to develop a sustainable resolution to IMI-C's current rise in product demand. The research question will ensure IMI-C examines its operations management style by understanding if the batch quantities planned to be produced through the production lines has the ability to influence costings across its highest volume products.

The allocated resource to formulate the most effective quantities lines included within the proposed study, will work towards establishing how to address un-balanced workstations including any potential bottlenecks, reducing overproduction which leads to an excessive inventory storage between manufacturing operations. ICO, ICoS and IFR production lines were chosen for the research to represent different sales volumes.

3.0 Title (Aim)

Identify factors which influence operations management framework of lean manufacturing production strategies in implementing batch flow vs single piece-flow.

3.1 Research Question:

- *Does the Lean Management methodology of single-piece flow or a traditional batch-flow production strategy produce the lowest product lead times and production costs?*

3.2 Project Objectives

1. Define the current performance of selected IMI-C product lines. This will be achieved by establishing processing lead times of the workstation. Recored times will allow production product costs and manufacturing lead-times to be calculated. Completed by the 9th December 2022.

2. Creating of a controlled study to reduce batch quantities of defined production lines in incremental stages to achieve single piece flow. All documentation required to record the

results in the form of quantitative data will also be created. Completed by 21st December 2022.

3. Undertake the research study as defined in objective two following the planned documentation to ensure collected data remains uncontaminated. The data collected by the planned production review will be of multiple data providing variety of data for analysis. Completed by 3rd March 2023.

4. The data sets collected will be subject to statistical analysis to identify if any correlation (strength of the relationship) and covariance (direction of the relationship) between product costings and the lean management philosophy single-piece flow or a traditional batch-flow production strategy. This will be achieved by 19th March 2023.

4.0 Literature Review

4.1 Literature Review - Operations Management Lean Manufacturing Philosophy

The engineering sector is continually driving competitiveness. IMI-C relates to Mayatra et al. (2015) because, as market leaders, they are encountering high volumes of sales orders from repeat customers who require cost-effective engineering systems. Customers are leading the global demand for competitiveness, with customer expectations higher than ever for competitive pricing, high quality and personalisation options, all within lead times (Mayatra et al. 2015). The risk to the organisations is if the sales price of the products were to increase due to higher production costs, customers might look to alternative IMI-C competitors.

This identifies the importance for IMI-C to constantly work to drive production costs as low as possible to retain customers. IMI-C introduced the philosophy of Lean Manufacturing (LM) into the organisation in 2020, intending to reduce the waste from its manufacturing processes, enhancing product quality whilst reducing production costs and lead times.

> “Lean means to make improvement as possible amount of material, time, money, space, effort or whatever is necessary to develop and deliver a process or product to customer. Anything more than the absolute minimum is essentially waste” (Ioana et al 2020).

LM originated as a modern variation of Toyota’s efficient Production methodology (TPS) (Shingo 1989; Mortimer 2006). LM’s purpose is to significantly reduce the time required from a customer production sales-order until the customer receives their goods (Womack and Jones, 2003). Production lead time minimisation is executed by implementation of the LM toolbox. LM toolbox contains several tools dedicated to reducing waste. Within the theory of LM, waste is characterised as a function/feature or process that does not add value from the customer's perspective.(Dixit et al. 2015; Ihueze and Okpala 2012 and Yadav et al. 2010).

In addition, Sundar et al (2014) explain that the perception of value is what LM works to define. Value has a variety of definitions across all customers. LM works to understand: what the customer is prepared to pay for? (Dixit et al. 2015; Womack and Jones 2003). Only then can an organisation improve the value stream flow as per customer requirements, creating a streamlined product or service (Sundar et al, 2014). During the streamlining of a process, this is referred to as removing non-value-adding steps or, as is more commonly known in LM waste reduction (Womack and Jones, 2003).

Mortimer (2006) explores the LM philosophy and highlights it is common practice for manufacturing organisations to implement LM without fully understanding its tools, resulting in little to no benefits. The downfall is described as focusing solely on on-time delivery and less on reducing non-value-adding steps within the process. In particular, Mortimer (2006) directs his journal towards manufacturers with multi-processes steps such as machining and assembling. Production styles and techniques need to be updated and aligned with customer demand.

Lawson (2002) described this disconnection between process and customer perception of value as contributing towards General Motors over reliance on LM principles which created a customer vulnerability resulting in lost production in excess of $2.2billion. Cusumano and Nobeoka (1998) explain that an over reliance on LM principles can negatively impact an organisation globally.

Mayatra et al. (2015) add to Mortimer's (2006) work by identifying one of the main benefits of LM introduction is the reduction of inventory held within a business. Defining excessive inventory as one of the most significant wastes impacting an organisation. Extreme inventory levels can hide many other inefficiencies and manufacturing wastes within a production line (Mayatra et al. 2015).

Mayatra et al (2015) and Mortimer (2006) have described why LM should be fully understood before implementation. The common mistakes highlighted by Mayatra et al (2015) and Mortimer (2006) are similar to IMI-C adoption of LM. IMI-C have implemented the philosophy across the business. However, the drive's focus has yet to address the current production lines. The methods used still represent the original production style with high work-in-progress inventory from batch-building production and high levels of finished stock held within the stores. Boute et al (2004) describe increased work in progress inventory between planned production processes as an indicator of poor production capacity planning and scheduling.

4.2 LITERATURE REVIEW - Lean Manufacturing- What Is Waste?

Evaluating LM academic journals has identified seven original categories of 'waste'. LM is based on the TPS, which calls waste "Muda", which is the original Japanese translation from the TPS (Yadav et al. 2010; Shingo 1989; Mortimer 2006). Womack and Jones (2003) and also Modi and Thakkar (2014) define each of the seven "wastes" as being responsible for non-value-adding activities during manufacturing.

Dixit et al (2015) explains that TIMWOOD can be used as a acronym reference for the seven wastes within the LM philosophy:

1. **Transportation** - Moving products across long journeys caused by poor factory layout.
2. **Inventory** - Holding high levels of finished product stock and also, work in progress stock,
3. **Motion** - Poor workstation layout causing operators to make excesses movements to complete their process.
4. **Waiting** - Products waiting to have processes completed.
5. **Overproduction -** Producing move than customer demand creating excessive burden on the production system.
6. **Over-processing** - Conducting process on a product which are not required.
7. **Defects** - Producing products which do not conform to their required specification.

Further research into the understanding of TIMWOOD has established that it is becoming excepted that an additional defined type of waste has been introduced to the original seven wastes. Increasing the acronym to TIMWOODS, the extra letter 'S' represents the word skills and refers to the employee's skills in the workforce not being utilised to their full potential (Okpala 2014). The utilisation of employees' skills helps drive an organisation's competitive advantage, increasing customer satisfaction and engagement. The eight wastes of LM has become accepted within the broader body of knowledge (BOK) for LM (Okpala 2014; Chahal and Narwal 2017; El-Kateb 2015).

Even with the additional waste incorporated into the BOK, the research identifies overproduction and excessive WIP/inventory as the most harmful of the eight wastes. Overproduction contributes to excessive inventory, which can contain all the other wastes. This can result in defective products being stored within the organisation (Lean tools.org, 2017).

The LM toolbox has simplistic straightforward rule for scheduling; A pull production system states that when customer demand is zero, production should cease (Lean Manufacturing junction.com, 2014).

Sumant and Thanki (2014) describe single-piece flow as one of the most beneficial tools from the LM toolbox. It creates the advantage for businesses to manufacture products at a much lower production cost whilst decreasing inventory levels.

4.3 LITERATURE REVIEW: Single Piece Flow Combating Overproduction

It was identified in section 4.2 that overproduction was one of the most significant factors negatively impacting production-based organisations. This justified further literature research on how to combat overproduction. However, the lifecycle status of the product being manufactured can define the style of production used. Product life cycles, according to the literature research, fall into one of three categories (Miltenburg 2000):

- Stage 1: The introduction stage follows a primary production method which focuses on producing the product to specification but involves high waste within the process, increasing the production costs.

- Stage 2: As the growth of a product increase and systematic approach becomes apparent and the introduction of batch flow is conceived as a standardised route of process steps to be followed. Production is segregated into planned batch quantities and different build stages are produced in order within dedicated product family production areas.

- Stage 3: Single-piece-flow (SPF). When a product increases to full maturity, and customer demand justifies mass production, a stabilised and dedicated production line should be implemented, providing single-piece flow production, and significantly increasing flexibility. The results of this are shorter lead times and further reduced production costs.

Haider et al (2007) further back Miltenburg (2000), stating that SPF allows a product to flow in a continuous motion throughout the required processes. From the purchasing of raw material until customer despatch. SPF is one of the most efficient production systems for improving capacity and reducing costs (Haider et al 2007). The literature has identified that SPF is a superior method over batch production (Stage 2) due to its ability to reduce long lead times. Ensuring products are delivered on time only at the ordered volumes. This helps to create a just-in-time (JIT) production system (Stevenson 1996).

To fully implement SPF there is a requirement for high customer demand. High customer demand enables the justification of dedicated SPF production lines. This allows the creation of product families, which may contain slight variations but must remain similar to the core product family it sits within (Norzaimi and Ani 2012). Once the implementation of SPF is justified, production workstations should be designed, so that material travel is reduced to a minimum between processes, forming a system of flow for the product and removing excessive travelling and waiting times clasified as 'waste' (Haider et al. 2007).

However, Okpala (2014) literature review also explains that SPF does have boundaries in its capability to improve production systems. It has been documented that specific manufacturing processes are not cost-effective to produce following the SPF theory from the LM toolbox and require using a batch flow system to justify the equipment, machinery and labour costs.

leadingtransformaion.com (2012) explore the concept of SPF and define batch production as a temporary measure within a high-volume environment. They state that true SPF may only sometimes be possible due to process restrictions. The organisation implementing SPF from the LM toolbox should use their product knowledge to best judge the minimum size of product quantities thats pass through a production line.
leadingtransformation.com (2012) acknowledge that complete SPF is only sometimes viable and agrees with Okpala's(2014) SPF research regarding the cost-effectiveness issues of making SPF the sole goal. leadingtransformaion.com (2012) takes a more feasible approach, defining SPF as unique to each organisation which implements it. With the organisation determining what their most cost-effective lowest batch size should be and not necessarily SPF quantity goal of a single product batch.

4.4 Literature review - SPF Implementation case studies:

Case study 1:

Ogie Kustiadi et al (2018) documented a case study involving a five-step process within the dies casting industry. The organisation struggled to meet customer demand and changed its production strategy from batch flow to SPF. The result generated a significant quality improvement leading to higher outputs. The quality of the products being manufactured increased as the safety net of stock was removed with SPF. Resulting in error proofing and corrective action becoming immediate, and operators lead because with only one product at a time moving along the production line, defectives are not hidden in excessive stock levels.

"Before the application of One Piece Flow, the output was 902 pieces, while after the application of One Piece Flow was 1332 pieces." (Ogie Kustiadi et al, 2018).

The results from the above case study show an increase in physical product output, but the case study also contains several advantages:

- Manufacturing flexibility increased, improving the organisation's ability to meet changing customer product demands.
- The inventory reduction directly removed significant amounts of investment to keep high stock levels.
- Enthusiasm improved within the factory due to faster work and the removal of operators conducting repetitive tasks when producing batches.

Case study 2:

Ioana et al (2020) explain the implementation of SPF through a case study based within the automotive manufacturing sector. The benefits resemble case study 1 by Ogie Kustiadi et al (2018) with a reduction in stock, product transportation, increased product quality and reduced production processing times. However, Ioana et al (2020) explain how the benefits were achieved. These involved certain conditions before starting the transition from batch flow to SPF.

- The production operator must be trained to a reasonable level to be defined as qualified to complete every step required in a product's manufacturing process.
- The manufacturing process must have significant customer demand, not necessarily mass production but enough to justify dedicated production lines. The SPF system should also have substantial customer fluctuation built into its design to allow for peaks and troughs in demand.
- The process cycle time must be similar, and any major time inconsistencies between processes must be eliminated to remove potential bottlenecks in the SPF setup.

Following these critical points, Iona et al (2020) report an increase in productivity of six per cent over six months after changing from a batch flow system to SPF.

4.5 LITERATURE REVIEW - Batch Sizes Reduction

A practicable organisational leading approach to SPF is complimented by Burcher and Dupernex (1996) who describe all types of stock queued, ready for large batch processing as being open to extended queuing times. The solution is identified as significantly reducing batch quantities. This can be used as a tool to minimise bottlenecks as the smaller the batch becomes, the shorter the processing time and less waiting times in the production chain.

Shafeek and Marsudi (2015) further add to batch flow research when SPF is not possible by explaining that production line stations can be designed in such a way they can be balanced with batch quantities increasing the flow across a production facility. The difficulty and organisational knowledge come into effect when the correct amounts to utilise all manufacturing equipment as efficiently as possible.

Zipkin (1991) describes that one of the fundamental mistakes an organisation can make when attempting to implement SPF is to reduce batch quantities to one immediately. The result of this is low stock levels which may not be able to keep up with customer demand, adding extra pressure to a business that cascades down to the employees, suppliers and customers.

Johnson (2003) further explores the negatives of implementing SPF. Reducing the batch sizes can create extra demand in the production planning department because less stock exists, which is a cost reduction to the organisation; however, this comes with a higher potential when issues occur due to less of a buffer.

4.6 Literature - Highlighting LM Waste In A Production Environment.

It is fundamental in defining a process's requirements that data is collected for analysis. Data collection allows value from the customer's perspective (Lacerda et al. 2016). Data collection enables a process to be reviewed and quantified as appearances of what is happening may not be the reality (Rahani and al-Ashraf, 2012). Customer focus must remain paramount, but over time, a disconnection between customer and supplier can occur. The result of this can be the analysis of the incorrect data within a process (Womack et al. 1990).

Okpala (2014) explains to fully embrace lean manufacturing as a philosophy, an organisation must first make all the non-value-adding activities (wastes) visible. The literature review has highlighted that before LM improvements can be made, a measuring period is required to fully understand a process before any changes are implemented (Okpala, 2014).

Further literature research was required regarding Okpala (2014) work to understand how LM toolbox can be used to measure process waste. Researching the literature determined value stream mapping (VSM). VSM is an LM tool that allows a process's flow to be mapped across the manufacturing cycle. Sundar et al. (2014) explain that the main advantage of producing a VSM is the simplistic visualisation it creates, ensuring that all of the manufacturing routes are captured and all areas are highlighted.

VSM is credited with pulling together several critical business analysis tools such as Material flow, problem-solving and the start of change management (Sundar et al. 2014).

Mortimer (2006) defines the creation of a value stream map in the form of a flow chart. This can be documented and stored for reference. Mayatra et al (2015) further add to Sundar et al (2014) by explaining that VSM is the beginning of an organisation identifying what steps are value-adding and what steps are non-value adding. Then as a process changes/develops over time, previous VSM can be referenced to show an LM journey and its knowledge used within other areas of an organisation to accelerate LM principles.

Product costings are also discussed by Baggaley & Maskell (2003), who state that product costings depend on the speed at which a product flows in its VSM. The VSM will highlight operations which are of concern, such as bottlenecks and potential delays. By highlighting these and organisations can work towards improving flow and reducing product costs, ultimately improving an organisation's bottom-line.

4.7 Literature Summary

This literature review has explored numerous academic journals regarding LM and the tools within its toolbox. The literature review has been taken from a wide range of various authors from different industrial backgrounds. The literature has highlighted that regardless of the applied industry, LM is a customer-focused methodology that reduces non-value-added tasks (wastes) defined by customer perception. The most effective production-enhancing LM tool is SPF. The purpose of SPF is to reduce batch sizes, creating a smoother reduction flow.

Most authors agree that overproduction is the most significant waste of the seven/eight wastes of LM as it hides individual or multiples of the other wastes. Overproduction has become common practice at IMI-C, which was actioned by management to build up a high stock level to meet customer demand. This was done by increasing the batch sizes.
However, from an operations management perspective, the high stock and work-in-progress (WIP) have caused more significant issues. These have resulted in defective products reaching customers, high levels of stock being scrapped due to design obsolescence changes and faulty batches of products completing their full manufacturing cycles resulting in lost potential revenue.

Miltenburg (2000) described a product life cycle of conception (stage one), growth (stage two) and maturity (stage three). Within this three staged process, IMI-C products are within Stage 3. They have significant customer demand to justify a high-volume production system, but the current strategy relies on stage two, high batch volumes generating stock and high WIP. IMI-C products fit within Stage 2 rather than Stage 1 because products are produced on dedicated production lines grouped by families of products. This means IMI-C are in a position to trial a move to SPF.

Haider et al (2007) and Miltenburg (2000) explored SPF as an LM tool to combat overproduction. LM as a philosophy is supported within IMI-C. However, the concept of SPF has never been implemented in a production environment at IMI-C. Sumant and Thanki (2014) explained that switching to an SPF system helps to reduce overall production, which would help IMI-C to remain competitive in its markets.

Contrary to this Okpala (2014) explained that there may be limitations in the smallest capable batch sizes, cost-effectiveness and feasibility within an organisation's production system. This will require IMI-C to take caution as this may not be cost-effective or viable to implement SPF immediately.

Zipkin (1991) identified issues that many organisations face when attempting to introduce SPF and reduce all batch sizes to one individual product at a time. However, Shafeek and Marsudi (2015) literature explored the option that SPF is not necessarily one product at a time. It could be the minimal viable quantity depending on the production/processing method.

This is where a gap is found with the LM tool SPF knowledge as the case studies reviewed within this report only highlight the productivity benefits and do not discuss the finalised SPF batch quantities or the SPF batch size stages implemented in the reduction.

This generates the question did both case studies implement SPF as one product flow line from the beginning? Or did they lower the batch manufacturing quantities in stages to the lowest cost-effective and viable quantity?

Based on the literature review, the results from this research project will contribute to the overall knowledge of operations management and the implementation of SPF as part of the LM philosophy. Due to the extensive range of literature regarding this topic and the inconsistencies in achieving SPF, more research and data collection are required. Further investigation will look to investigate the research question:

- *Does the Lean Management methodology of single-piece flow or a traditional batch-flow production strategy produce the lowest product lead times and production costs?*

This research will also benefit IMI-C in their lean journey to help understand if a correlation exists between SPF or batch and product lead times. This will also allow production costs to be calculated and correlated between SPF and batch production. These results will be used in assisting other manufacturing facilities across all global IMI sites.

5.0 Project Methodology

The methodology used within this project requires comparing two primary variables to determine if a correlation exists. The research question:

- Does the Lean Management methodology of single-piece flow or a traditional batch-flow production strategy produce the lowest product lead times and production costs?

The first variable is the physical batch quantity, and the second variable is the production processing time (product lead time). It can then be determined if the batch size run through the production lines directly impacts the lead product times. Once the product lead time has been

determined, the production costs of the products can then be calculated to highlight the impact of the results as a cost to IMI-C. This will test the directional hypothesis identified during the Literature review that a reduction in batch sizes through the principles of LM tool SPF reduces production costs.

A quantitive system has been implemented within this data collection research. A qualitative system was not used as the available data will be in a measurable form. Antonius (2003) explains that the use of quantitive data provides data collection, which is less exposed to interpretation. Quantitative removes the requirement and reliance on opinions and other subjective factors. Allowing the collected data to be verified, statistically analysed, and re-validated.

Qualitative data could provide inconclusive results by subjectively attempting to find a correlation between batch sizes and production times. This would have prevented final product costings from being calculated, generating an answer to the research question.

During the data collection process, observations were conducted with no interaction being between the data collector and IMI-C line workers. This approach was remained the same throughout. Creating an environment which replicated everyday working conditions without any abnormal influencing factors. All production line workers involved in the study were briefed before any data collection began and were given the option to be exempt from the research study. It was also explained that all production operators working on the production lines during the study would remain anonymous.

5.1 Area of Research

It was decided to conduct the research across three different production areas within IMI-C. This was done to ensure that the results were not specific to one product family. The three selected production lines also contained different manufacturing processes and different sales volumes. The results from the study of each production line to be compared against each other, creating a wide range of data.

The first production line selected was the ICO line. This is IMI-C's highest output product and the most extensive product line within the organisation regarding footprint, employee and process steps. The ICO is well-established and can be defined as a premium market-leading product. Current sales demand is sixty-thousand per year, with an estimated eight per cent year-on-year growth.

The second production line produces a product called an IFR. This has a steady customer demand of twenty-five thousand units a year. Currently, the IFR as a product is in the market penetration (growth) stage of its life cycle.

The third product is labelled the ICoS. This is a new product launched by IMI-C in 2018. The ICoS is a relatively new product with a new process, which will help determine batch vs SPF at the new product introduction stage of the life cycle. Currently, sales are around eight thousand units per year.

5.2 Benchmarking Current Production Lines

The first step was to create a baseline to define the current state of the three selected production lines (ICO, ICoS and IFR). The baseline results would be used as comparative data during the research project. This initial data collection exercise's importance is defining a benchmark that can be referenced during and after the research study. This will provide supporting evidence to asses if any changes in batch sizes or SPF to the production strategy do significantly impact changing production times, costs, etc.

5.3 Mapping The Process

Using the toolbox of LM, process maps were created to show the process flow in sequential steps. This was done to ensure that all of the manufacturing steps across the three production lines was documented. This was vital as all production stages require resources from IMI-C. Examples of this are:

- Employees with set skills for the set process.
- The physical equipment to produce a manufacturing process.
- The processing time of the step.

The process maps work towards preventing production steps across the ICO, ICoS and IFR from being missed from the study, which could generate inconclusive results. The creation of the process maps involved physically walking the operations from beginning to end.

After all the production operations had been documented in sequential steps, all of the processing times were logged. Processing times were recorded and logged in seconds to provide the most accurate way of timing a process. It was identified during the process mapping that the following production lines operate under these conditions:

ICO - Always produces in batches of twenty.
ICoS - Always produced in batches of twenty.
IFR - Always produced in batches of twenty.

5.4 Production Takt Time Requirements

Nagaraj et al (2015) define takt time as the drumbeat of production. The takt time shows the production lead times that an organisation has to produce a product to keep up with customer demand.

Establishing the takt time across the three production lines was fundamental in the project's initial documentation stages as this set the maximum time that IMI-C's products can be manufactured to meet customer demand and achieve the sales forecast.

It was decided to review the potential future sales orders for the ICO, ICoS and IFR for the year ending 2022. IMI-C is predicting business growth of around ten per cent during 2023 due to the business expansion into new markets. The following paragraphs will explain the approximate Takt times for each selected product line in detail. With the predicted sales forecast being used to show the demand for IMI-C if the production strategy remains the same as it currently is.

5.41 ICO Takt Time Calculation Baseline

The ICO has predicted sales for 2023 of sixty thousand units based on a forty-nine-week working year (This accounts for six weeks of unplanned resources covering the annual shutdown and the Christmas shutdown).
This calculates that for every 1.96 minutes of a production shift, a single complete ICO product must be built and tested on the ICO production line to achieve the sales demand. This is based on a forty-hour working week.

The final stage was to calculate how much resource is available to IMI-C based on a forty-hour working week. It was when the variables of unplanned stoppages, operator breaks, lunch, and other day-to-day operator requirements. It was discovered that IMI-C only has, in reality, the availability of a thirty-six-hour working production week. This puts extra pressure on the IMI-C as the recalculation of the Takt time equals 1.76 minutes per complete ICO product.

5.42 ICoS Takt time Calculation Baseline

The ICoS has predicted sales for 2023 of thirty-thousand units based on a forty-nine-week working year. This calculates that for every 3.92 minutes of a production shift, a single complete ICoS valve must be built and tested on the dedicated ICoS production line to achieve the sales demand. This is based on a forty-hour working week.

However, just like Section 5.31 the actual production availability of resources to build the ICoS is limited. Due to this being a newly launched product, the operator resource is not dedicated to this product line and has thirty hours per week assigned to ICoS. After calculating IMI-C's actual production capacity, the result shows that a single ICoS must be produced every 2.94 minutes.

5.43 IFR Takt time Calculation Baseline

The IFR has a predicted sales forecast for 2023 of twelve-thousand units based on a forty-nine-week working year. Following the same methodology to calculate the Takt time, this would equate to 9.8 minutes per unit.

The current availability of resources at IMI-C to produce the IFR, taking into account available operators and resource allocation of 35 hours per week, changes the Takt time to 8.57 minutes per single IFR unit.

5.5 Batch Reduction study methodology

The research questions to be reviewed within this report is:

- Does the Lean Management methodology of single-piece flow or a traditional batch-flow production strategy produce the lowest product lead times and production costs?

As identified in section 5.3 the process for each production line (ICO, ICoS and IFR) have all been documented. These process steps create the foundation for the order each of the studies would work across:

- ICO - has nine workstations
- ICoS - has seven workstations
- IFR - has five workstations

As a logical starting point, the research study was designed to start at the first workstation regardless of which production line was being measured. From workstation one, the study would then track the defined batch throughout its production cycle until the batch had been finished. The collected data would ensure a logical stage process with the data being identifiable for traceability and data verification if required at a later stage. Every study run through a production line was labelled with an identification code to improve data traceability further.

Creating a repeatable study that could be cross-referenced against the other three production lines. The decision was taken to run the studies within a controlled environment to ensure that collected data could be used comparably. The approach was taken to control day-to-day working conditions for the production line operators.

The control required planning designated production batch runs. This was decided over a sampling methodology as a unique production run would simulate real-world conditions of different batch sizes of products. Furthermore, a sampling style of data collection would only partially reflect the changes in reducing the batch sizes or implementing SPF.

Banerjee and Chadhury (2010) state that when a sampling methodology is implemented, data collection can become less relevant to the purpose of the aim. Sampling can hide/mask other factors which would be identifiable with a population data collection methodology.

The use of designated production batch runs started with the current batch sizes currently manufactured at IMI-C:

ICO - Batch of twenty.
ICoS - Batches of twenty.
IFR - Batches of twenty.

Regardless of the area of study (production line), the principles of analysis remain the same. All batches were followed from the first production workstation all the way through their processing until the final stage of manufacture had been completed.

The study would see a reduction of two from the selected products' current batch size, which would then be repeated until an actual single-piece flow (one product) batch size was completed.

The decision to reduce the batch sizes by a factor of two units allowed the research data to be collected within the allocated timeframe whilst maximising the amount of collectable data. There would be eleven batch runs each for ICO, ICoS and IFR. This amount of products would total three-hundred-thirty-one products across ICO,IFR and ICoS, providing a wide range of data for analysis and comparison.

Zipkin (1991) states the importance of capability studies within a business is imperative to stop the escalation of tensions rising when employees and the production strategy remain unclear and need to be tested this is also, backed by Johnson (2003).

5.6 - Research Documentation

A document was designed and then created to ensure the information/data collected from the study was accurate. Each time a study was run, the following information was captured within the document:

- The recorded process time from each production line station.
- The workstation number - This allowed the processing time of the workstation to be linked to the corresponding documented time.
- What process would be conducted? IMI-C uses automated (equipment/machinery) and manual operator processing.
- The first pass yield of the product batch size (this would help to establish the actual product costs).

5.7 - Executing the batch study

At the start of the study, an employee meeting was conducted for all the staff across the ICO, ICoS and IFR production lines. The purpose was to ensure that the employees knew the following:

1. How the study would run.
2. What was required from them?
3. The reason why the study was taking place.

This provided the opportunity to communicate in detail and record ideas that the production line workers had for future product improvements from their perspectives at IMI-C. This created a communication channel for the employees to ask any questions. Treville and Antonakis (2006) explain that providing employees with opportunities to discuss process/business changes helps further increase overall employee engagement.

During the study, the collection of data from each workstation was collected through two different methods. Method one involved visual observation. A time-in-motion traditional survey was conducted this way to measure the time to complete each processing workstation from the start of production until the final operation. This method was required because it is the most accurate way to collect data from an independent witness and ensure the validity of the data.

Throughout the study, no interaction occurred with the data collector and the shop floor employees. This guaranteed that natural production environment was replicated through out the research project.

The second method required specific production processes to extract their processing time from the automated equipment. These processes were still visually observed during the study. However, the data was extracted from the equipment/machinery.

During the batch reduction study, the number of components which did not pass final inspection

testing was counted and deducted from the original batch size. This would allow the FPY to be calculated during data analysis. It was possible for the FPY to be identified during the study as the final workstation across ICO, ICoS, and IFR involves a strict pressure testing regime. It is vital for the products supplied for critical applications to conform with high-pressure industry regulations.

The collection of FPY data during the designated production batch studies across the three production lines would allow a correlation to be statistically calculated between FPY and batch sizes, further adding to the research question regarding product costings and lead times.
This would also work towards providing evidence from the research study that supports or disprove the literature review area, which highlighted SPF as a way to increase product quality resulting in a higher FPY.

6.0 Study Results layout:

This section of the report will deliver the results from the collected data during the batch reduction studies of the ICO, ICoS and IFR lines.

To reach a conclusion and answer the research project question:

- Does the Lean Management methodology of single-piece flow or a traditional batch-flow production strategy produce the lowest product lead times and production costs?

A statistical correlation method was used to understand the relationship between the two variables. The two variables are as follows:

1. The batch size run during a study will be labelled as variable X.
2. The processing time per product will be labelled as variable Y.

6.1 Data Analysis - Correlation Independent and Dependant

The batch size was defined as the independent variable X. This will be identified on the X-axis of the correlation charts. This will be the same across all studies conducted on the ICO, ICoS and IFR production lines.
The batch sizes were assigned the independent variable X because, as defined by (Laerd, 2018) independent variables can be controlled and modified as required.

The processing times were defined as the dependent variable, identified on the Y-axis of the correlation charts. This will be the same across all studies conducted on the ICO, ICoS and IFR production lines. For the analysis of the FPY, processing times were substituted with FPY. This means that for that the Y-axis will become FPY during the investigation.
The Y-axis has been labelled as the dependent variable as these factors are predicted to be impacted by a change in the X-axis (batch size).

6.2 Research Project Data

The results of all the studies conducted across ICO, ICoS and IFR were designed, so any variation between each reduction of batch sizes was limited. This involved using the same operators for each of the studies and ensuring the studies were taking place within the same amount of working shift time, for example, conducted during the morning or afternoon shifts.
The following sections have arranged the results:

ICO correlation results:

1. Reduction study one (Batch size).
2. Analysis of the First Pass Yield.

ICoS correlation results:

1. Reduction study one (Batch size).
2. Analysis of the First Pass Yield.

IFR correlation results:

1. Reduction study one (Batch size).
2. Analysis of the First Pass Yield.

6.21 ICO Processing times (Raw Data Collection)

ICO Processing times

Work-Flow Steps	Process Type	Batch Qty 20	Batch QTY 18	Batch QTY 16	Batch QTY 14	Batch QTY 12	Batch QTY 10	Batch QTY 8	Batch QTY 6	Batch QTY 4	Batch QTY 2	Batch QTY 1
Workstation 1 Coil build	Automated Process	4800	4320	3840	3360	2880	2400	1920	1440	960	480	240
Workstation 2 housing build	Manual Process	1790	1550	1339	1180	1020	873	664	502	329	166	99
Workstation 3 Resin Fill	Robotic Process	2400	2160	1920	1676	1440	1200	960	720	480	240	120
Workstation 4 Mechanical Assembly	Manual Process	1790	1501	1340	1160	980	827	625	450	268	148	57
workstation 5 Electrical Assembly	Manual Process	1915	1780	1545	1334	1136	914	670	638	400	221	106
workstation 6 Electrical test	Manual Process	5490	5120	4539	3955	3424	2848	2293	1712	1138	563	272
workstation 7 Valve assembly	Manual Process	2547	2111	1888	1640	1419	1178	946	717	466	221	112
workstation 8 Final Valve Assy	Manual Process	3790	3590	3141	2753	2355	1967	1611	1138	790	350	179
workstation 9 ICO3 Autotester	Robotic Process	1800	1620	1440	1260	1080	900	720	541	360	180	90
Single ICO3 Valve production total (Secs)		1316.1	1319.56	1312.00	1308.43	1311.17	1310.7	1301.125	1309.67	1297.75	1284.50	1275.00
Quantity of conforming Products manufactured		18	14	15	13	10	10	8	6	4	2	1
Total time to produce entire batch (Secs)		26322	23752	20992	18318	15734	13107	10409	7858	5191	2569	1275
Total time to run the complete batch reduction study (Hours)		40.50										

Table 1: ICO Raw Data Batch Reduction

6.22 ICO correlation Batch Size & Production Timings

Batch QTY	Production times (Secs)
1	1275
2	1284.50
4	1297.75
6	1309.67
8	1301.12
10	1310.70
12	1311.17
14	1308.43
16	1312.00
18	1319.56
20	1316.10

Table 2: ICO Batch QTY vs Processing times

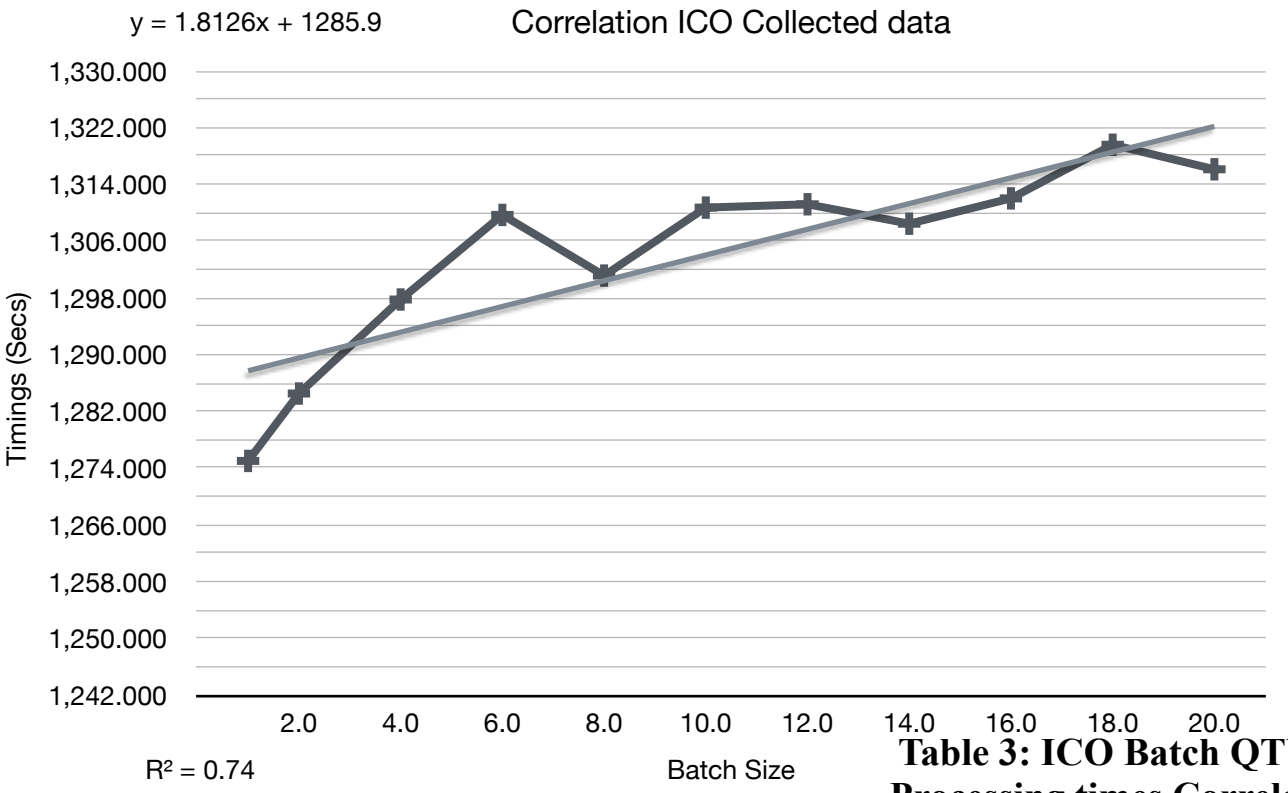

Table 3: ICO Batch QTY vs Processing times Correlation

The data points when compared against a line of best fit show a strong positive correlation as batch sizes increase so does the processing time per product

6.23 ICO Batch Size X-Axis Standard Deviation

After the data had been collected for the SPF study across all of the production processes along the ICO production line, an analysis could be calculated. The first step was to calculate the standard deviation of X (the independent variable), which has been labelled as batch quantities.

The table below displays the points of data (Batch Quantities) processed and data logged for this research project. The batch quantities are represented in column one. Column number two represents the Mean.

The following calculation was conducted to find the Mean:

$$(\bar{x}) = \frac{\Sigma X}{n} = \frac{111}{11} = 10.09$$

Column 1	Column 2	Column 3	Column 4
Data for X	**Calculation of the Mean**	**Data X Subtract Mean**	**Squared**
X	**$\bar{x}$**	**$(X - \bar{x})$**	**$\Sigma (X - \bar{x})^2$**
1	10.09	-9.09	82.63
2	10.09	-8.09	65.45
4	10.09	-6.09	37.09
6	10.09	-4.09	16.73
8	10.09	-2.09	4.37
10	10.09	-0.09	0.01
12	10.09	1.91	3.65
14	10.09	3.91	15.29
16	10.09	5.91	34.93
18	10.09	7.91	62.57
20	10.09	9.91	98.21
111			**420.91**

Table 4: ICO Batch QTY standard deviation (x-axis)

The final stage in calculating the standard deviation of X (Batch Quantities) required the Mean to be subtracted from each of the original X points of data as defined in column three of the table above. Finally, column four involved taking the results of column three and squared. The total result of the sum of column 4 was then applied to the calculation:

$$\text{Variance } \sigma^2 = \frac{\Sigma (X - \bar{x})^2}{n} = \frac{420.91}{11} = 38.26$$

The last part of the calculation required the answer to the variance calculation, which was then included in the standard deviation formula:

$$\text{Standard deviation } \sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$$

The standard deviation of X will remain the same across all three Batch reduction studies and also, during the FPY studies due to all product batch sizes reducing method being used.

6.24 ICO Processing times Y-Axis Standard Deviation

After the data had been collected for the SPF study across all of the production processes along the ICO production line, an analysis could be calculated. The standard deviation of Y (the dependent variable), which has been labelled as processing times, required calculating.

The table below displays the points of data (Batch Quantities) processed and data logged for this research project. The batch quantities are represented in column one. Column number two represents the Mean.

The following calculation was conducted to find the Mean:

$$\text{Mean } (\bar{y}) = \frac{\Sigma\, y}{n} = \frac{14346.00}{11} = 1304.18$$

Column 1	Column 2	Column 3	Column 4
Data for Y	**Calculation of the Mean**	**Data Y Subtract Mean**	**Squared**
y	**$\bar{y}$**	**$(y - \bar{y})$**	**$\Sigma\,(y - \bar{y})^2$**
1275	1304.18	-29.18	851.4724
1284.50	1304.18	-19.68	387.30
1297.75	1304.18	-6.43	41.34
1309.67	1304.18	5.49	30.14
1301.12	1304.18	-3.06	9.36
1310.70	1304.18	6.52	42.51
1311.17	1304.18	6.99	48.86
1308.43	1304.18	4.25	18.06
1312.00	1304.18	7.82	61.15
1319.56	1304.18	15.38	236.54
1316.10	1304.18	11.92	142.09
14346.00			**1868.84**

Table 5: ICO Processing Times standard deviation (Y-axis)

The final stage in calculating the standard deviation of Y (Processing Times) required the Mean to be subtracted from each of the original Y points of data as defined in column three of the table above. Finally, column four involved taking the results of column three and squared. The total result of the sum of column 4 was then applied to the calculation:

$$\text{Variance } \sigma^2 = \frac{\Sigma (y - \bar{y})^2}{n} = \frac{1868.84}{11} = 169.89$$

The last part of the calculation required the answer to the variance calculation, which was then included in the standard deviation formula:

$$\text{Standard deviation } \sigma y = \sqrt{\sigma^2} = \sqrt{169.89} = 13.03$$

6.25 Study 1 ICO - Covariance (relationship) with Correlation (Strength)

Batch quantities (X) and processing time (Y) standard deviations allows next step calculating covariance. It will highlight the relationship direction from the variables as positive or negative between the batch quantities (X) and processing times (Y).

The next step is to calculate the correlation factor. The purpose of this is to determine the strength of the correlation. Column three below shows the calculation used to form part of the final correlation calculation.

	Column 1	Column 2	Column 3
	$(X - \bar{x})$	$(y - \bar{y})$	$\Sigma (X - \bar{x})(y - \bar{y})$
	-9.09	-29.18	265.2462
	-8.09	-19.68	159.2112
	-6.09	-6.43	39.1587
	-4.09	5.49	-22.4541
	-2.09	-3.06	6.3954
	-0.09	6.52	-0.5868
	1.91	6.99	13.3509
	3.91	4.25	16.6175
	5.91	7.82	46.2162
	7.91	15.38	121.6558
	9.91	11.92	118.1272
Σ			762.94

Table 6: ICO Correlation and covariance calculation

Calculation of the deviation $\sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$ (Standard deviation)

Calculation of the deviation $\sigma y = \sqrt{\sigma^2} = \sqrt{169.89} = 13.03$ (Standard deviation)

Calculation of the Covariance using the following formula:

$$(Sxy) = \frac{\Sigma\ (X - \bar{x})\ (y - \bar{y})}{n} = \frac{762.94}{11} = \frac{762.94}{11} = 69.35$$

(Strength of relationship not determined only a positive direction)

Calculation of the correlation using the following formula:

$$(rxy) = \frac{Sxy}{(Sx)(Sy)} = \frac{69.35}{(6.18)(13.03)} = \frac{69.35}{80.52} = 0.86$$

Strong correlation exists - this will always be a result between -1 and 1.0

6.251 True Individual Production Costs

The true cost of production has been displayed in the table below. This has been calculated by taking the batch quantity measured during the batch reduction study and then calculating the average time to produce an individual product. This time in seconds has then been converted into minutes and finally multiple against IMI-C standard works shop rate.

Cost of production per ICO

Batch Size	processing times (Secs) Per Product	Minutes	Cost Of Production
1	1275	21.25	£8.15
2	1284.50	21.41	£8.21
4	1297.75	21.63	£8.29
6	1309.67	21.83	£8.37
8	1301.12	21.69	£8.31
10	1310.70	21.85	£8.37
12	1311.17	21.85	£8.38
14	1308.43	21.81	£8.36
16	1312.00	21.87	£8.38
18	1319.56	21.99	£8.43
20	1316.10	21.94	£8.41

Table 7: ICO Cost of Individual Production

6.26 Correlation Batch Quantities (X) & First Pass Yield (Y)

The table shows the batch reduction study, which reduced the amount of ICO products with each run. This is represented in column one. Column two is the record of how many from the batch reduction study confirmed the product specification once built. This has then been converted into a percentage showing the FPY of each quantity reduction study, displayed in column three.
The FPY has been converted to a percentage before being plotted. Using a percentage as a measurement creates a comparable data set that can be compared between each batch reduction study.

ICO FPY Table

column 1	column 2	column 3
Batch Size	**ICO Batch FPY QTY (Built within Spec)**	**FPY batch size percentage**
1	1	100%
2	2	100%
4	4	100%
6	6	100%
8	8	100%
10	10	100%
12	10	100%
14	13	83%
16	15	93%
18	14	77%
20	18	90%
111	101	91%

Table 8: ICO Batch QTY vs First Pass Yield

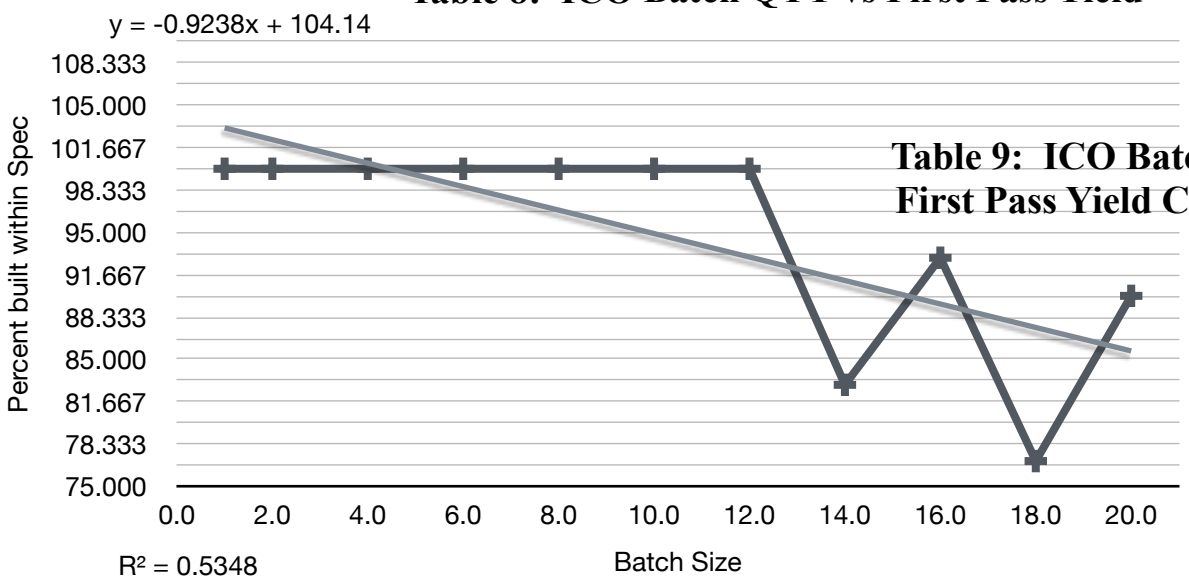

Table 9: ICO Batch QTY vs First Pass Yield Correlation

The data points when compared against a line of best fit show an average negative correlation as batch sizes increase the FPY decreases. However the FPY data remains unchanged until batch size reach above 12 QTY.

6.27 ICO FPY Batch Size X-Axis Standard Deviation

The same calculations as 6.23, calculating standard deviation of the batch quantities (X-axis) Calculations below conducted to find the Mean:

$$(\bar{x}) = \frac{\Sigma X}{n} = \frac{111}{11} = 10.09$$

Data for X	Calculation of the Mean	Data X Subtract Mean	Squared
X	**$\bar{x}$**	**$(X - \bar{x})$**	**$\Sigma (X - \bar{x})^2$**
1	10.09	-9.09	82.63
2	10.09	-8.09	65.45
4	10.09	-6.09	37.09
6	10.09	-4.09	16.73
8	10.09	-2.09	4.37
10	10.09	-0.09	0.01
12	10.09	1.91	3.65
14	10.09	3.91	15.29
16	10.09	5.91	34.93
18	10.09	7.91	62.57
20	10.09	9.91	98.21
111			**420.91**

Table 10: ICO FPY Batch QTY standard deviation (x-axis)

(Calculation of Variance) $\sigma^2 = \frac{\Sigma (X - \bar{x})^2}{n} = \frac{420.91}{11} = 38.26$

Calculation Standard deviation $\sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$

The standard deviation of X will remain the same across all three Batch reduction studies and also, during the FPY studies due to all product batch sizes reducing method being used.

6.28 ICO FPY Y-Axis Standard Deviation

The same calculations as 6.24. Calculating standard deviation of the FPY (Y-axis)
The following calculation was conducted to find the Mean:

$$\text{Mean } (\bar{y}) = \frac{\Sigma\, y}{n} = \frac{1043}{11} = 94.81$$

Data for Y	Calculation of the Mean	Data Y Subtract Mean	Squared
y	$\bar{y}$	$(y - \bar{y})$	$\Sigma\,(y - \bar{y})^2$
100.00	94.81	5.19	26.94
100.00	94.81	5.19	26.94
100.00	94.81	5.19	26.94
100.00	94.81	5.19	26.94
100.00	94.81	5.19	26.94
100.00	94.81	5.19	26.94
100.00	94.81	5.19	26.94
83.00	94.81	-11.81	139.48
93.00	94.81	-1.81	3.28
77.00	94.81	-17.81	317.20
90.00	94.81	-4.81	23.14
1043.00			671.64

Table 11: ICO FPY Percentage standard deviation (Y-axis)

$$\text{Variance } \sigma^2 = \frac{\Sigma\,(y - \bar{y})^2}{n} = \frac{671.64}{11} = 61.05$$

$$\text{Standard deviation } \sigma y = \sqrt{\sigma^2} = \sqrt{61.05} = 7.81$$

6.29 First Pass Yield Study 1 - Covariance (relationship) and Correlation (Strength)

The same calculations as section 6.25 to determine Covariance (relationship) and Correlation (Strength) of the batch quantity and first pass yield.

Table 12: ICO FPY Correlation and covariance calculation

	$(X - \bar{x})$	$(y - \bar{y})$	$\Sigma (X - \bar{x})(y - \bar{y})$
	-9.09	5.19	-47.18
	-8.09	5.19	-41.99
	-6.09	5.19	-31.61
	-4.09	5.19	-21.23
	-2.09	5.19	-10.85
	-0.09	5.19	-0.47
	1.91	5.19	9.91
	3.91	-11.81	-46.18
	5.91	-1.81	-10.70
	7.91	-17.81	-140.88
	9.91	-4.81	-47.67
Σ			-388.82

(Calculation of Standard deviation) $\sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$

(Calculation of Standard deviation $\sigma y = \sqrt{\sigma^2} = \sqrt{61.05} = 7.81$

Calculation of the Covariance using the following formula:

$$Sxy = \frac{\Sigma\ (X - \bar{x})\ (y - \bar{y})}{n} = \frac{-388.82}{11} = \frac{-388.82}{11} = -35.34$$

(Strength of relationship not determined only a negative direction)

Calculation of the correlation using the following formula:

$$rxy = \frac{Sxy}{(Sx)(Sy)} = \frac{-35.34}{(6.18)(7.81)} = \frac{-35.34}{48.26} = -0.73$$

Strong correlation exists - this will always be a result between -1 and 1.0

6.30 ICoS Processing times (Raw Data Collection)

ICoS Processing times

Work-Flow Steps	Process Type	Batch QTY 20	Batch QTY 18	Batch QTY 16	Batch QTY 14	Batch QTY 12	Batch QTY 10	Batch QTY 8	Batch QTY 6	Batch QTY 4	Batch QTY 2	Batch QTY 1
Workstation 1 Coil joining	Automated Process	4130	3600	3200	2800	2400	2000	1600	1200	800	400	200
Workstation 2 coil build	Manual Process	2790	2450	2336	2070	1756	1449	1158	880	598	300	145
Workstation 3 Coil + Pot Assembly	Automated Process	960	864	768	672	576	480	384	288	192	96	48
workstation 4 Valve assembly	Manual Process	4988	4160	3790	3246	2769	2430	1837	1369	935	450	230
workstation 5 Diode Installation	Manual Process	2780	2380	2109	1760	1437	1206	964	730	460	220	119
workstation 6 Final Valve Assy	Manual Process	3768	3369	3017	2603	2179	1920	1470	1097	710	340	180
workstation 7 ICoS Auto-tester	Automated Process	2400	2160	1920	1680	1440	1200	960	720	480	240	120
Average Single ICoS production total (Secs)		1090.80	1054.61	1071.25	1059.36	1046.42	1068.5	1046.63	1047.33	1043.75	1023.00	1042.00
Quantity of conforming products manufactured		19	17	16	13	9	10	8	5	4	2	1
Total time to produce entire batch (Secs)		21816	18983	17140	14831	12557	10685	8373	6284	4175	2046	1042

Table 13: ICoS Raw Data Batch Reduction

6.31 ICoS correlation Batch Size & Processing Times

Batch Size	processing times (Secs)
1	1042
2	1023.00
4	1043.75
6	1047.33
8	1046.62
10	1068.50
12	1046.42
14	1059.36
16	1071.25
18	1054.61
20	1090.80

Table 14: ICoS Batch QTY vs Processing times

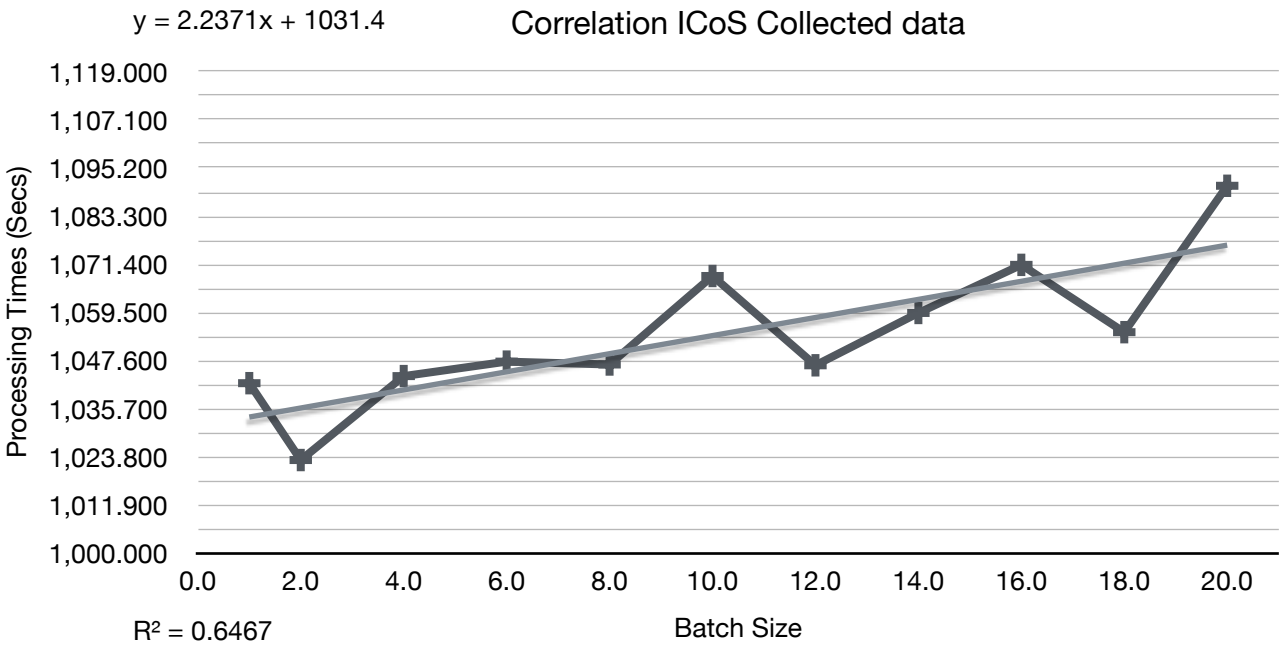

Table 15: ICoS Batch QTY vs Processing times Correlation

The data points when compared against a line of best fit show a positive correlation as batch sizes increase so does the processing time per ICoS

6.32 ICoS - Batch Size X-Axis Standard Deviation

$$(\bar{x}) = \frac{\Sigma X}{n} = \frac{111}{11} = 10.09$$

Column 1	Column 2	Column 3	Column 4
Data for X	**Calculation of the Mean**	**Data X Subtract Mean**	**Squared**
X	$\bar{x}$	$(X - \bar{x})$	$\Sigma (X - \bar{x})^2$
1	10.09	-9.09	82.63
2	10.09	-8.09	65.45
4	10.09	-6.09	37.09
6	10.09	-4.09	16.73
8	10.09	-2.09	4.37
10	10.09	-0.09	0.01
12	10.09	1.91	3.65
14	10.09	3.91	15.29
16	10.09	5.91	34.93
18	10.09	7.91	62.57
20	10.09	9.91	98.21
111			**420.91**

Table 16: ICoS Batch QTY standard deviation (x-axis)

$$(\text{Variance})\ \sigma^2 = \frac{\Sigma (X - \bar{x})^2}{n} = \frac{420.91}{11} = 38.26$$

$$(\text{Standard deviation})\ \sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$$

The standard deviation of X will remain the same across all three Batch reduction studies and also, during the FPY studies due to all product batch sizes reducing method being used.

6.33 ICoS- Processing times Y-Axis Standard Deviation

$$\text{Mean } (\bar{y}) = \frac{\Sigma y}{n} = \frac{11593.64}{11} = 1053.96$$

Data for Y	Calculation of Mean	Data Y Subtract Mean	Squared
y	**$\bar{y}$**	**$(y - \bar{y})$**	**$\Sigma (y - \bar{y})^2$**
1042	1053.96	-11.96	143.04
1023.00	1053.96	-30.96	958.52
1043.75	1053.96	-10.21	104.24
1047.33	1053.96	-6.63	43.96
1046.62	1053.96	-7.34	53.88
1068.50	1053.96	14.54	211.41
1046.42	1053.96	-7.54	56.85
1059.36	1053.96	5.40	29.16
1071.25	1053.96	17.29	298.94
1054.61	1053.96	0.65	0.42
1090.80	1053.96	36.84	1357.19
11593.64			**3257.62**

Table 17 : ICoS Processing Times standard deviation (Y-axis

$$\text{Variance } \sigma^2 = \frac{\Sigma (y - \bar{y})^2}{n} = \frac{3257.62}{11} = 296.14$$

$$\text{(Standard deviation) } \sigma y = \sqrt{\sigma^2} = \sqrt{296.14} = 17.20$$

6.34 ICoS Batch Reduction Study 2 - Covariance (relationship) and Correlation (Strength)

	(X - x̄)	(y - ȳ)	Σ (X - x̄)(y - ȳ)
	-9.09	-11.96	108.72
	-8.09	-30.96	250.47
	-6.09	-10.21	62.18
	-4.09	-6.63	27.12
	-2.09	-7.34	15.34
	-0.09	14.54	-1.31
	1.19	-7.54	-8.97
	3.91	5.40	21.11
	5.91	17.29	102.18
	7.91	0.65	5.14
	9.91	36.84	365.08
Σ			947.06

Table 18: ICoS Correlation and covariance calculation

Calculation of the deviation $\sigma y = \sqrt{\sigma^2} = \sqrt{296.14} = 17.20$ (Standard deviation)

Calculation of the deviation $\sigma x = \sqrt{\sigma^2} = \sqrt{31.29} = 6.18$ (Standard deviation)

Calculation of the Covariance using the following formula:

$$Sxy = \frac{\Sigma\ (X - \bar{x})\ (y - \bar{y})}{n} = \frac{947.06}{11} = \frac{947.06}{11} = 86.09$$

(Strength of the relationship not determined only a positive direction)

Calculation of the Covariance using the following formula:

$$rxy = \frac{Sxy}{(Sx)(Sy)} = \frac{86.09}{(6.18)(17.20)} = \frac{86.09}{106.29} = 0.80$$

Strong correlation exists - this will always be a result between -1 and 1.0

6.341 True Individual Production Cost ICoS

The true cost of production has been displayed in the table below. This has been calculated by taking the batch quantity measured during the batch reduction study and then calculating the average time to produce an individual product. This time in seconds has then been converted into minutes and finally multiple against IMI-C standard works shop rate:

Cost of production per ICoS

Batch Size	processing times (Secs)	Minutes	Cost Of Production
1	1042	17.37	£6.66
2	1023.00	17.05	£6.54
4	1043.75	17.40	£6.67
6	1047.33	17.46	£6.69
8	1046.62	17.44	£6.69
10	1068.50	17.81	£6.83
12	1046.42	17.44	£6.69
14	1059.36	17.66	£6.77
16	1071.25	17.85	£6.84
18	1054.61	17.58	£6.74
20	1090.80	18.18	£6.97

Table 19: ICoS Cost of Individual Production

6.35 ICoS - Correlation Batch Quantities (X) & First Pass Yield (Y)

ICoS FPY Table

Batch Size	ICoS Batch FPY QTY	FPY batch size percentage
1	1	100%
2	2	100%
4	4	100%
6	5	83%
8	8	100%
10	10	100%
12	9	75%
14	13	92%
16	16	100%
18	17	94%
20	19	95%
111	104	94%

Table 20: ICoS Batch QTY vs First Pass Yield

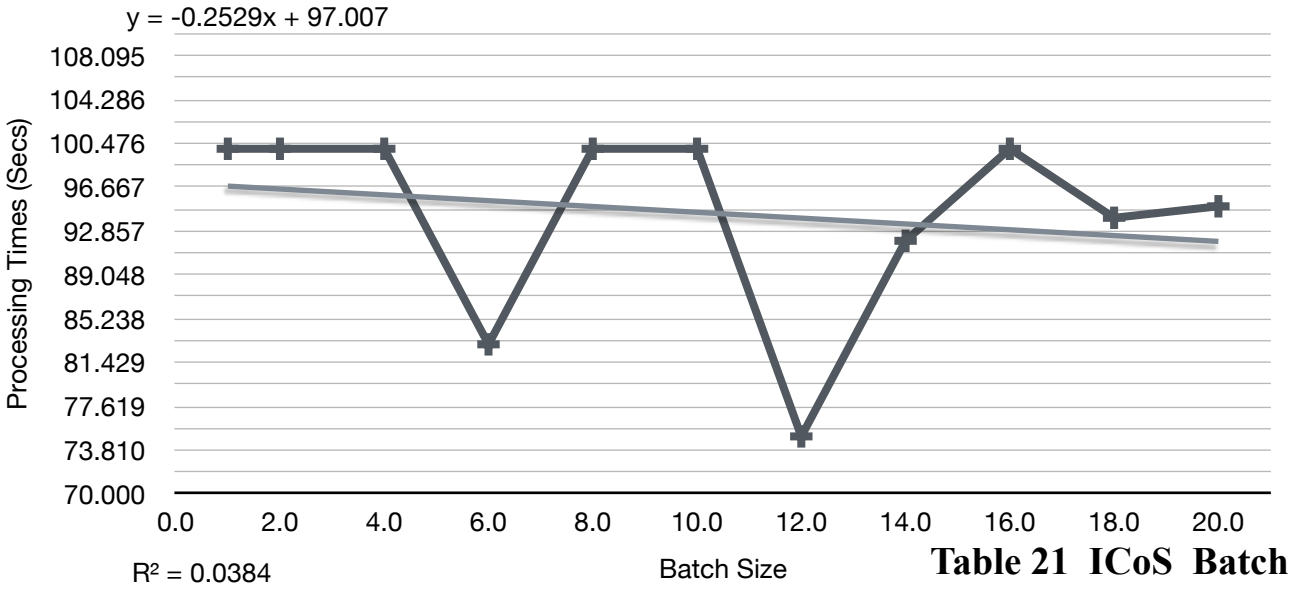

Table 21 ICoS Batch QTY vs First Pass Yield Correlation

The data points when compared against a line of best fit show a weak to no correlation exists as batch sizes increase the FPY decreases at certain points and but not continually

6.36 ICoS Batch Size X-Axis Standard Deviation

The same calculations as 6.23, calculating standard deviation of the batch quantities (X-axis) calculations below conducted to find the Mean:

$$(\bar{x}) = \frac{\Sigma X}{n} = \frac{111}{11} = 10.09$$

Data for X	Calculation of the Mean	Data X subtract Mean	Squared
X	**$\bar{x}$**	**$(X - \bar{x})$**	**$\Sigma (X - \bar{x})^2$**
1	10.09	-9.09	82.63
2	10.09	-8.09	65.45
4	10.09	-6.09	37.09
6	10.09	-4.09	16.73
8	10.09	-2.09	4.37
10	10.09	-0.09	0.01
12	10.09	1.91	3.65
14	10.09	3.91	15.29
16	10.09	5.91	34.93
18	10.09	7.91	62.57
20	10.09	9.91	98.21
111			**420.91**

Table 22: ICoS FPY Batch QTY standard deviation (x-axis)

$$\text{Variance } \sigma^2 = \frac{\Sigma (X - \bar{x})^2}{} = \frac{420.91}{} = 38.26$$

$$\text{(Standard deviation) } \sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$$

The standard deviation of X will remain the same across all three Batch reduction studies and also, during the FPY studies due to all product batch sizes reducing method being used.

6.37 ICoS First Pass Yield Y-Axis Standard Deviation

The same calculations as 6.24 calculating standard deviation of the first pass yield (Y-axis)
Calculation below conducted to find the Mean:

$$(\bar{y}) = \frac{\Sigma y}{n} = \frac{1039}{11} = 94.45$$

Data Points	Mean Data	Data Point Subtract Mean	Data point Subtract Mean Squared
y	**$\bar{y}$**	**$(y - \bar{y})$**	**$\Sigma (y - \bar{y})^2$**
100	94.45	5.55	30.80
100	94.45	5.55	30.80
100	94.45	5.55	30.80
83	94.45	-11.45	131.10
100	94.45	5.55	30.80
100	94.45	5.55	30.80
75	94.45	-19.45	378.30
92	94.45	-2.45	6.00
100	94.45	5.55	30.80
94	94.45	-0.45	0.20
95	94.45	0.55	0.30
1039			**700.73**

Table 23: ICoS FPY Percentage standard deviation (Y-axis)

$$\text{Variance } \sigma^2 = \frac{\Sigma (y - \bar{y})^2}{n} = \frac{700.73}{11} = 63.70$$

$$\text{(Standard deviation) } \sigma y = \sqrt{\sigma^2} = \sqrt{63.70} = 7.98$$

6.38 ICoS First Pass Yield Study 2 - Covariance (relationship) and Correlation (Strength)

The same calculations as section 6.25 to determine Covariance (relationship) and Correlation (Strength) of the batch quantity and first pass yield:

	$(X - \bar{x})$	$(y - \bar{y})$	$\Sigma (X - \bar{x})(y - \bar{y})$
	-9.09	5.55	-50.45
	-8.09	5.55	-44.90
	-6.09	5.55	-33.80
	-4.09	-11.45	46.83
	-2.09	5.55	-11.60
	-0.09	5.55	-0.50
	1.91	-19.45	-37.15
	3.91	-2.45	-9.58
	5.91	5.55	32.80
	7.91	-0.45	-3.56
	9.91	0.55	5.45
Σ			-106.45

Table 24: ICoS FPY Correlation and covariance calculation

(Calculation of Standard deviation) $\sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$

(Calculation of Standard deviation) $\sigma y = \sqrt{\sigma^2} = \sqrt{63.72} = 7.98$

Calculation of the Covariance using the following formula:

$$Sxy = \frac{\Sigma (X - \bar{x})(y - \bar{y})}{n} = \frac{-106.45}{11} = \frac{-106.45}{11} = -9.67$$

(strength of relationship not determined only a negative direction)

Calculation of the correlation using the following formula:

$$rxy = \frac{Sxy}{(Sx)(Sy)} = \frac{-9.67}{(6.18)(7.98)} = \frac{-9.67}{} = -0.19$$

weak/no correlation exists - this will always be a result between -1 and 1.0

6.39 IFR Processing times (Raw Data Collection)

IFR Processing times

Work-Flow Steps	Process Type	Batch QTY 20	Batch QTY 18	Batch QTY 16	Batch QTY 14	Batch QTY 12	Batch QTY 10	Batch QTY 8	Batch QTY 6	Batch QTY 4	Batch QTY 2	Batch QTY1
Workstation 1 Shell build	Manual Process	647	535	480	410	350	320	240	210	130	73	30
Workstation 2 housing build	Manual Process	2100	1760	1529	1340	1130	940	790	610	410	192	95
Workstation 3 Filter build	Manual Process	2935	2520	2214	1890	1624	1353	1107	850	536	280	138
Workstation 4 Final Valve Assy	Manual Process	4187	3758	3402	2968	2608	2120	1610	1100	830	390	200
Workstation 5 Final Test	Manual Process	849	745	615	580	456	387	346	297	156	95	40
												85
Single IFR Valve production total (Secs)		535.90	517.67	515.00	513.43	514.00	512.00	511.63	511.17	515.50	515.00	503.00
Quantity of conforming Products manufactured		12	17	16	12	10	10	8	6	4	2	1
Produce entire batch (Secs)		10718	9318	8240	7188	6168	5120	4093	3067	2062	1030	503

Table 25: IFR Raw Data Batch Reduction

6.40 IFR correlation Batch Size & Processing Times

Batch Size	processing times (Secs)
1	503
2	515.00
4	515.50
6	511.17
8	511.62
10	512.00
12	514.00
14	513.43
16	515.00
18	517.67
20	535.90

Table 26: IFR Batch QTY vs Processing times

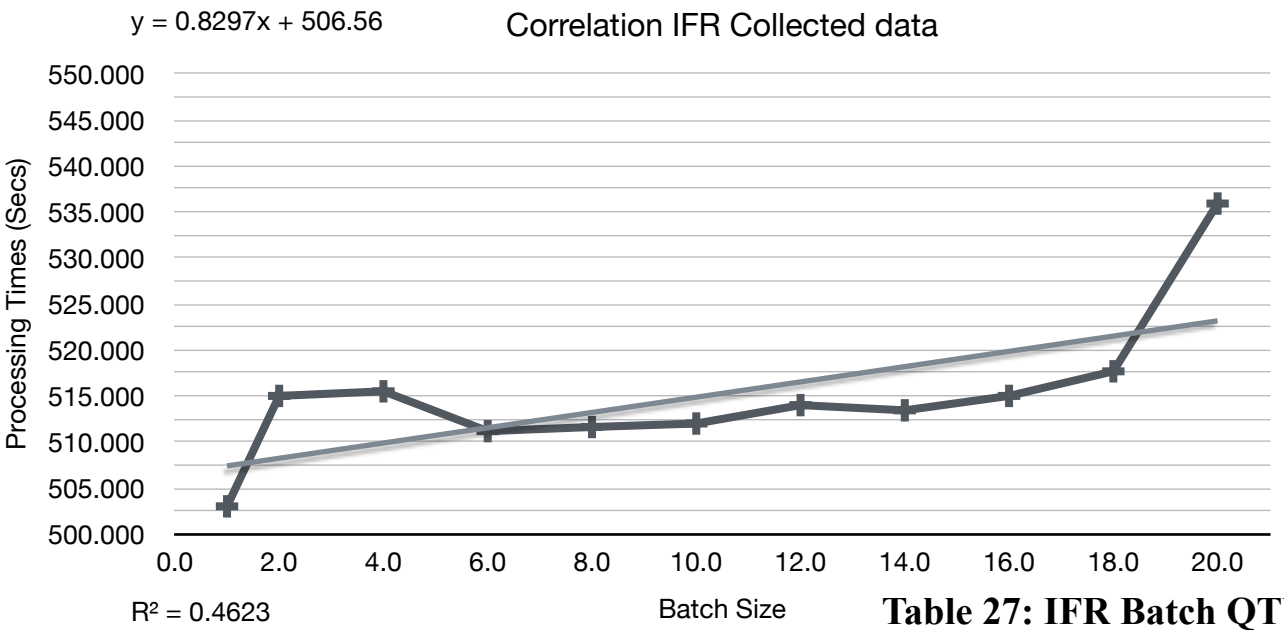

Table 27: IFR Batch QTY vs Processing times Correlation

The data points when compared against a line of best fit show a weak correlation as batch sizes increase so does the processing time per IFR. However, the correlation data is weak unlike the two prior studies.

6.41 IFR - Batch Size X-Axis Standard Deviation

$$(\bar{x}) = \frac{\Sigma X}{n} = \frac{111}{11} = 10.09$$

Data for X	Calculation of the Mean	Data X Subtract Mean	Squared
X	**$\bar{x}$**	**$(X - \bar{x})$**	**$\Sigma (X - \bar{x})^2$**
1	10.09	-9.09	82.63
2	10.09	-8.09	65.45
4	10.09	-6.09	37.09
6	10.09	-4.09	16.73
8	10.09	-2.09	4.37
10	10.09	-0.09	0.01
12	10.09	1.91	3.65
14	10.09	3.91	15.29
16	10.09	5.91	34.93
18	10.09	7.91	62.57
20	10.09	9.91	98.21
111			**420.91**

Table 28: IFR Batch QTY standard deviation (x-axis)

$$\text{Variance } \sigma^2 = \frac{\Sigma (X - \bar{x})^2}{n} = \frac{420.90}{11} = 38.26$$

$$\text{(Standard deviation) } \sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$$

The standard deviation of X will remain the same across all three Batch reduction studies and also, during the FPY studies due to all product batch sizes reducing method being used.

6.42 IFR- Processing times Y-Axis Standard Deviation

$$(\bar{y}) = \frac{\Sigma y}{n} = \frac{5664.29}{11} = 514.93$$

Data for Y	Calculation of the Mean	Data Y Subtract Mean	Squared
y	**$\bar{y}$**	**$(y - \bar{y})$**	**$\Sigma (y - \bar{y})^2$**
503	513.92	-10.92	119.2464
515.00	513.92	1.08	1.17
515.50	513.92	1.58	2.50
511.17	513.92	-2.75	7.56
511.62	513.92	-2.30	5.29
512.00	513.92	-1.92	3.69
514.00	513.92	0.08	0.01
513.43	513.92	-0.49	0.24
515.00	513.92	1.08	1.17
517.67	513.92	3.75	14.06
535.90	513.92	21.98	483.12
5664.29			**638.04**

Table 29: IFR Processing Times standard deviation (Y-axis)

$$\text{Variance } \sigma^2 = \frac{\Sigma (y - \bar{y})^2}{n} = \frac{638.04}{11} = 58.00$$

$$\text{(Standard deviation) } \sigma y = \sqrt{\sigma^2} = \sqrt{58.00} = 7.61$$

6.43 IFR Batch Reduction Study 3 - Covariance (relationship) and Correlation (Strength)

	(X - x̄)	(y - ȳ)	Σ (X - x̄)(y - ȳ)
	-9.09	-10.92	99.26
	-8.09	1.08	-8.74
	-6.09	1.58	-9.62
	-4.09	-2.57	10.51
	2.09	-2.3	-4.81
	-0.09	-1.92	0.17
	1.91	0.08	0.15
	3.91	-0.49	-1.92
	5.91	1.08	6.38
	7.91	3.75	29.66
	9.91	21.98	217.82
Σ			338.88

Table 30: IFR Correlation and covariance calculation

Calculation of the deviation $\sigma x = \sqrt{\sigma^2} = \sqrt{38.91} =$

Calculation of the deviation $\sigma y = \sqrt{\sigma^2} = \sqrt{58.00} = 7.61$

Calculation of the Covariance using the following formula:

$$Sxy = \frac{\Sigma\ (X - \bar{x})\ (y - \bar{y})}{n} = \frac{338.88}{11} = \frac{338.88}{11} = 30.80$$

(Strength of relationship not determined only a positive direction)

Calculation of the Correlation using the following formula:

$$rxy = \frac{Sxy}{(Sx)(Sy)} = \frac{30.80}{(6.18)(7.61)} = \frac{30.80}{47.02} = 0.65$$

Strong correlation exists - this will always be a result between -1 and 1.0

6.431 True Individual Production Cost IFR

The true cost of production has been displayed in the table below. This has been calculated by taking the batch quantity measured during the batch reduction study and then calculating the average time to produce an individual product. This time in seconds has then been converted into minutes and finally multiple against IMI-C standard works shop rate:

Cost of production per IFR

Batch Size	processing times (Secs)	Minutes	Cost Of Production
1	503	8.38	£3.21
2	515.00	8.58	£3.29
4	515.50	8.59	£3.29
6	511.17	8.52	£3.27
8	511.62	8.53	£3.27
10	512.00	8.53	£3.27
12	514.00	8.57	£3.28
14	513.43	8.56	£3.28
16	515.00	8.58	£3.29
18	517.67	8.63	£3.31
20	535.90	8.93	£3.42

Table 31: IFR Cost of Individual Production

6.44 IFR - Correlation Batch Quantities (X) & First Pass Yield (Y)

Table 32 IFR Batch QTY vs First Pass Yield

Starting Batch Size	Passed final inspection (%)
1	100
2	100
4	100
6	100
8	100
10	100
12	83
14	85
16	100
18	94
20	60

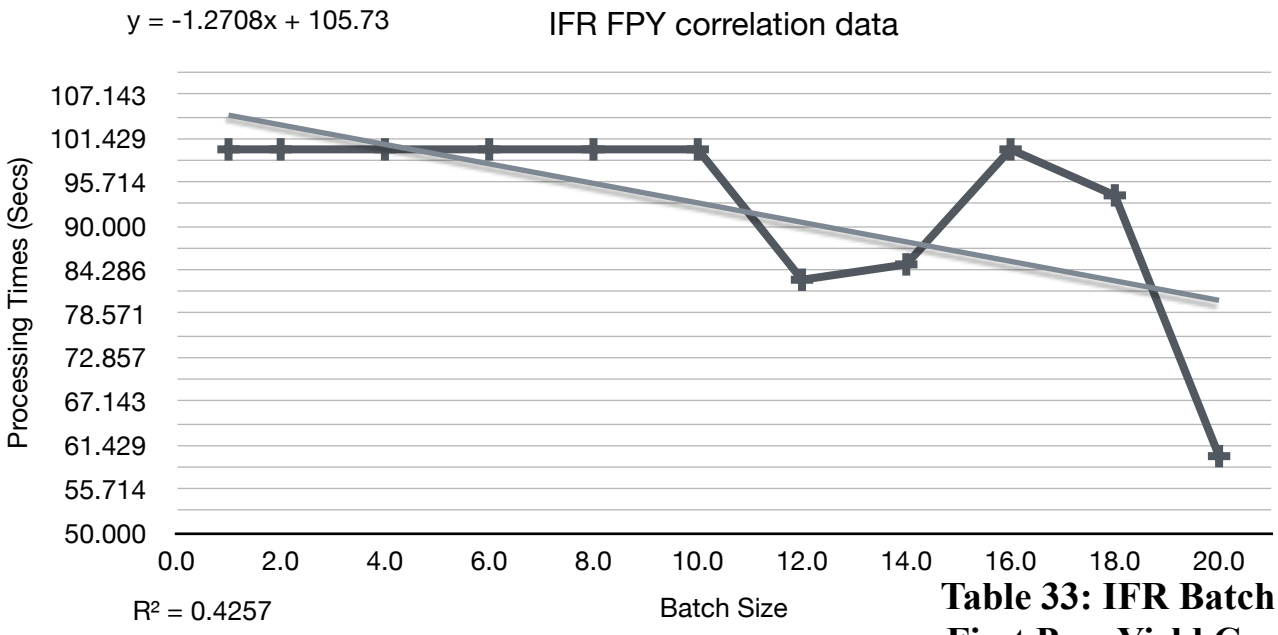

Table 33: IFR Batch QTY vs First Pass Yield Correlation

The data points when compared against a line of best fit show some form of a negative correlation as batch sizes increase the FPY decreases. However the FPY data remains unchanged until batch size reach above 10 QTY.

6.45 IFR Batch Size X-Axis Standard Deviation

The same calculations as 6.23, calculating standard deviation of the batch quantities (X-axis)
Calculations below conducted to find the Mean:

$$(\bar{x}) = \frac{\Sigma X}{n} = \frac{111}{11} = 10.09$$

Data for X	Calculation of the Mean	Data X Subtract Mean	Squared
X	**$\bar{x}$**	**$(X - \bar{x})$**	**$\Sigma (X - \bar{x})^2$**
1	10.09	-9.09	82.63
2	10.09	-8.09	65.45
4	10.09	-6.09	37.09
6	10.09	-4.09	16.73
8	10.09	-2.09	4.37
10	10.09	-0.09	0.01
12	10.09	1.91	3.65
14	10.09	3.91	15.29
16	10.09	5.91	34.93
18	10.09	7.91	62.57
20	10.09	9.91	98.21
111			**420.91**

Table 34: IFR FPY Batch QTY standard deviation (x-axis)

Calculation of Variance $\sigma^2 = \frac{\Sigma (X - \bar{x})^2}{n} = \frac{420.91}{11} = 38.26$

Calculation of Standard deviation $\sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$

The standard deviation of X will remain the same across all three Batch reduction studies and also, during the FPY studies due to all product batch sizes reducing method being used.

6.46 IFR First Pass Yield Y-Axis Standard Deviation

The same calculations as 6.24, calculating standard deviation of the FPY (Y-axis)
The following calculation was conducted to find the Mean:

$$(\bar{y}) = \frac{\Sigma y}{n} = \frac{1022}{11} = 92.90$$

Data for Y	Calculation of the Mean	Data Y subtract Mean	Squared
y	**$\bar{y}$**	**$(y - \bar{y})$**	**$\Sigma (y - \bar{y})^2$**
100	92.90	7.10	50.41
100	92.90	7.10	50.41
100	92.90	7.10	50.41
100	92.90	7.10	50.41
100	92.90	7.10	50.41
100	92.90	7.10	50.41
83	92.90	-9.90	98.01
85	92.90	-7.90	62.41
100	92.90	7.10	50.41
94	92.90	1.10	1.21
60	92.90	-32.90	1082.41
1022			**1596.91**

Table 35: IFR FPY Percentage standard deviation (Y-axis)

$$\text{Variance } \sigma^2 = \frac{\Sigma (y - \bar{y})^2}{n} = \frac{1596.91}{11} = 145.17$$

$$\text{Standard deviation } \sigma y = \sqrt{\sigma^2} = \sqrt{145.17} = 12.04$$

6.47 IFR First Pass Yield Study 2 - Covariance (relationship) and Correlation (Strength)

The same calculations as section 6.25 to determine Covariance (relationship) and Correlation (Strength) of the batch quantity and first pass yield:

	$(X - \bar{x})$	$(y - \bar{y})$	$\Sigma (X - \bar{x})(y - \bar{y})$
	-9.09	7.10	-64.54
	-8.09	7.10	-57.44
	-6.09	7.10	-43.24
	-4.09	7.10	-29.04
	-2.09	7.10	-14.84
	-0.09	7.10	-0.64
	1.91	-9.90	-18.91
	3.91	-7.90	-30.89
	5.91	7.10	41.96
	7.91	1.10	8.70
	9.91	-32.90	-326.04
Σ			-534.91

Table 36: IFR FPY Correlation and covariance calculation

(Calculation of the Standard deviation) $\sigma x = \sqrt{\sigma^2} = \sqrt{38.26} = 6.18$

(Calculation of the Standard deviation) $\sigma y = \sqrt{\sigma^2} = \sqrt{145.17} = 12.04$

Calculation of the Covariance using the following formula:

$$Sxy = \frac{\Sigma (X - \bar{x})(y - \bar{y})}{n} = \frac{-534.91}{11} = \frac{-534.91}{11} = -48.62$$

(strength of relationship not determined only a negative direction)

Correlation formula:

$$rxy = \frac{Sxy}{(Sx)(Sy)} = \frac{-48.62}{(6.18)(12.04)} = \frac{-48.62}{74.40} = -0.65$$

Strong correlation exists- this will always be a result between -1 and 1.0

7.0 Critical Evaluation of the Results

After the completion of the research study, the Pearson correlation factor was selected to highlight the strength of the relationship between batch size and processing times. The Pearson correlation factor was calculated as the next stage from the covariance calculation due to the covariance being an infinite scale that does not provide a comparable scale between each of the studies. It only provides the direction of the relationship between the two variables (Processing time vs Batch size). It was vital to understand the results of each of the studies in a similar format to provide an answer to the research question.

The theory of the Pearson correlation coefficient allows the covariance to be calculated and defined within in determined scale. The scale is as follows: R=+1 identifies a strong positive correlation, whilst a result of R=-1 identifies a strong negative correlation. The theory of Pearson also states that R=0 highlights that no correlation exists between a variable and a potential dependent (Lared, 2018).

The study has identified that the ICO and ICoS studies identify a strong positive correlation between the two variables, product processing times and batch sizes. With ICO calculated at R0.86 and ICoS calculated at R.08. A positive correlation does exist within the IFR production line. However, the strength of the correlation is moderate at R0.65, but the result shows that significant correlations exist.

The combined analysis of all three studies completed generated a correlation of R0.91. This was achieved by taking the average data sets from each of the studies (ICO, ICoS and IFR) and calculating the mean value of each. This allows the project variables within each of the studies to be taken into account from the combined data set analysis using Pearson's correlation coefficient theory. A result of R0.91 highlights a strong positive correlation between the batch sizes run through the production lines and the individual processing times of products.

The three studies (ICO, ICoS and IFR) and the combined analysis all support the literature review findings, which identified smaller batch sizes and, ultimately, SPF reduces product lead times over traditional high batch manufacturing production strategies (Burcher and Dupernex 1996: Miltenburg 2000: Stevenson 1996).

Below shows the differences in the current standard batch size of twenty produced at IMI-C and the smallest batch size during the study (SPF). The result show:

ICO batch 20 vs batch 1
1316.10 - 1275 = 41secs

ICoS batch 20 vs batch 1
1090.8 - 1042 = 48.8 secs

IFR batch 20 vs batch 1
535.99 - 503 = 32.99 secs

It was identified that a positive correlation exists between the cost of production per unit and the batch sizes run through each of the three production lines.

Unfortunately, the cause of the correlation is not identified using linear correlation. Only the acknowledgement of its existence is established. This has generated further questions regarding how the identified variables impact the results. Do any unknown variables exists which could be influencing the study data? Could the skill level of the operators used within the study impact the study?

This is the main disadvantage of using Pearson's correlation coefficient. It does not solve the reason for causation. The results of the project have answered the research question (aim):

- *Does the Lean Management methodology of single-piece flow or a traditional batch-flow production strategy produce the lowest product lead times and production costs?*

The research data collected during this project has identified that IMI-C needs to review further the ICO, ICoS and IFR production lines to understand the causation of the linear correlation. The investigation for future research should focus on why a correlation exists. The following questions must be answered before any official changes are made to IMI-C's current production strategy.

- What is the causation of the correlation?
- Are there any additional unknown variables influencing the study?

The causation is critical to establishing a new production strategy that maximises resource effectiveness and gains for IMI-C. For example, understanding the causation for the reduction of 41secs per ICO product built using SPF over traditional twenty-sized batches over a year period creates an increase in IMI-Cs capacity of over six-hundred hours.

The correlation coefficient for all three of the batch studies (ICO, ICoS and IFR) highlights strong repeatability in the process across all the production lines. It must be noted that the discrepancies within the data do not exist across the automated process, only the manual processes. This raises the point IMI-C should focus on fully automating its production lines to help generate a more stable and repeatable set of processes, which would also reduce labour overheads across its products. This level of review regarding automation is outside the scope of this project timescale.

7.1 FPY critical evaluation

The results of the FPY show:

ICO - Strong negative correlation.
ICoS - very weak negative correlation.
IFR - Medium to strong negative correlation.

There is evidence from the study that a correlation exists between batch size and FPY. The result of the data supports that as batch sizes decrease, the quantity of the FPY percentage increases, resulting in a higher level of defect-free products. This supports the literature review, which identified that case studies had reported the implementation of SPF to have increased the output and quality and reduced scrap products leading to lower production costs (Ogie Kustiadi et al, 2018).

The result of this data requires further investigation to determine causation and if there are any variables within the causation which are variables such as:

- Is it operator training
- Unknown production factors?
- What are the limitations of the equipment used within the production lines?

The correlation factors for ICO, ICoS and IFR production lines were not fundamental in answering the project aim. However, this data will assist IMI-C in investigating causation and improving manufactured product quality.

The limitations of the FPY study are that the FPY was only collected at the end of the production lines once a batch was completed. So, the actual FPY could be lower than recorded within this study. There is the possibility that defective products, such as sub-assemblies, could have been built at certain stages of the line and then replaced.

The data results collected during this study will be sent to IMI-C senior management team for review as a baseline starting point to help shape the business's current production strategy.

7.2 Critical Evaluation of the Project

The objectives of the project as defined in section 3.2. The project was completed within the designed schedule. This was achieved by following a systematic, structured approach. This level of time management was instrumental in delivering the project. However, it must be noted that due to time constraints, the project did not allow for any re-testing of batch runs to revalidate data. This further leads to whether the same results would be achievable or close if the batch study was re-run across ICO, ICoS and IFR production lines.

The project could have been delayed if any of the studies' data had been corrupted due to no time within the plan to re-conduct any batch studies. This highlights the importance of building extra time allowance into projects to account for unforeseen circumstances.

As defined in section 5.3 of the report, process maps were created for all three production lines, ICO, ICoS and IFR, allowing each batch reduction study to be determined from the start until the end of production. This provided a clear starting point for the beginning of the studies.

All the results of the batch reduction studies show some form of correlation, showing that to some degree, as the batch sizes increase, so do the processing times of an individual product. It must be noted these studies were only completed with one operator per production line, and further studies would have to be conducted to determine if more employees should be added to the production lines in an attempt to balance the lines before reducing batch sizes and defining an optimal batch size.

The data collected from the project will be fundamental in supporting the literature regarding SPF and the body of knowledge on operations management and creating production strategies. It will help IMI-C formulate a plan and internally review its existing production strategies across multiple global sites.

The use of specially designed production batch studies under the same conditions as everyday production allowed an exact amount of batch runs to take place and provided a comprehensive

data set. This had a substantial advantage over a random sampling approach as the method was controlled and simulated as close to normal day production across the three production lines ICO, ICoS and IFR. The batch reduction studies also ensured a wide and varied data spread was recorded, and the traceability of the data collected could be linked back to which individual study it was collected. Had random sampling been selected, this could have caused inconclusive data to be collected, creating a false result, for example, if an outlier had occurred during random sampling.

The knowledge gained from conducting this research within a live production environment will allow IMI-C to research further across its multiple product lines to establish if SPF theory applies across multiple product production lines and introduce variables within the studies to assess the impact of the changes. This further research will contribute to how the operations managment team at IMI-C addresses the growing demand on the business from customer expectations such as short lead times and competitive product costs.

8.0 Project Conclusion

The methodical planning and systematic steps followed during the research project have provided an answer to the research question.

- *Does the Lean Management methodology of single-piece flow or a traditional batch-flow production strategy produce the lowest product lead times and production costs?*

The answer to the research question during the data collection studies at IMI-C has shown that a correlation exists between the size of a batch and the production time per product. As the batch quantities were reduced, the individual processing times were reduced across all three production lines analysed (ICO, ICoS and IFR).

This supports the literature review exploring the benefits of SPF. The literature identified SPF as the most production-efficient method to produce high-volume products, which is a requirement of IMI-C. Butcher and Dupernex (1996) described SPF as a catalyst to help drive shorter manufacturing lead time, as identified during this research project. However, the literature review also discovered that SPF might only be applicable to some process and manufacturing facilities (Okpala 2014). This was not identified as an issue at IMI-C, as the data sets of results show the production lines selected for the project are suited to SPF implementation.

Reviewing the original project objectives:

1. Define the current performance of selected IMI-C product lines. This will be achieved by establishing processing lead times of the workstation. Recored times will allow production product costs and manufacturing lead-times to be calculated. Completed by the 9th December 2022 - COMPLETED - Process steps for each product line included in the tables included within the report.

2. Creating of a controlled study to reduce batch quantities of defined production lines in incremental stages to achieve single piece flow. All documentation required to record the results in the form of quantitative data will also be created. Completed by 21st December 2022. - COMPLETED - Tables included within the report show a consistent batch study reduction completed across all three production lines (ICO, ICoS and IFR).

3. Undertake the research study as defined in objective two following the planned documentation to ensure collected data remains uncontaminated. The data collected by the planned production review will be of multiple data providing variety of data for analysis. Completed by 3rd March 2023. - COMPLETED - multiple data sets collected by an independent party during the studies.

4. The data sets collected will be subject to statistical analysis to identify if any correlation (strength of the relationship) and covariance (direction of the relationship) between product costings and the lean management philosophy single-piece flow or a traditional batch-flow production strategy. This will be achieved by 19th March 2023. COMPLETED all data followed the same statistical process and included within the report.

Ultimately reducing production to single components (SPF) across all the production lines. Before SPF can be implemented as a production strategy at IMI-C, the business will need to research further if the waiting time between each processing station will allow for the current batches to be reduced. This requires a line-balancing study to determine if the correlation between batch size and processing times still exists when the steps between the production stations are taken into account, as this could result in the production lines becoming unbalanced and creating longer production queues and potentially delaying customer orders.

The research project collected the FPY for ICO, ICoS and IFR production lines. This was not a critical element in answering the research question. However, the FPY data collected will be used as supporting information and submitted to the IMI-C operations management team to help shape the current production strategy, as this will help work towards improving overall product quality and reinforce the market-leading IMI-C brand.

It was identified within the report that FPY data does not show the causation of the FPY results, just that a correlation exists. Shows that batch size does impact the quality levels of the products covered within this report,.However, further causation investigation needs to be conducted as the problem's root cause may differ across production lines (ICO, ICoS and IFR).

There was a level of disruption caused to production from the research project. However, the information/data acquired works towards shaping the organisation's production strategy model. The data and experience from reviewing three of the IMI-C production lines have increased the justification for further studies to b conducted across other product ranges.

Assuming the data collected from this research can be revalidated and further studies replicated across other product lines with the same results. In that case, there is a serious business case and justification for IMI-C to switch to an SPF model to reduce product lead time and cost.
As explained by (Miltenburg 2000) during the literature review, SPF production is the final lifecycle stage of an established product driven by consumer demand. The data combined with the literature review provides a new mindset for IMI-C in planning daily production.

The research project has generated several further questions requiring future investigation work by IMI-C. The next section of the report will highlight the key areas of further research.

9.0 Future Work

There is a requirement for further future work to be conducted to define the causation of the results from this research. As the research project data established, a strong correlation does exist between batch size and individual processing time. The studies require further observation to identify the reasons for the results and if the data collected from this project can be replicated across other IMI-C global production lines. It also provides the opportunity to investigate further how FPY can be impacted when an SPF production model is applied to a broader set of IMI-C products.

Further research is needed before any official changes are made to the current operations management production strategy at IMI-C. The more data that is collected, the more it can be compared. As explained by Antonius (2003), data collected in the form of quantitative allows a bigger picture to be understood, with minimised obscurities which provides a substantial advantage when hypothesis testing.

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