Improving the Manufacturing Process of brick based products using FIT Principles and Discrete Event Simulation

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This thesis is submitted to Cardiff University in fulfilment of the requirements for the Degree of Master of Philosophy

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Abstract

The aim of the study was to improve the current manufacturing process through the application of FIT manufacturing principles with the aid of Discrete Event Simulation (DES) technique.

FIT principles focus on making the manufacturing process lean, agile and sustainable while maintaining the productivity rates, profitability and waste at their optimum levels. Discrete Event Simulation (DES) is a powerful tool which can be used to build a model of the current manufacturing process and later utilised to study the effects on the process flow by simulating the model under different scenarios corresponding to different key process parameters. In this study, WITNESS software was used as a platform to build the DES model and run simulations. The simulations were carried out manually i.e. by an intuitive approach and later run automatically i.e. using the embedded optimising module within WITNESS to collect the necessary data for improving the current manufacturing process.

This study has been conducted as part of a Knowledge Transfer Partnership (KTP) program within a traditional manufacturing industry. Data has been collected from the company, process flow was mapped for 3 different product categories, plant layout of existing manufacturing facility was created in CAD package and a DES model was created to test different methodologies suggested by FIT manufacturing. For the simulation model, specific rules and functions were created to mimic the process flow based on the extracted knowledge of current practice.

Three different FIT scenarios were tested against measured outputs to see the potential benefits to the company. The results were validated by setting the process parameters to the values suggested by the optimised DES model. The fourth scenario was tested by modelling breakdown pattern of the machines in the simulation.

In the first scenario, manual improvements were made intuitively using FIT principles to allow the process to be more lean, agile and sustainable by critical evaluation and analysis such as line balancing of existing processes.

However, due to thresholds met by this approach in terms of improvements to the manufacturing process, the DES model was simulated for the second and third scenarios using the Experimenter module in WITNESS to capture the complex relationships that exist between the 3 FIT components considering the level of investment required as a constraint for decision making. The fourth scenario was used to study the effect of breakdowns of the machines on the production line and the effect of predictive maintenance on the overall manufacturing process.

The study showed that, in general, resources such as machines and labour that are shared between production lines caused undue pressure on the production line. Also, maximum allocation of resources does not always lead to maximum increase in productivity. On the contrary, lesser but smarter investment on resources improved productivity by a higher margin. Employing people with multiple skills who can carry out multiple operations was found to improve productivity significantly. It was also found that increasing the efficiency of one production line did not always increase the overall efficiency due to cross-functional relationships within the manufacturing processes and increasing the efficiency of one production line is likely to cause a bottleneck on the other inter-dependent operations.

Breakdown of machinery were found to impact the production process flow negatively. In contrary to the belief that preventive maintenance is the effective solution, it was found that a reactive maintenance strategy of having a spare machine is more cost effective, in this case. This option is viable in the current manufacturing model, but not always on all scenarios.

Overall, the study showed that the application of FIT manufacturing principles applied with the help of a DES model could add significant value to the organisation and increase the operational efficiencies. This work can be easily adapted to other manufacturing industries to identify the inefficiencies in the manufacturing process and remedy the bottlenecks as well as remove non-value adding activities.

Acknowledgements

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Abbreviations and Acronyms

AMT	-	Advanced Manufacturing Technologies
BS	-	British Standard
CAD	-	Computer Aided Design
CO	-	Cooling time
CU	-	Curing time
DES	-	Discrete Event Simulation
EU	-	European Union
FIT	-	Flexible Integrated Technology
FMF	-	FIT Manufacturing Framework
FMS	-	Flexible Manufacturing Systems
GDP	-	Gross Domestic Product
GRP	-	Glass Reinforced Plastic
GVA	-	Gross value added
KPI	-	Key Performance Indicators
KTP	-	Knowledge Transfer Partnership
OEE	-	Overall equipment efficiency
OTD	-	On-time delivery
PMASEE	-	Plan, Measure, Analyse, Solve, Execute and Embed
RMS	-	Reconfigurable Manufacturing Systems
SME	-	Small & medium sized enterprises
TPS	-	Toyota Production System
UK	-	United Kingdom
USA	-	United States of America
VRTM	-	Vacuum resin transfer moulding
WIP	-	Work-in progress

1 Introduction

United Kingdom (UK) has one of the strongest economies in the modern world. Based on the gross domestic product (GDP), UK is the fifth largest economy in the world which comprises of 4% of the world GDP (Exchequer, 2015). Considering the European Union (EU), UK is the second largest economy after Germany. In the world, UK has a strong position for job creation and attracting industries.

While the figures above infer a good state of affairs, the UK Government and the Bank of England has raised concerns about the labour productivity per hour. The Government suggests measures for narrowing the productivity gap and predicts a rise in GDP by 31% if productivity would match that of the United States (US) (Exchequer, 2015). The Figure 1.1 is an extract from a report by the Bank of England showing the actual and predicted shortfall in labour productivity per hour.
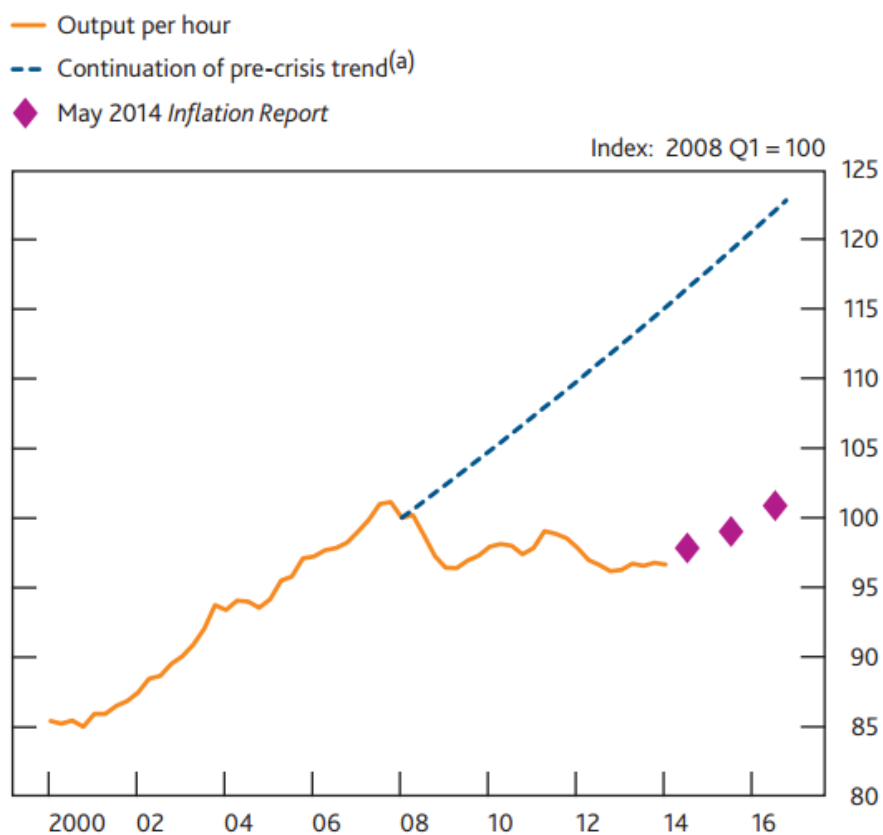
Figure 1.1 Whole-economy labour productivity per hour (Alina Barnett, 2014)

The sudden drop is due to the recession period and the recovery following recession is at a slow pace than predicted.

A series of long-term measures were announced by the UK Government to fix the economy in 2015, a few of which are given below (Treasury, 2015).

- Competitive tax system
- Highly skilled workforce
- World leading universities
- Modern transport system
- Low carbon energy

The most important of these is a detailed plan to increase the UK productivity outlined *'Fixing the foundations: Creating a more prosperous nation'* (Treasury, 2015). In this document, 16 various strategies or focus points are specified to increase the whole-economy labour productivity per hour.

This is even more critical in manufacturing industries as the most value-adding processes in the internal supply chain are within the Production department. Thus, increasing the labour productivity per hour would be most useful for sustainability for all industries as well as the economy.

Traditional manufacturing industries have created various methodologies to achieve this increase over the last couple of decades. Of which the most common accepted standard is the implementation of Lean manufacturing principles which was originally developed by the Toyota Production System (TPS). Other manufacturing philosophies include Agile manufacturing, Sustainable manufacturing and so on.

In this thesis, an investigation is carried out into the implementation of FIT (Flexible Integrated Technology) manufacturing within the context of promoting its use in a traditional manufacturing firm. The work is part of a Knowledge Transfer Partnership (KTP) funded by the Welsh Government between Cardiff University Engineering School and Brick Fabrication Ltd in Pontypool, details of which are given below.

1.1 KTP Project overview

The KTP project was for the duration of 21 months starting in June 2013. The aims and objectives of the project are given below.

KTP Project Aim: To increase production output and sustainability of the current process via the integration of CAD-CAM, and design and commissioning of an automated brick cutting machinery together with the introduction of a 'FIT' manufacturing system.

The project was broken down into stages with clear objectives, which are given below:

KTP Project Objectives: To design and implement a 'FIT' manufacturing system for the company which features automated brick cutting machinery with 3D CAD-CAM design capabilities.

- Stage 1 – Undertake a review of the current company order processing and manufacturing system to identify potential cost saving improvements via a 'FIT' system redesign.
  - Output 1: (a) Agreed manufacturing system improvement plan and (b) automation solution for the brick cutting process.
- Stage 2 – Design and develop a suitable automation enhancement to the existing brick cutting machinery to achieve a product and production rate improvement.
  - Output 2: Implemented and validated 3D CAD-CAM design, automatic production capability and process improvement.
- Stage 3 – Implementation and integration of initial automatic production process capability within a revised 'FIT' manufacturing system.
  - Output 3: Enhanced production capability and performance via an integrated 'FIT' manufacturing system featuring 3D CAD-CAM design and fully automated brick cutting system in-service.
- Stage 4 – Investigate current assembly systems for employing cut bricks in pre-fabricated building products, and evaluate ideas for improvement.

o Output 4: Introduction of advanced assembly processes resulting in improved assembly processes integrated with 'FIT' brick cutting manufacturing system.

The research into exploring the application of FIT manufacturing was carried out as part of the KTP Project. Data was collected from the company and the main aims and objectives of this thesis were formulated based on the KTP Project.

1.2 Company overview

The project was undertaken in collaboration with Brick Fabrication Ltd in Pontypool. The company manufactures pre-fabricated building products for the UK house building industry. The customer base is niche and blue-chip. Major products include decorative chimneys, pre-fabricated arches, brick specials, GRP (Glass Reinforce Plastic) canopies and dormers.

The company turns over £3 million per annum, and has experienced sustainable growth even during recession periods. It has 2 factories in UK, with a workforce of around 80 and a strong 20 years of trading history.

As the current stimulus policy of the UK government is to support and expand the house building sector, the company has an expectation that the demand for its pre-fabricated building products will continue to increase.

1.3 Project Aims and Objectives

The aims and objectives of this thesis are given below.

Aim: The project aims to improve the manufacturing process of brick based products using FIT principles and Discrete Event Simulation of the process flow model.

Objectives: To design and implement a FIT manufacturing system for the company using DES. This work can be broken down into the following objectives:

i.   Undertake a review of the current company order processing and manufacturing system. Process flow maps, value-stream maps, layout models in CAD, resource allocation were all carried out. This is discussed in Chapter 3.

ii. Build a DES model using WITNESS software to replicate the manufacturing process in the factory. This is discussed in Chapter 4.

iii. Design and develop a suitable enhancement to the existing manufacturing process to build a product and achieve production rate improvement using FIT principles. This is discussed in Chapters 5 and 6.

iv. Investigate the effect of machine breakdowns on the manufacturing process flow and suggest potential options to reduce the impact. This is discussed in Chapter 7.

v.   Review the effect of changes on real time vs. simulation to validate theories. This is discussed in the sub-section 'Validation of results' in Chapters 5 to 7 and in detail in Chapter 8.

1.4   Research methodology

Data was collected on the current manufacturing processes of 3 different production lines from the company shop floor. Previous order history, manufacturing performance and data on resources such as machines and labour were collected from the factory.

Process flow maps, value-stream maps, factory layout and data on breakdown of machines were collected and formulated into presentable form of information as part of this project. Personal interviews/online questionnaire/meetings were used to identify requirements of brick cutting systems.

The above information was utilised to develop a DES model using WITNESS software. The model and the results were validated using both data and feedback from the management and people on the shop floor.

The viability of suggested changes was verified using the same methodology and changes were implemented in the factory.

1.5 Project timeline

The research timeline is to follow the KTP Project timeline and writing up of the thesis to follow completion of the KTP Project.

1.6 Software used

The DES software chosen to build the model and simulate the manufacturing processes is called Witness supplied by Lanner Ltd., based in Henley-in-Arden in UK. Witness is a process modelling and simulation software widely used in the industry worldwide especially for business planning, decision making and risk management.

The manufacturing process within the company was modelled in Witness by using the data collected from the shop floor and the knowledge extracted from the operators and management team. The accuracy of the model was validated with real-time outputs obtained by implementing the changes to the production process. This validated model was then used to test the results of introducing FIT manufacturing principles and for optimisation purpose.

Other software used in the research are AutoCAD and Autodesk Inventor for modelling the factory and Microsoft Office packages.

1.7 Organisation of the thesis

A literature review of FIT manufacturing principles is given in Chapter 2. The manufacturing process in the factory for 3 production lines are explained in detail in Chapter 3. This information is then used to build the DES model, which is given in Chapter 4. In Chapter 5, the first FIT scenario (where changes are identified intuitively) to improve the manufacturing model is discussed. Second and third FIT scenarios using automatic optimisation feature in WITNESS is discussed in Chapter 6. The effect of machine breakdowns on the production flow is discussed in Chapter 7. The results of the research are discussed in Chapter 8 and conclusions in Chapter 9.

2 Literature Review

The aim of this chapter is to critically review current state of the art literature on FIT manufacturing to see how best they could be adopted by different manufacturing processes.

2.1 Global economic situation

Numerous developments have been made in manufacturing strategies. Enhancing productivity and reducing waste has been the focus of all these. Notable examples of advanced manufacturing strategies include Total Quality Management, Just-In-Time, Business Process Re-engineering, Agile manufacturing, Lean manufacturing and Six Sigma. Many of these are proven to be successful under various circumstances. Companies take pride in tagging themselves with the manufacturing strategy they use.

Arguably these advanced methods are seen to fail as a long-term strategy although they bring short term economic benefits as the work force resort to previous working (Pham & Thomas, 2012). The validity of this claim is subject to debate as increasing number of manufacturing companies adopt these modern manufacturing strategies.

2.2 Advanced manufacturing strategies

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subject to debate as increasing number of manufacturing companies adopt these modern manufacturing strategies.

2.2.1 Manufacturing Systems

Modern manufacturing systems have become sophisticated and automated compared to traditional model which were based on people as primary resource. Manufacturing was considered to be a transformative process. (Parnaby, 1979). This was classified as a system which transforms raw materials into products. In this process, the value of the product is increasing. This was refined into inputs which are transformed into outputs. The integration of all sub-systems into one integrated system was also one of the outputs of earlier research (Parnaby, 1979). In the same literature, it was stated that *"manufacturing systems involve many people and exist to serve people, and clear recognition of this fundamental point is critical to good control"*. This compared to the latest evolution in the field of manufacturing systems through the introduction of Industry 4.0 as a standard to follow focusses more on technologies than people, thus introducing a paradigm shift.

Defining Manufacturing systems has also been subject to debate. Manufacturing systems which are subject to change were classified as 'flexible' (Jim Browne, 1984). '*A flexible manufacturing system (FMS) was defines as an integrated, computer-controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium sized volumes of variety of part types'* (Jim Browne, 1984). This definition when comparing with advanced automated factories is still relevant and shows the growth of the sector and change. It is worth noting that the overall change is due to the advancement in technologies rather than the philosophy behind it.

According to Jim Browne, the following 8 flexibilities are vital for healthy operation of the manufacturing sector:

   i.   Machine flexibility
   ii.   Process flexibility
   iii.   Product flexibility

iv.   Routing flexibility

v.   Volume flexibility

vi.   Expansion flexibility

vii.   Operation flexibility and

viii.   Production flexibility
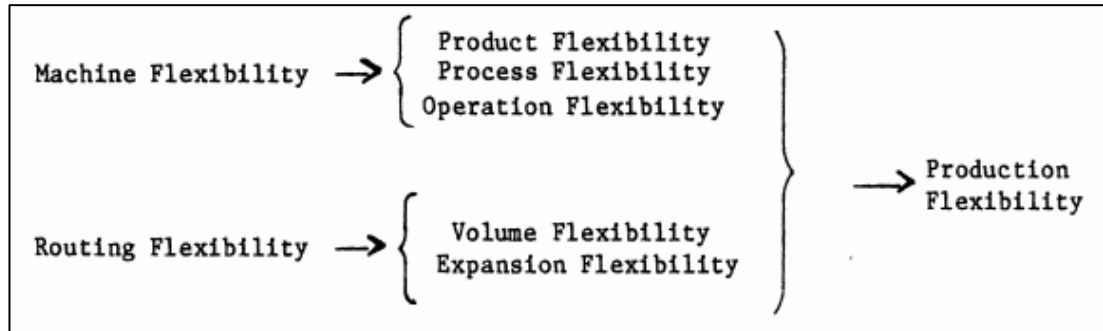
Figure 2.1: Relationship among flexibility types (Jim Browne, 1984)

But the literature also concludes that the FMS's consists of similar components even though the machine types and numbers may vary.

Another manufacturing system concept was Reconfigurable Manufacturing System (RMS). According to ElMaraghy (ElMaraghy, 2005), this has seven core characteristics which are given below:

i.   *Automatability: the ability to change degree of automation and upgrade or downgrade automation in assembly level.*

ii.   *Diagnosibility: the ability of system to automatically detect the current situation and understand defects in production and the reason for deflections. Thus, this system can control the operations.*

iii.   *Modularity: the way that different elements in manufacturing unit change in order to response to requirements of production plan and obtain the best optimum arrangement to meet the production need.*

iv.   *Convertibility: the ability of system to shift from one function to another function inside the system. For instance machines, tools and control interfaces to meet new production requirements.*

> *v.*   *Scalability: the ability of system to easily change current production volume through changes in arrangement of production system (change in components).*
>
> *vi.*   *Integrability: the ability of system for putting together all existing modules. It should be quick and accurate and system will use different interfaces (mechanical, electrical, etc) for this purpose.*
>
> *vii.*   *Mobility: The ability to move the whole system or change the location of elements or sub parts.*

These systems have evolved into the latest Industry 4.0 standard which connects the embedded system production technologies and smart production processes. The history of industrial revolution has been projected as shown in Figure 2.2.
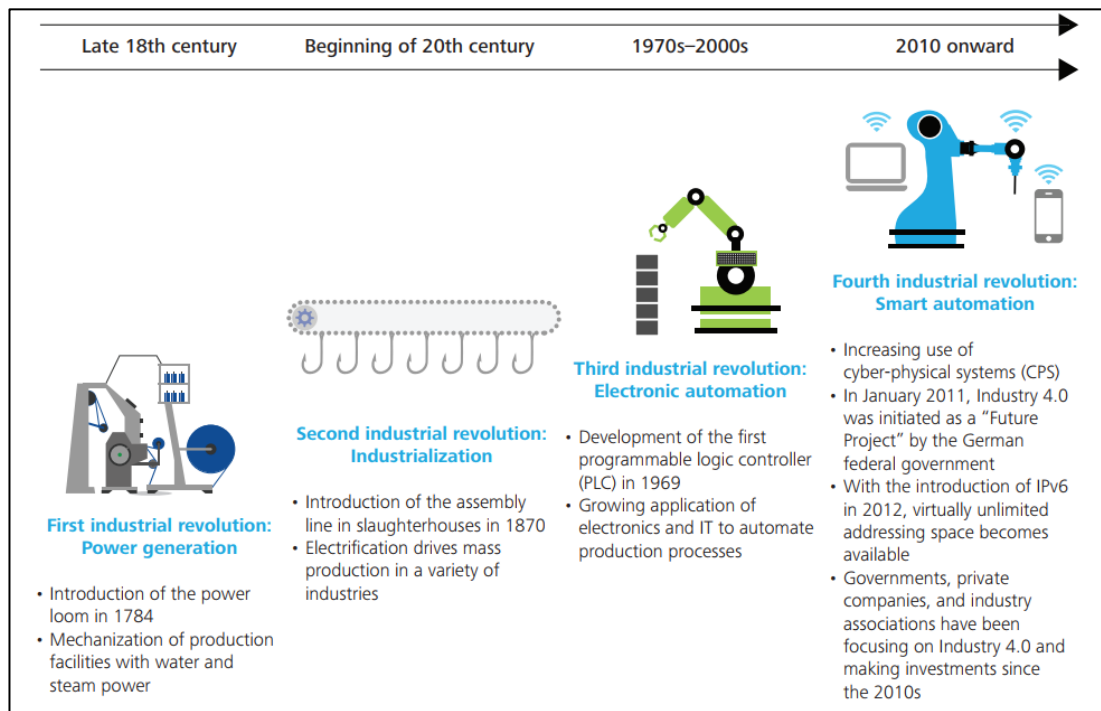
Figure 2.2: A history of industrial revolutions (Brenna Sniderman, 2016)

In the current KTP project, particular focus is given to the implementation of FIT manufacturing, components of which are explained below.

2.2.2 Lean manufacturing

This is a set of production philosophy or management principles that focusses on value addition by elimination of waste. The philosophy is developed from

the perspective of the customer. The term "value" is defined as any process or action that the customer is ready to pay for. Thus, everything else is classified as waste and is reduced to a minimum (Womack & Jones, 1996). Lean manufacturing has evolved from the Toyota Production System (TPS) during the 1990's.

Waste is classified into seven categories, the reduction of which improves customer value. The seven waste classifications per TPS are given in Figure 2.1. The success story is evident as almost 50% of UK manufacturing firms adopt lean techniques in manufacturing (Pham & Thomas, 2012).

Figure 2.3: Waste in Lean philosophy (The Basics of Lean Six Sigma)

On the contrary, the sustainability of Lean principles is often questioned. It is stated that *"the success of "Lean" in companies often mirrors the classic change curve – improvements in productivity after an intervention are soon*

followed by a steady decline to baseline, and sometimes even below baseline levels" (Pham & Thomas, 2012).

Lean is seen to lack the ability to implement a holistic approach as it is mainly process driven. Involvement of Information Technology into manufacturing, leadership styles, long term strategy are other areas that Lean manufacturing does not address.

2.2.3 Agile manufacturing

The ability of an organisation to quickly adapt to changing customer demands and market fluctuations is defined as agility. It gives the company competitive advantage as it could deliver its products at greater speed than its competitors.

If lean focusses on value addition through waste reduction, agility focusses on rapid response to customer demands. Agile manufacturing is seen to build on lean manufacturing (Dewson, 2006).
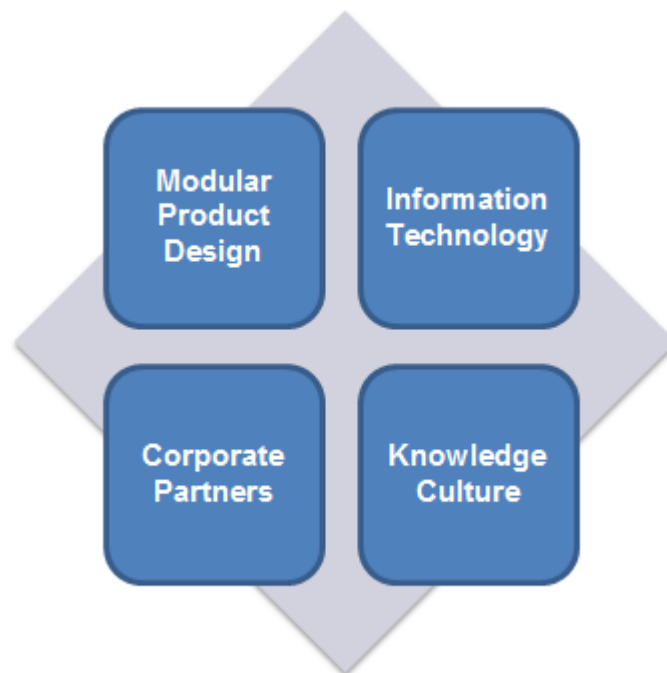
Figure 2.4: Agile manufacturing model (Dewson, 2006)

The key elements of agility shown in Figure 2.2 are:

- Modular product design: Designing products in modular fashion which enables rapid response to changes.
- Information technology.

- Corporate Partners.
- Knowledge Culture: Indicates investing in employees to promote rapid change.

Agile manufacturers define their manufacturing process in such a way that it can respond to customer demands quickly without significant capital investment.

2.2.4 Sustainable manufacturing

The ability of the organisation to penetrate new markets, expand and prosper through improved product and customer diversification is referred to as sustainable. It is not just considered to be a strategy to penetrate new markets while maintaining current production capacity. Sustainability is the ability to meet the current needs as well as the ability of future generations to meet future demands (Pham & Thomas, 2012).

As Lean and Agile manufacturing does not address the aspect of new market penetration, sustainability is critical to business development and for the future of the company as shown in Figures 2.3 and 2.4.

Figure 2.5: Cost, volume and profit analysis (Pham & Thomas, 2012)

Considering an organisation only to be Lean and Agile and not sustainable, it is only a matter of time that escalation of operating costs meets the sales pushing the company to loss.
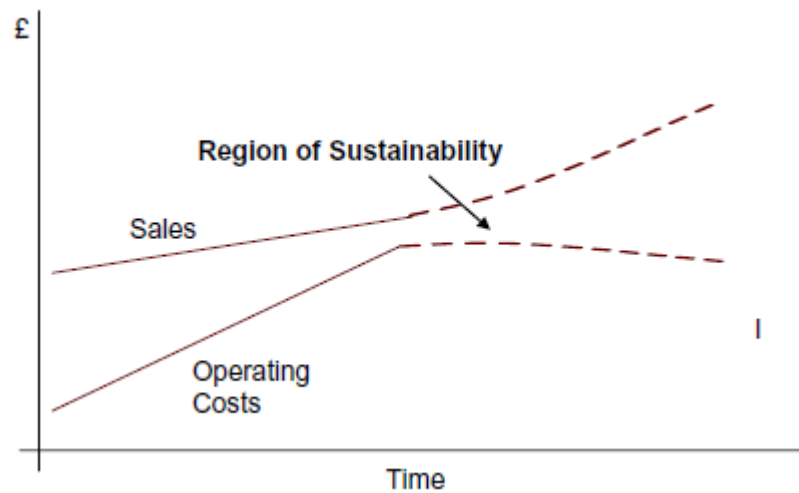
Figure 2.6: Region of sustainability (Pham & Thomas, 2012)

Thus, a combination of Lean, Agile and Sustainable framework is required in the long term for any manufacturing organisation to be profitable sustainably. This is the basic idea of FIT manufacturing framework.

2.3 FIT manufacturing perspective

A FIT company is defined to be lean, agile and sustainable at the same time all be it at varying levels. Leanness focusses on value addition and waste reduction to improve efficiency resulting in increased production. Agility is the ability to adapt to changing demands and circumstances in minimal time. Sustainability refers to the idea of constant renewal by process and product innovation along with identifying new market opportunities (Baines et al, 2005)

Leagility considers Lean and Agile aspects at the same time combining the benefits of both paradigms. Leagility is a philosophy best suited the entire supply chain. Leagile supply chain separates the lean and agile principles through a decoupling point. The aim of the leagile supply chain remains to postpone the products as far as to the customer end, in order to efficiently handle the demand uncertainties. The FIT concept further advances the theory of combining different manufacturing paradigms for maximum benefit to the organisation (Chan 2014).

Adoption of a FIT Manufacturing Framework (FMF) is thought to help manufacturing firms increase their operational efficiency and economic

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sustainability. The concept is based on integrating innovative concepts to existing manufacturing ideas, the success of which is proven by Thomas and Pham (Pham & Thomas, 2012) on three SME's.

Hence, from the above definition, a company has to be lean, agile and sustainable in order to be classified as a FIT enterprise.

2.4 Need for FIT manufacturing

Lean and Agile manufacturing are proven to deliver desirable results. But the effectiveness of lean and agile manufacturing depends on the demand and volume of production. These are less effective for companies whose products require a greater level of customisation leaving the company at a disadvantaged position. However, lean approach is seen not to include strategy, process, leadership and technology (Pham & Thomas, 2012).

FMF proposes a holistic approach that can be implemented in any manufacturing firm to improve operational efficiency and economic sustainability. The new paradigm focusses on linking the four major themes discussed in the previous paragraph: strategy, process, leadership and technology.

2.5 Strategies for a manufacturing company to be FIT

Various strategies/methodologies are defined to measure the fitness of a company or to convert a manufacturing company to be fit. Some of the fitness enhancing ideas proposed on various sources is given below.

2.5.1 What manufacturing companies can learn from the Martial Arts

This column by Duc Pham (Pham, 2008) tries to bring to the forefront the link between the skills required in martial arts and in manufacturing to maximise efficiency. Some of the fitness enhancing factors is given below.

- Focus: One major idea defined which enhances the fitness of a company is the focus on the target. The focus on target makes the company concentrate efforts on deliverables which results in value addition and waste reduction.

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- Leverage: Companies that uses force to enhance different sections such as finance, resources and human elements to maximise production are seen to increase the fitness of the company.

- Momentum: A fit company is considered to use the momentum within the commercial environment to its advantage.

Every manufacturing firm engages in all these different aspects in various degrees. Hence all manufacturing firms can arguably be defined as fit manufacturing firms. This creates confusion while trying to define the fitness of a company.

Thus, for a company to be effectively called a fit manufacturing firm, there should be a defined level of leanness, agility and sustainability. Hence, it becomes necessary to quantify or determine the fitness of a company.

An effort in this direction is discussed in the following section.

2.5.2 Fit manufacturing: a framework for sustainability

This paper by Duc T. Pham and Andrew J. Thomas (Pham & Thomas, 2012) proposes a framework to identify the parameters that can be used to define the fitness of a company.

Different approaches are taken to determine the fitness of a company one of which is shown in Figure 2.7. The challenges in this method are to identify the parameters for quantifying and defining the fitness of the company. Secondly, it should be broken down to action lists for implementation.

The second step of determining the actions for implementation is not discussed in this paper. The question that is being answered is the elements contributing towards fitness of a company.
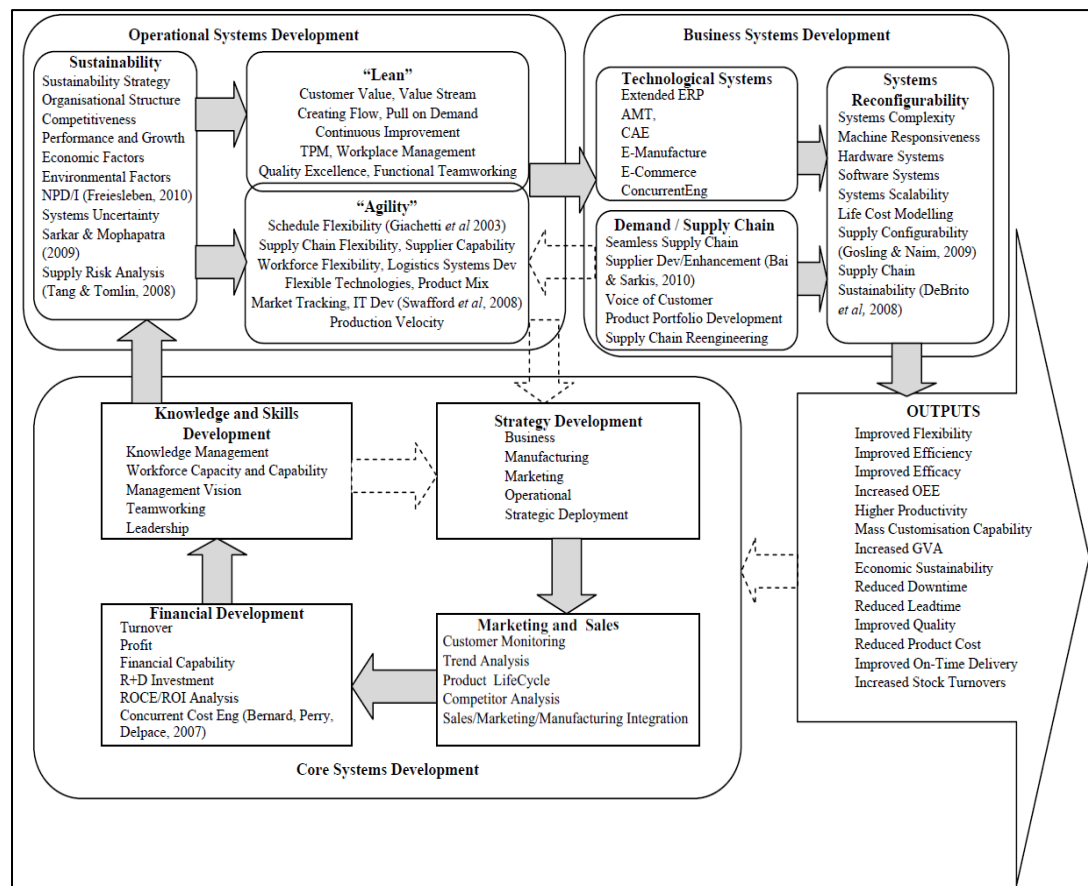
Figure 2.7: Fit manufacturing framework (Pham & Thomas, 2012)

A fit manufacturing company is not defined only to maximise its potential but it also penetrates new markets, encourages development of new products depending upon the viability of the product idea.

The FMF is broken down into 3 stages: core, operational and business. The movement is sequential starting with core, operational and then business. The next stage is to be started only after successful completion of the previous stage.

A brief outline of the strategy in each stage proposed in the paper is given below.

Core

The first step is to create one combined strategy which integrates marketing, manufacturing, operational and all relevant key strategies into one document. This is the initial step to be taken in implementing a FMF. The aim of creating one core strategy is to ensure that there is only one vision for the entire

organisation which guides all different aspects such as marketing, manufacturing, operations and so on.

The next step suggested is to carry out a fiscal analysis of the company. The aim of which is to identify the profitability of each product, financial profile of the company and potential to support further changes.

Simultaneously, the company should identify competitors, customers and potential markets. It is also important to identify the product life cycle if it is relevant and this information enables the company to design strategies to maximise performance. The company is advised to also get information on areas of under-performance.

The last stage suggested in the core of the FMF is to audit and identify the current knowledge base and skill set of the workforce. This includes analysis of managerial and leadership as well as shop floor skills of the entire workforce. This is to identify the gap in skills and resources within the company that will enable them in developing the strategy to meet future demands and comply with the company vision.

The overall activity can be summarised below as shown in Figure 2.8 and Figure 2.9.

Figure 2.8: Core structure of FMF

As the organisation successfully completes the 'Core' stage, it moves on to the operational stage.

Operational

The starting point in developing an operational strategy is to have a clear sustainability agenda. The operational strategy is defined according to the sustainability agenda aiming at wealth creation and cost reduction. New product ideas and customer needs are discussed within this section.

The lean and agility requirements are defined and discussed within the operational frame work of the FMF. An integrated approach is required at this

stage as to identify the correct lean/agility requirement. Companies that mass produce same product sets focus more on lean elements whereas companies that survive on bespoke products focus on agility factor.

The output of this stage is the well-defined operational strategy for the company that links with the core strategy.
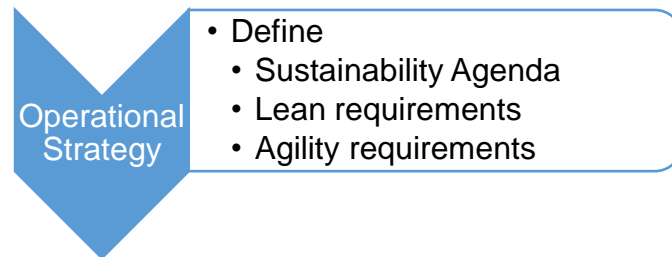
Figure 2.9: Operational framework for FMF

Business

The basic difference of a fit manufacturing business system to lean or agile is the multi strategic approach. The fit manufacturing system is not just the ability to change but also adapt and meet changes in the customer demands and market fluctuations. The company's response is more rapid to changes in circumstances.

The aim of developing three core strategies: core, operational and business is to support each other and to support the single company vision as the design of each stage building on to the next one makes the implementation effective. The FMF suggested emphasises on review meetings and stage gate implementation of the project to make sure the satisfactory completion of each stage. They serve as quality check points.

Case Study

The effectiveness of the FMF is outlined in the case study presented in the paper. Six similar companies (SME's) were chosen to study the effectiveness of FMF. Three companies developed FMF for 2 years and the other two companies implemented lean principles only to identify the difference.

The effectiveness of FMF was measured using four Key Performance Indicators (KPI's) namely:

- Overall equipment effectiveness (OEE)
- Manufacturing lead time from point of enquiry
- On-time delivery (OTD)
- Gross value added (GVA) contribution

Detailed procedure to measure the above factors are given in Appendix A: Gross Value Added (GVA) Estimation. The results based on KPI's following the 2-year application of the FMF are given in Figures 2.8, 2.9, 2.10 and 2.11.
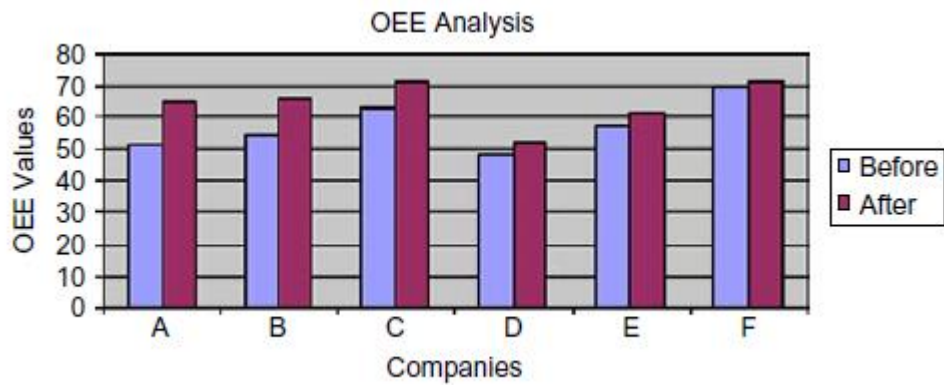
Figure 2.10: OEE (Pham & Thomas, 2012)
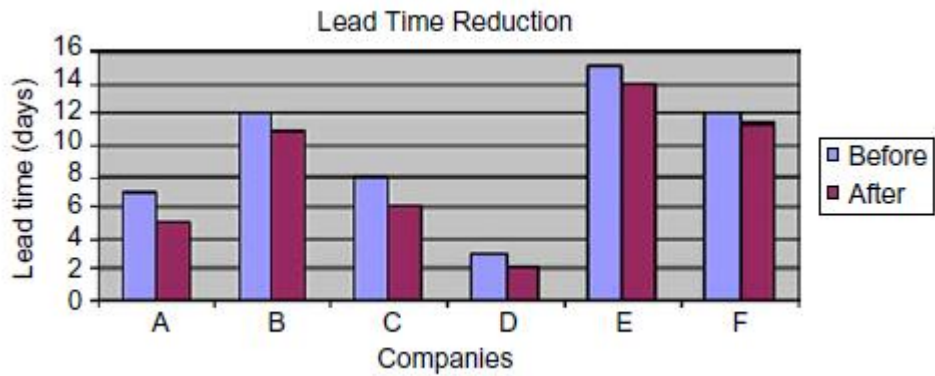
Figure 2.11: Lead time reduction (Pham & Thomas, 2012)

Figure 2.12: On-time delivery (Pham & Thomas, 2012)
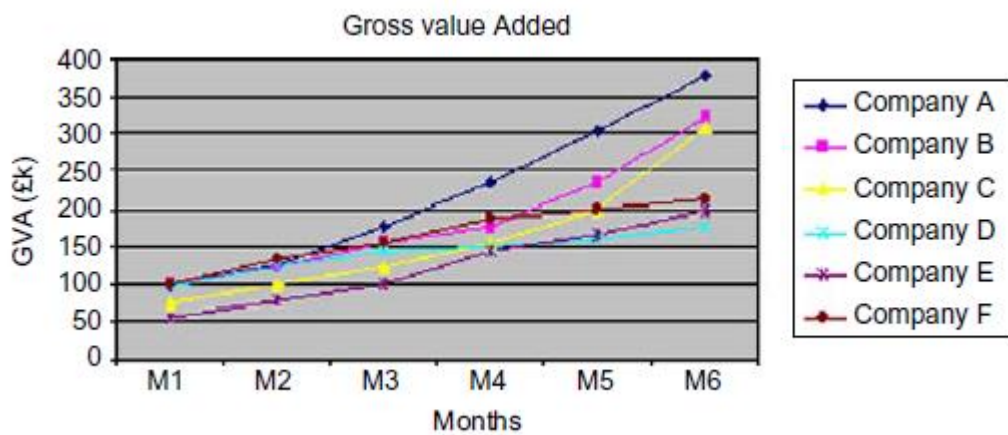
Figure 2.13: Gross value added (Pham & Thomas, 2012)

For all selected companies over the entire range of KPI's, significant improvements of 10-20% are noted clearly indicating the effectiveness of implementing FMF framework.

Though the effectiveness of the FMF has been undoubtedly proven, the author has not failed to mention that the workforce tends to adhere to traditional ways of working. This makes it difficult to quantify the extent of FMF application and the individual contributions of lean, agile and sustainable manufacturing are still not clear. Also, efforts need to be made to minimize the influence of noise factors.

2.5.3 FIT Sigma – An Integrated Strategy for Manufacturing Sustainability

The premise of this article argues that the integration of lean and six sigma concepts have failed to introduce a coherent business improvement system.

The author goes further questioning the ambiguity of Lean Six Sigma concepts. The solution to the stated problem is the proposed FIT Sigma framework (Thomas and Barton, 2008).

The proposed FIT-Sigma strategy is argued to increase sustainability via cost reduction. The initial step in this direction is suggested to lay down applicable lean principles and Six Sigma methodology. This might vary depending upon the type of company.

Three major areas are identified which will improve because of FIT-Sigma strategy as shown in Figure 2.12.

- Achieve Performance target,
- Reduce variation in performance and
- Increase efficiency of performance.
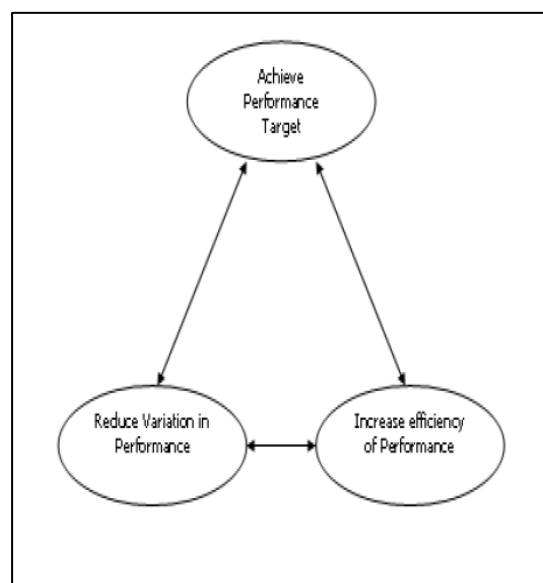
Figure 2.14: The FIT Sigma triad (Thomas and Barton, 2008)

The implementation strategy proposed is: Plan, Measure, Analyse, Solve, Execute and Embed (PMASEE). This is different from the traditional Six Sigma implementation as the proposal is to integrate lean principles to come up with a FIT-Sigma strategy. The integrated concept is shown in Figure 2.13.
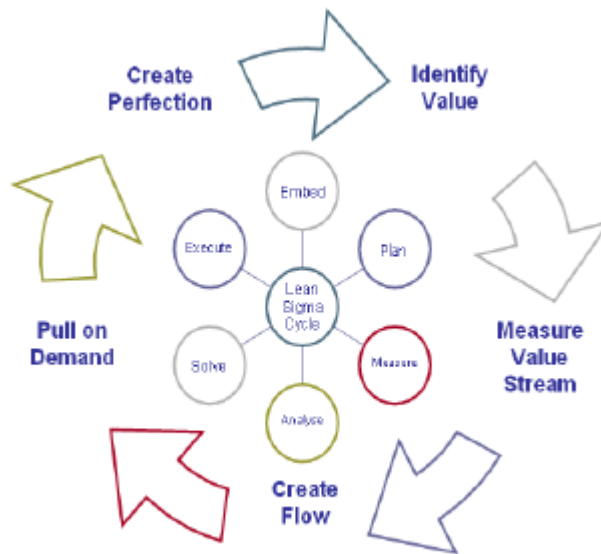
Figure 2.15: Integrated FIT-Sigma strategy (Thomas and Barton, 2008)

The paper also proposes development of a control system which helps monitor the developments as there is the tendency to resort back to previous ways of working.

The proposed control system design is given in Figure 2.14.
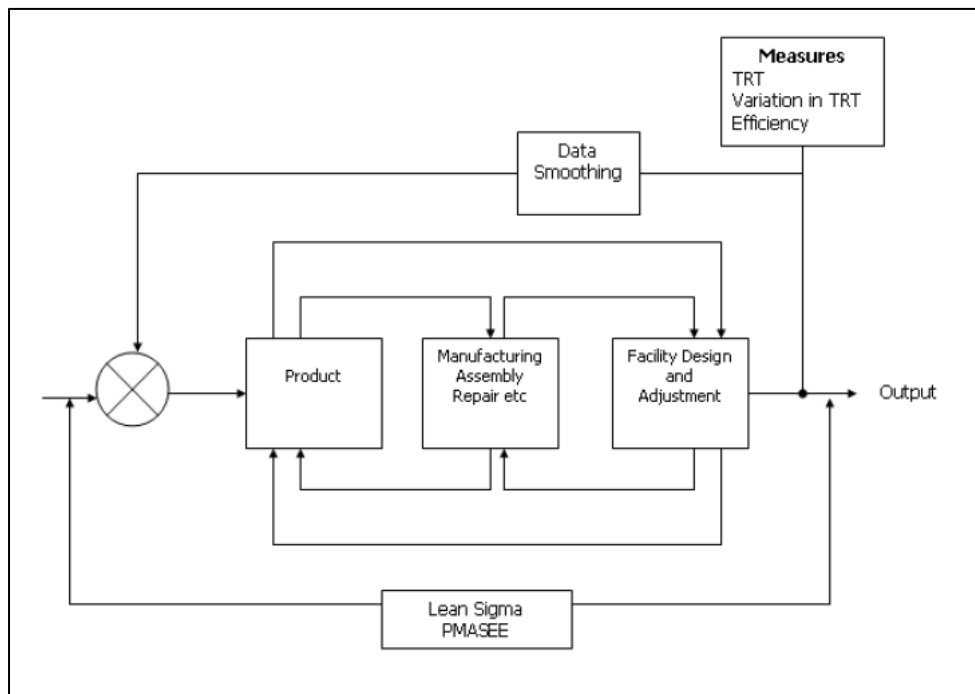
Figure 2.16: FIT Sigma control system (Thomas and Barton, 2008)

Overall the article calls for an integrated FIT-Sigma strategy which incorporates:

- Highly effective supply chain system

- Combined lean and agile manufacturing system and

- Development of a sustainability system.

Thus, the holistic FIT-Sigma structure integrates lean, agile and six sigma principles to improve the economic sustainability. The framework for implementation is given in Appendix B: FIT-Sigma Process, Tools and Techniques.

But again, the theoretical model of FIT-Sigma suggested here has no proven track record. There are no quantified benefits anticipated. All companies will already be using most of these principles in the form of trying to reduce waste, improve economic sustainability and so on. Thus, it is important to specify where the company stands in the scale of things and to define potential improvements. Different FIT strategies need to be defined based on industry and size such as SME's or large firms, service sectors or manufacturing firms and so on.

2.5.4 Advanced manufacturing technology implementation

This paper (Thomas, et al., 2007) discusses the attitude of SME's towards Advanced Manufacturing Technologies (AMT), reasons for the approach and a proposal of a strategic model for effective implementation.

Pre-decided qualitative and quantitative data were captured during the survey which is given below for companies who have implemented and yet to implement AMT's.

- Financial data

- Company profile

- Business type

- Attitude to technology

- Attitude to developing business

- Operational process

- Working process

- IT, information and communication process

The most important inference from the survey states the inability to bring culture change within the company. There is also reluctance in recognising the full benefits of AMT's. The implementation phase has been identified as the most difficult phase where maximum numbers of failures occur. The size of the company also played a vital role in implementation of AMT.

SME's also failed to measure the impact of AMT implementation as they lacked the benchmark against which to measure (Mohsen, et. al., 2010). The FIT model given in Figure 2.17 shows the structure that could be applied to different scenarios (Thomas, et al., 2007).
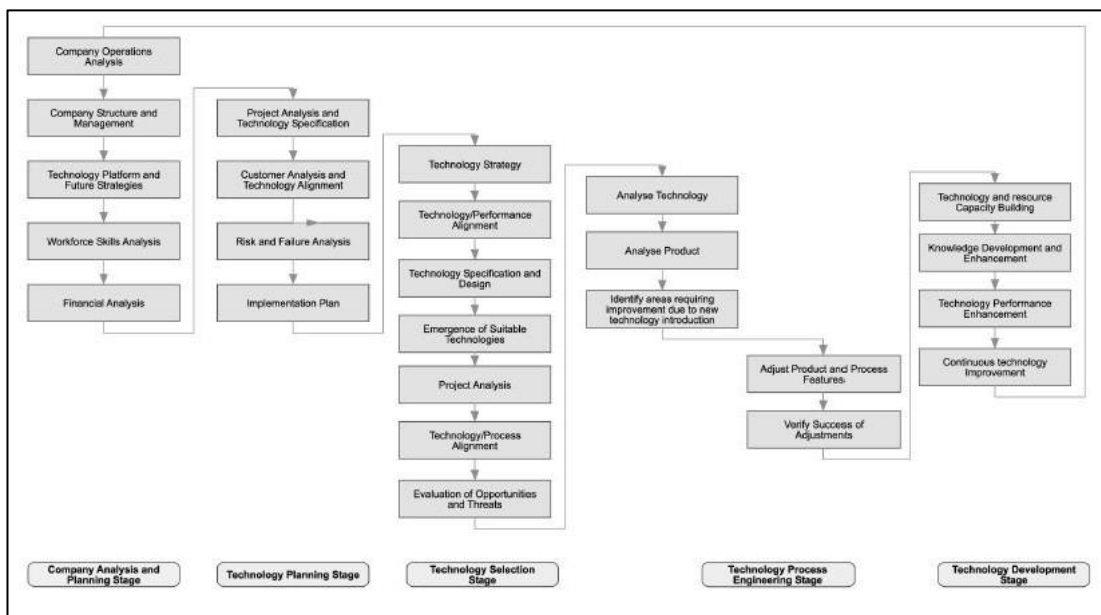
Figure 2.17: FIT model (Thomas, et al., 2007)

In this study, approaches mentioned in sections 2.5.1 & 2.5.4 will be investigated. This is identified due to the requirements of the KTP objectives and company preferences.

2.6 Simulation

Simulation is the imitation of an act or process (Hollocks, 2006). In this study, the production operations that are to be investigated are simulated using the software called Witness provided by Lanner Ltd.

There are different types of simulations being used in the industry. The most common types of simulation used in manufacturing industry are (Bangsow 2012):

- Continuous simulation and
- Discrete event simulation (DES)

2.6.1 Continuous simulation

Continuous simulation tracks the response of the system over a period of time continuously. Fluid model simulation in a factory can be a typical example of a continuous simulation. The output obtained from continuous simulation is a continuous graph (Banks, 2007) The result obtained from a continuous simulation for the sales output against time for a simulation model is given in Figure 2.18.
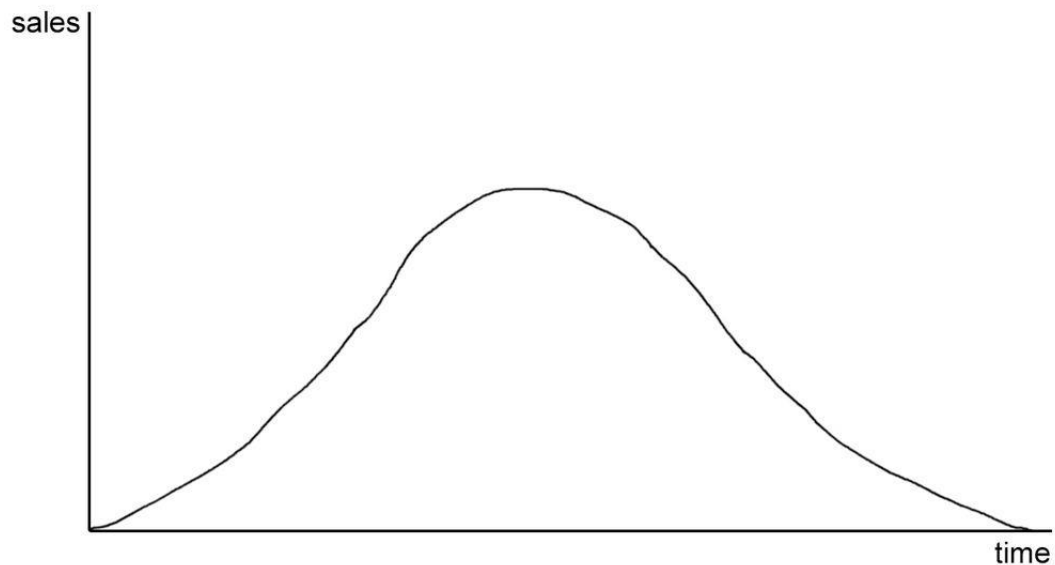
Figure 2.18: Continuous simulation output (Banks, 2007)

Mathematical models when simulated will give an output which is continuous. Simulation of physical phenomenon such as flight dynamics, electric motors, hydraulics and so on are examples of continuous simulation phenomenon.

2.6.2 Discrete Event Simulation (DES)

Mimicking the operations or events occurring as discrete events in time are called Discrete Event Simulation (DES). The change in the simulation are captured at different intervals and reported. Over the progressing time scale the changes over the system are captured from event to event whereas in continuous simulation, it varies continually over time (Diamond, 2010).

An example of a DES would be the modelling of a widget factory where each process has a cycle time to complete the operation. The events and parameters are captured after the completion of an operation. The outputs of a DES, if plotted in a graph for the outputs from a Sales office against time is shown in Figure 2.19.
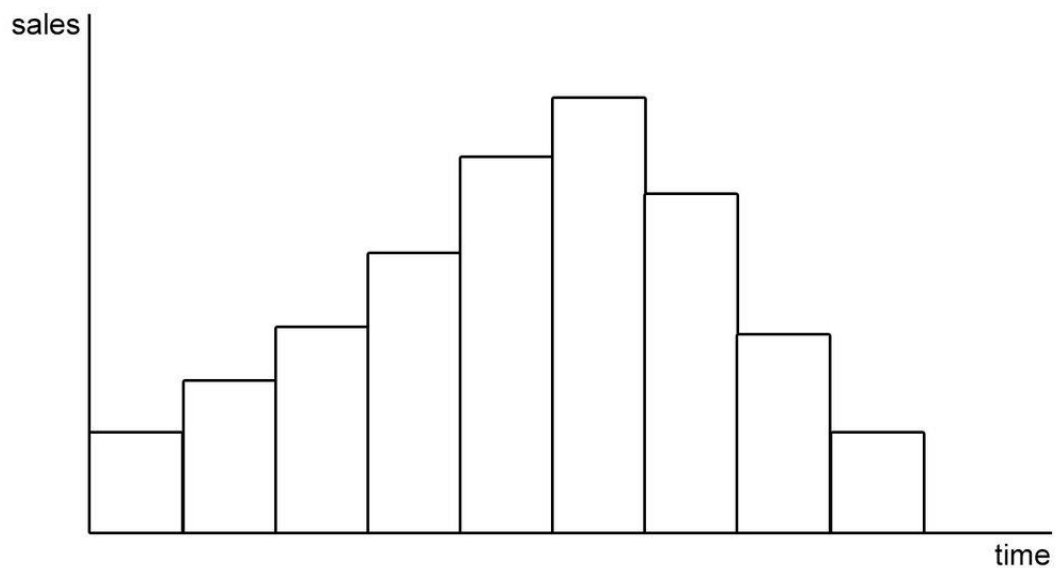
Figure 2.19: DES output (Banks, 2007)

Simulation is widely used in the manufacturing industry for mainly prediction and decision making for getting ahead of the competition. In this thesis, simulation is used to create a working model of the production facility that is being studied to investigate different scenarios before implementing the proposed ideas for improving the production process.

Both continuous and discrete event simulations are used in the industry depending on the application. The simulation model of a hydraulics

manufacturing industry would be continuous whereas of a widget manufacturing industry would be discrete.

Manufacturing industries use simulation for a variety of purposes from simulating office functions to factory operations. The benefits vary depending upon the application. There are direct and indirect benefits of the application of simulation in the manufacturing industry. A few of which are given in Table 2.1.

Indirect Benefits	Direct Benefits
• Inter-departmental communication improves • Helps in change management • Improves data management and collection of data • Helps in design of factories • Increases creativity • Use as a training tool	• Helps in decision making • Predicts current and future business performance • Minimum investment decisions can be made • Reduces the risk of failure during implementation • Provides overview of the whole process

Table 2.1: Simulation benefits (Faget, et al., 2005)

In this thesis, the simulation model is developed to study the behaviour of existing manufacturing facility and to investigate the potential benefits of implementing FIT manufacturing principles to the brick cutting industry.

The section below shows the factory layout for the product types based on which the simulation model is built.

2.7 Chapter Summary

Four different FIT approaches have been presented in this chapter together with their advantages and disadvantages. Due to the availability of data collection and company requirements along with KTP objectives, the FIT manufacturing used in this study will consider lean, agile and sustainability aspects of the process. The current manufacturing process at Brick Fabrication Ltd will be presented in the following chapter.

3 Existing manufacturing capability at Brick Fabrication Ltd.

The product range for the company is categorised into 2 major streams, specifically:

- Brick-clad chimneys &
- Cut & bond products which include
    - Prefabricated arches and
    - Brick Specials

The production process is modelled using the Discrete Event Simulation (DES) package called Witness (Lanner, 2013).

It contributes to a turnover of circa £3 million pounds per year supplied premium products that are difficult to make on the house building site. This makes installation of the products easier and reduces the dependence on trained operatives on the building sites.

With the predicted increase and higher demand for housing in UK, with regulations and house designs including the supplied products, future of this industry looks promising. Thus, it is significant to investigate the potential benefits of introducing FIT manufacturing using discrete event simulation to identify process improvements

The sections below explain the existing manufacturing processes using the process map tool. In the following sections, the production process for each product is explained in detail. For simulation purposes, the categorisation is limited to materials, labour and machines.

The product hierarchy diagram is given in Figure 3.1.

PRODUCT HIERARCHY DIAGRAM

brickfab

BRICK CLAD

BRICK, BLOCK & STONE SPECIALS
- AN.1 SQUINT
- AN.2 EXTERNAL ANGLE
- AN.3 INTERNAL ANGLE
- AN.5 SINGLE CANT
- BD.1 HALF BAT
- PL.2 PLINTH HEADER
- PL.3 PLINTH STRETCHER
- PS.1 PISTOL SOLDIER
- PS.2 PISTOL STRETCHER
- SL.1 BRICK SLIP
- GBL GABLE CUT

PREFABRICATED ARCHES
- FLAT GAUGE
- SEMI-RAISED FLAT GAUGE
- DEVELOPER
- CILL PANELS
- SEGMENTAL
- SEMI CIRCULAR
- RESTORATION
- BULLSEYE
- DIAMOND WINDOW SURROUND

BRICK CLAD CHIMNEYS
- AVON 440x552
- EDEN 440x777
- DERWENT 552x552
- WYE 552x777
- FROME 665x665
- SEVERN 777x777
- THAMES 665x890

MISCELLANEOUS
- BAT BOX
- BELL CHIME

GRP

BRICKLITE CLADDING PANELS
- FLAT PANEL
- CORNER PANEL

GRP CHIMNEYS
- HASTINGS 552x777x1200
- WARWICK 665x665x1200
- TAMWORTH 665x890x1200

GRP CANOPIES
- DERBY 1250-4650x400-1050x200
- CHELTENHAM 1550x600x225
- ASCOT 1450x750x880
- BEDFORD 1550x800x780

ARCH OPTIONS

Options and Extras
*Not available with infill panel

Options and Extras	Flat Gauge Arch	Semi-Raised Flat Gauge Arch	Developer Arch	Segmental Arch	Semi Circular Arch	Restoration Arch
Non-Structural Backing						
Panelite	✓	✓	✓	✓	✓	✓
Loose Cut	✓	✓	✓	✓	✓	x
Height & Pattern						
Single Brick 140mm High	✓	x	x	✓	x	x
Brick & Bat 215mm High	✓	✓	✓	✓	✓	✓
Brick & Bat 290mm High	✓	✓	✓	✓	✓	✓
Brick & Bat 365mm High	✓	✓	✓	✓	✓	✓
Soldier 215mm High	✓	x	x	✓	✓	x
Single Header 102mm High	x	x	x	✓	✓	x
Double Header 215mm High	x	x	x	✓	✓	x
Stretcher Double Header 150mm	✓	x	x	x	x	x
Solider Header 290mm High	x	x	x	✓	✓	x
Soffit Options						
Non-Faced Soffit	✓	✓	✓	✓	✓	✓
Faced Soffit	✓	•	✓	•	✓	✓
Infill Panels						
Plastic	x	✓	x	✓	✓	x
Brick	x	x	x	✓	x	x
Features						
Keystone	✓	x	✓	✓	✓	x

*Structural arches are available on request

BRICK CLAD CHIMNEY OPTIONS

		AVON 440mm 552mm	EDEN 440mm x 777mm	DERWENT 552mm x 552mm	WYE 552mm x 777mm	FROME 665mm x 665mm	SEVERN 777mm x 777mm	THAMES 665mm x 890mm
DIMENSIONS	WIDTH & DEPTH	AVON 440mm 552mm	EDEN 440mm x 777mm	DERWENT 552mm x 552mm	WYE 552mm x 777mm	FROME 665mm x 665mm	SEVERN 777mm x 777mm	THAMES 665mm x 890mm
	HEIGHT	900mm · 975mm · 1050mm · 1125mm · 1200mm · 1275mm · 1350mm · 1425mm · 1500mm · 1575mm · 1650mm · 1725mm · 1800mm · BESPOKE						
BASE	BASE TYPE	STANDARD · PARAPET · PYRAMID · 3-WAY · HIPPED · STEPPED						
	ROOF POSITION	MID-RIDGE · MONO-PITCH · GABLE END · GABLE LADDER						
	PITCH	30° · 35° · 40° · 45° · BESPOKE						
FINISH & CORBEL	FINISH	BRICK · STONE · RENDER · BESPOKE						
	CORBEL	NONE · TYPE 1 · TYPE 2 · TYPE 3 · TYPE 4 · BESPOKE						
CAPPING	CAPPING TYPE	NONE · PREMIUM · FLAUNCHED · DEVELOPER · GRP CAP & POT COMBINATION						
	CAPPING COLOUR	BUFF · BESPOKE						
POT & FLUE	POT HEIGHT	NONE · 300mm · 450mm · 600mm						
	POT TYPE	GRP · CLAY						
	FLUE *Not available for AVON	NONE · CLASS 1 (Wood Burning) · CLASS 2 (Gas)						

Figure 3.1: Product hierarchy diagram

3.1 Process map of existing manufacturing layout

The process map for 3 different products within the company is given in Figure 3.2.

Figure 3.2: Production process map for arches, brick specials & brick-clad chimneys

The above process map is for the production only. Tasks pertaining to the offices are not included in this Figure 3.2. No decision elements are included in this process map as it represents only the operations carried out in the factory. Most of the decisions pertaining to the operations are taken by Production Management from the Office. The production process for each product is explained below:

3.2 Production process for Brick Specials

Another product range offered by the company is Brick Specials that conform to BS 4729:2005 standard. There are over hundred varieties of brick specials offered by the company. Figure 3.3 and Figure 3.4 show 2 different types of Brick Specials offered from the product range.
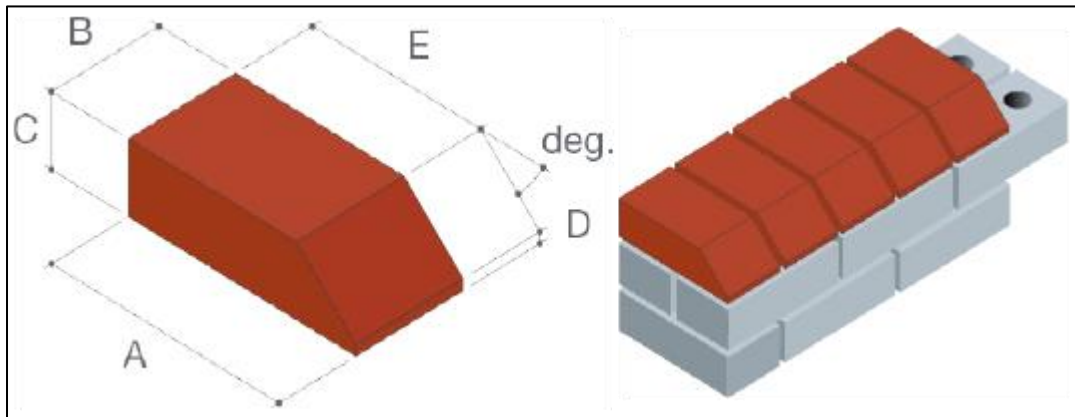
Figure 3.3: PL.2 Plinth Header (Brick Specials, 2017)
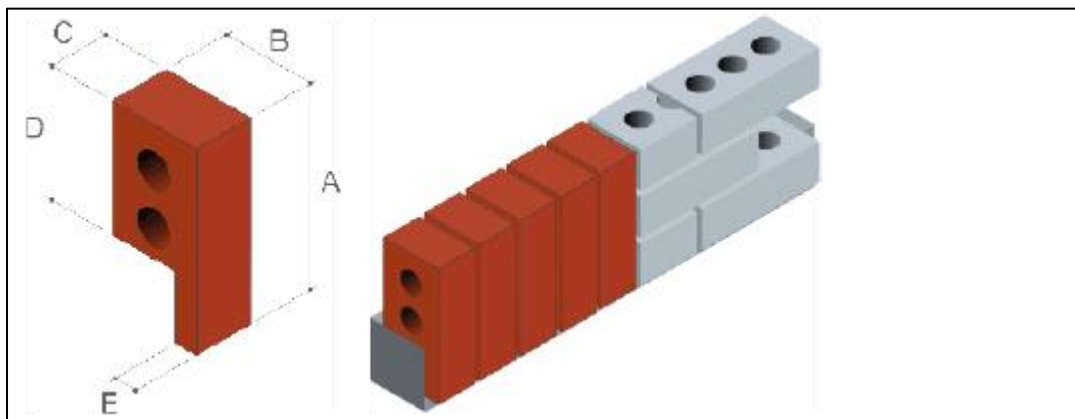
Figure 3.4: PS.1 Pistol Soldier (Brick Specials, 2017)

The materials used for manufacturing Brick Specials are:

- **Bricks:** Same as for pre-fabricated arches, bricks are supplied by customers to match the colour and texture of the bricks used in building houses. These are collected by the company and delivered to the factory for processing.

- **Bonding materials:** For brick specials that require cut bricks to be bonded together, bonding materials are used. The type of bonding material used depends upon whether the bricks are dry or wet. As explained in 3.3, 2 different types of glue are used for bonding cut bricks together.

- **Colouring materials:** This is not applicable for all brick specials. Certain type of brick specials requires re-facing of the surface to regain the texture lost during the cutting process. This is achieved by mixing sand with colouring pigments which is then mixed to proportion in the glue to achieve the colour.

The process for manufacturing Brick Specials are given below:

- **Brick Cutting:** This is the first stage process where bricks delivered to the company are cut to required shapes conforming to the BS 4729:2005 standard. The Slip machine and 2 manual brick cutting machines are used for this purpose. 1 operator per machine amounts to 3 operators overall used for this purpose. Not all 3 machines are utilised for cutting for one product. Per product, depending upon the type, only one machine and one operator will be used in manufacturing. The cycle time also depends upon the type of products. For a batch quantity of 100, the cycle time is 30 minutes.

- **Kiln:** All brick cutting machines are water cooled which leaves the cut bricks wet following the process. This leads to the requirement of drying the bricks for better adhesion while using the bonding materials. The drying process is in the kiln where cut bricks are dried in a large oven to remove moisture. As explained, this does not require labour resource, has a cycle time of 2 hours followed by a cooling time of 2 hours, thus amounting to a total cycle time of 4 hours. The kiln is a shared resource between all the products.

- **Bonding:** The cut bricks are bonded together in this process. It is a 4 men operation done in batches of 100. The colouring of the surface of the brick also happens during this process. The cycle time for this process depends upon the type of the brick special required by the customer. For analysis purposes, the cycle time is taken as the average of 35 minutes for a batch of 100. Following bonding process, there is a curing time of 8 hours for the glue to ensure bonded bricks are adhered together for full strength as the brick specials are structural components in the building.

- **Quality Control & Packaging:** The finished brick specials are checked for quality of the surface, order quantity and product type before being labelled, packed and passed to the logistics department for delivery. The packaging is a one labour one machine operation with a cycle time of 10 minutes and is a shared resource between all departments.

Overall, manufacturing of brick specials requires 3 different types of materials, 3 operations, 5 machines, 8 labour resources and 75 minutes of values added time and 12 hours of cooling and curing times without any overhead operation times as given in Table 3.1**Error! Reference source not found.**.

Materials	Operations	Labour resources	Total cycle time
3	3	5	13 hours 15 minutes

Table 3.1: Resource requirement summary for Brick Specials

This information is used in the simulation modelling to understand the integration of shared resources and predict the behaviour of systems. Brick specials amount to circa 30% of company's turnover. Brick specials and prefabricated arches combined are termed as Cut and Bond department within the company.

3.2.1 Value-Stream Map for Brick Specials

The value-stream map for manufacturing of the brick special product called AN.2.5 and AN.3.8 for 100 order quantity is given below.

				Operation	Transport	Inspection	Store	Delay
	AN2.5 & 3.8 (100 quantities)							
Ref No.	Activity Description	Departm ent	Time (minutes)					
1	Load brick to Super Saw	Brick Cutting	5		5			
2	Get the templates to cut bricks		2			2		
3	Set-up the machine to cut bricks		5			5		
4	Cut the bricks (batch of 100)		30	30				
5	Move cut bricks to storage		2		2			
6	Move from storage to kiln		2		2			
7	Drying bricks in kiln		120	120				
8	Cooling time		120	120				
9	Move to bonding storage area		2		2			
10	Move to bonding area		2		2			
11	Bonding bricks together	Bonding	35	35				
12	Curing time		480	480				
13	Stack down on pallets		20		20			
14	Stretch wrap pallets		5				5	
15	Move to packing		2		2			
16	Packing		10	10				
17	Move to yard		3		3			
			845	**795**	**38**	**7**	**5**	**0**
			795					
			94%					

Table 3.2: Value-stream map - Brick Specials

Table 3.2: Value-stream map - Brick Specials explains the value adding activities in manufacturing of products AN.2.5 & AN.3.8.

The total production time is classified into:

i.   Operation: This is where the actual value adding activities take place which changes the state of the product.

ii. Transport: This includes activities that involve moving the product from one location to another.

iii. Inspection: The stages where the operator must the check equipment or product such as checks done on machinery and so on will be classified in this category.

iv. Store: If a product must be stored in a location before the next process is taken place, the time is recorded in this category.

v. Delay: The delay in any process such as waiting for raw-materials and so on are captured in this category.

All stages except the Operation are considered non-value adding. In this case, the total time required to manufacture is 845 minutes, of which 795 minutes are value-adding. This amounts to 94% of the total time. The value adding activities in the process are the ones that change the nature of the product.

3.3 Production process for Prefabricated Arches

An arch is generally a structure which covers a space within a building. Arches are generally installed above doorways and windows. A picture of one type of arch is shown in Figure 3.5.

Figure 3.5: Semi-raised flat gauge arch (Prefabricated Arches, 2017)

The materials used for manufacturing arches are:

- **Bricks:** They are usually supplied by the customers as the colour of the brick has to match the bricks used to build houses. Thus, to avoid any discrepancy, the bricks required are supplied by the customers.
- **Backing board:** This holds the bricks together which is made of cement particles and foam. This is purchased from a regular supplier and contributes a large percentage towards the cost of materials.
- **Bonding material:** Bricks are stuck on to the backing board using bonding materials such as glue. There are 2 different types of bonding materials used – type 1 glue which is used to bond dry bricks to the

backing boards and type 2 glue which is used to bond wet bricks to the backing board. The curing time after bonding process varies depending upon the type of glue used.

The process for manufacturing is explained below:

- **Panel & Board Cutting:** This process cuts the backing board to the required size and shape based on the order requirements. This is carried out using a CNC machine. This resource is shared with the brick-clad chimney production line. It is a one operator process. The time required to cut the backing board per arch varies according to the size and type of arch, but for modelling purposes, an average of 2 minutes is taken.

- **Brick cutting:** The bricks supplied by the customers are cut into specified size and shapes in this process. This operation happens in the cutting room. For arches, one semi-automated (slip machine) and 2 manual brick cutting machines are available for this purpose. For a single arch, the process starts with the slip machine followed by a manual brick cutting machine. The cycle time for cutting arches on the slip machine is 15 minutes and for manual brick cutting machine is 90 minutes per flat-gauge arch and 20 minutes per segmental arch. 2 machines and 2 operators are required in the Brick Cutting process.

- **Kiln:** In this process, the cut bricks are dried inside the kiln to remove moisture. This enables bricks to be glued to the backing board using type 1 glue. This is a machine operation and does not require labour. A minimum cycle time of 2 hours is required for this operation. Following this operation, a cooling time is also required (represented by CO in Figure 3.2). The minimum required cooling time is 2 hours. The temperature of the bricks after being taken out of kiln is higher for manual handling. Thus, the total cycle time for the process is 4 hours, require 1 machine and no labour.

- **Bonding:** The bricks following the previous process are glued on to the backing board in this process. This is a manual operation (1 operator) and does not include any machinery. The cycle time for this operation per arch is 5 minutes. Following bonding, the arches are stored in

racking for curing for the glue. This is represented by CU in Figure 3.2. The minimum curing time is 8 hours.

- **Quality Control:** Before products are packed, labelled and sent to the customers, they go through final quality inspection. This is a one-man operation. Products at random are selected and checked for quality, not all products. Thus, this process is not modelled in the simulation.

- **Packing:** This is the final process before the product is passed on to be delivered to the customer. This operation is a shared resource between all the products in the company. The cycle time for this process is 10 minutes. It is a one operator one machine operation. In simulation modelling, Packing is considered as the last operation and counters are set at this stage.

Overall, to manufacture one single arch, it would take 3 different types of materials, 6 operations, 5 labour resources and 14 hours and 2 minutes (including cooling and curing times) as shown in Table 3.3.

Materials	Operations	Labour resources	Total cycle time
3	6	5	14 hours 2 minutes

Table 3.3: Resource requirement summary for pre-fabricated arches

This only includes the production time and not overheads such as delivery, planning etc. The calculation of value-added time and non-value-added time for pre-fabricated arch production line is given in Appendix D: Value-stream map for pre-fabricated arches.

3.4 Production process for Brick-clad chimneys

Chimneys have been an essential part of UK houses for centuries which act as a ventilation for hot gases arising from fireplace, boilers, stove and so on. The gases are released to the atmosphere using the ventilation inside the chimneys. The majority of UK houses are equipped with chimneys.

Although, recent developments and innovations in the UK housing sector especially in the boiler and heating systems has made the requirement of a

live working chimney redundant. But due to building regulations and aesthetic requirements, UK house builders use chimneys on the house design. A typical chimney supplied by the company is shown in Figure 3.6.
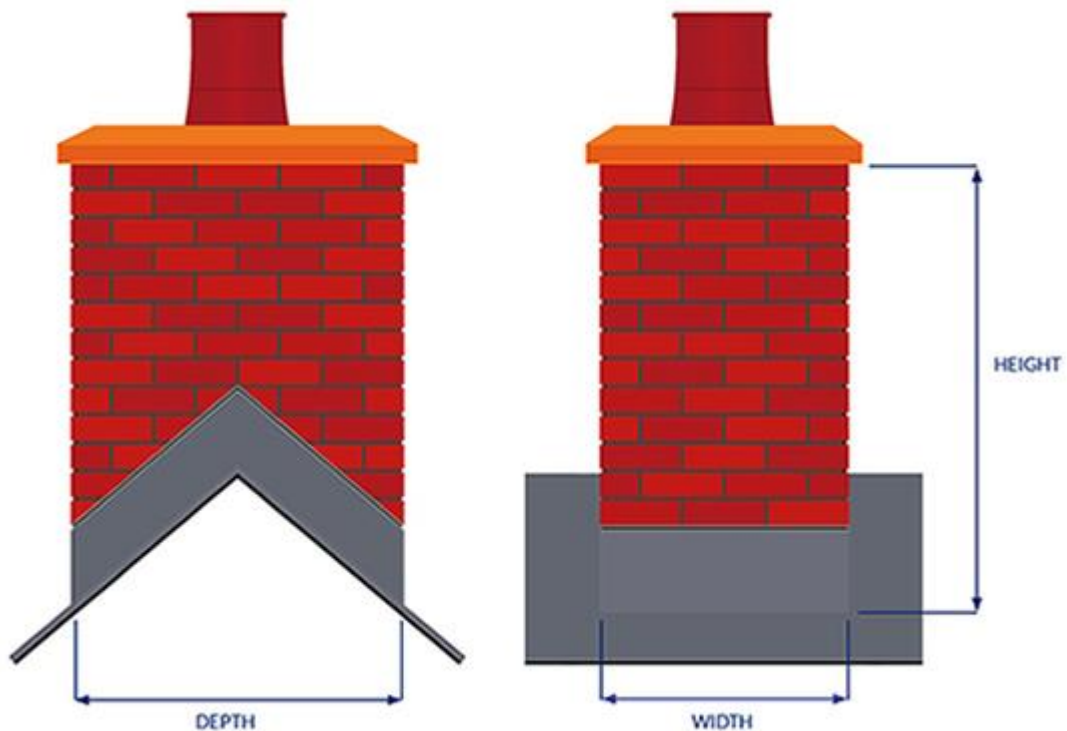
Figure 3.6: Brick-clad chimney

As there is no requirement for a live working chimney with ventilation in most of the houses, the chimneys supplied by the company are decorative and not functional. The company also supplies live functional chimneys upon request by customers but is not a standard option offered. A typical chimney is fitted to the roof along the ridge of the roof.

The defining characteristics of the chimney are:

- **Width:** This is the dimension of the chimney along the roof ridge.
- **Depth:** This is the dimension of the chimney across the roof ridge.
- **Height:** This is the dimension from the bottom of the core to the top of the chimney core excluding the height of the pot.
- **Roof pitch:** This is the angle of the roof.
- **Roof position:** This specifies the location of the chimney on the roof. There are 4 standard positions which are given below:

| Mid-Ridge | Mono-Pitch | Gable End | Gable Ladder |
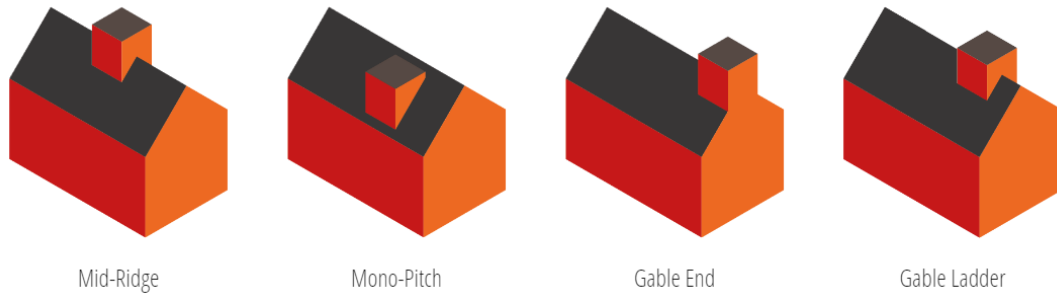
Figure 3.7: Chimney roof position

Other features that can be specified on a chimney are corbel details, cap options, pot options and brick-bond pattern.

The company offers 2 types of chimneys to customers:

- **Brick-clad chimney:** In this option, the chimney core is made of laminated ply wood and brick slips are attached to the core to make a look alike decorative brick-clad chimney.
- **GRP chimney:** Glass Reinforced Plastic (GRP) is another type of chimney which looks alike like a brick-clad chimney but is made of plastic materials. GRP is a matrix of glass fibre sheets which is set in resin.

As over 80% of chimney orders are brick-clad with standard options, for analysis purposes, it is being considered and the processes explained below. As the company offers many options on different features such as width, depth, roof pitch etc., the total number of combinations of a chimney that can be specified are over 10,000.

The manufacturing process explained below is for a brick-clad chimney without a live flue in it.

The materials used for manufacturing are:

- **Bricks:** Same as for previous products, to match the brick type and brick colour on the construction site, bricks are supplied by the customer. This is collected from the site by the company and delivered to the factory for processing.

41

- **Laminated ply wood:** The core of the chimney is made from laminated ply. There are 2 different types of laminated by used in manufacturing – 5.5 mm thick ply and 12mm thick ply sheets. They are purchased and cut to the required size as per order in the manufacturing facility.

- **Timber:** The cut sheets of ply are assembled together using 3"x2" timber. Timber is bought in lengths and supplied to the factory which is cut to size as required.

- **GRP laminate & resin:** Even though the chimney is not GRP, the core of the chimney is made waterproof by spraying the core with GRP laminate and impregnating with resin. Essential components that are specified with the chimney are caps and/or pots. This is made using a moulding process using GRP and resin materials.

- **Bonding materials:** The brick slips are glued on to the core of the chimney using bonding materials like arches and brick specials.

- **Nuts, bolts, nails, lifting eyes:** Various kinds of fixing materials such as nuts, bolts and nails are used along the processes. Examples include fixing the core of the chimney to pallets to using lifting eyes to lift the chimney from the floor to the roof.

- **Plastic sheets:** This is used to pack the chimney to prevent any damage during transport to the customer. After the manufacturing is complete, the chimney is packed using plastic sheets and secured on to a pallet, ready for delivery.

Not all materials used for manufacturing are specified below. Only the significant items that contribute to the cost and environmental sustainability are specified above.

The processes for manufacturing brick-clad chimneys are given below:

- **Cut Boards:** This is the start of the process. In this the laminated ply sheets are cut to the required size and shape using an automated 3-axis CNC router. The operator programs the pieces to be cut using a CAD-CAM software and then cuts the 12mm and 5.5 mm to shapes and sizes. One operator is required for this operation with a cycle time

of 45 minutes per average chimney. This varies depending upon the size and features on the chimney.

- **Assemble Core:** The cut sheets of ply are assembled to make the core of the chimney in this process. The sheets of ply are assembled together using 3"x2" timber frame. Two operators are required for this operation with a cycle time of 65 minutes.

- **Laminate Core:** In this operation, the assembled chimneys are spray laminated using the GRP fibreglass and resin. This is to make sure the chimney is waterproof and provides structural integrity to the core of the chimney. One machine and 2 operators are working simultaneously in the process with a cycle time of 45 minutes. Following the laminating process, there is a curing time of 8 hours for the resin to cure. This is temperature dependant and varies. Generally, it takes longer (greater than 8 hours) to cure in colder climate especially in winter season and shorter (less than 5 hours) during summer season.

- **Trim Core & Add Flow-coat:** Following the laminating process, after the resin has cured, the edges of the core of the chimney are left with sharp GRP materials. In this process, the edges are trimmed and sanded down to ensure no sharp laminate is present. Following this a special material is coated to the edges and corners of the chimney core to ensure water tightness. This is a thick layer (around 3mm) of flow coat. This is a one operator function with a cycle time of around 20 minutes. Following this process, there is a curing time of 8 hours for the flow coat. This is not dependent on the ambient temperature. The operation is a one man one machine operation

- **Cut Brick Slips:** The brick slips supplied by the customer are cut to 25mm thick slips. A standard brick is 215 x 102 x 65 mm. This is cut to 215 x 65 x 25 mm. The face of the brick is maintained. The other portion of the brick is waste unless the brick is double faced where two 25mm thick brick slips are obtained from a standard brick. This is a one-operator one machine operation with a cycle time of 60 minutes. This is a sub-assembly line which is carried out separate to the main assembly line as shown in Figure 3.2.

- **Dry brick slips:** The cut brick slips are dried in a Kiln like arches and brick specials as the brick cutting machines are all water cooled. The Kiln removes moisture and makes the bricks dry which are easier to bond it to the core of the chimney. This operation does not require a labour resource, has a cycle time of 2 hours followed by the cooling time for bricks which is another 2 hours. Thus, the total cycle time for this operation is 4 hours irrespective of the type of product.

- **Brick Cladding:** In this process, the cut brick slips are glued to the core of the chimney. The chimney core after flow coating is cured and supplied to this process. The core of the chimney is sanded down to make it rough for the brick slips to be glued correctly. The cut slips are glued to the core using adhesive. This operation requires 2 operators and a cycle time of 45 minutes. Following this process, there is a curing time of 8 hours for the adhesive.

- **Manufacturing Caps & Pots:** This is not represented in the process map as it is a sub-assembly process. In this process, the caps and pots are manufactured using injection moulding process and using open laminating process. This is then fed to a Kanban storage system which stores minimum specified of each category of cap and pot. According to the order quantity and type, this is then picked and delivered to the operation. This is a 2-operative process with a cycle time of 60 minutes.

- **Adding Caps & Pots/Finishing:** Caps and pots are specific to the order. Some chimneys may not have them and some might have 2 pots. Caps and pots manufactured are delivered to this operation. This is a single operative no machine operation with a cycle time of 20 minutes. Adhesive is used to fix the cap and pot to the core of the chimney. There is a curing time for this operation of 8 hours.

- **Quality inspection:** This is the final process where the chimney is inspected by a trained quality co-ordinator before passing on to the packaging department. It is a one-person operation and required 10 minutes' cycle time.

- **Packaging:** In this final stage, the chimney that is being signed-off by the quality inspector is packed using polythene sheets to prevent any

damage during transport. The chimney is secured on to the pallet, wrapped with plastic sheets; labels are attached and are moved to the yard to deliver on-time in full to the customer.

Overall, manufacturing of brick-clad chimneys requires 7 major different types of materials, 10 operations, 9 machines, 11 labour resources and 305 minutes of value added time and 28 hours of cooling and curing times without any overhead operation times as given in Table 3.4.

Materials	Operations	Labour resources	Total cycle time
7	10	11	33 hours 05 minutes

Table 3.4: Resource requirement summary for Brick-clad chimneys

3.5 Chapter Summary

The existing process flow of the nature and complexities of manufacturing three different products have been described in detail. Overall, the manufacturing facility discussed has 24 operatives not including fork lift drivers and 16 operations to produce 3 different types of products. This information will be used in the next chapter to build the simulation model of the production process.

4 Simulation Model

Before proceeding with the decision that simulation is the solution, the techniques used in simulation needs to be analysed. The queuing nature of the model and the randomness in the system, simulation modelling is found appropriate to solve the situations. (Beck, 2011) They model of Brick Fabrication Ltd is of similar nature which makes simulation appropriate to the situation.

4.1 Simulation Methodology

The simulation is carried out following the methodology given below as described by Ulgen (Onur M. Ulgen, 2016). This is to ensure the robustness of the process and to make sure all the steps are followed to achieve the result.

    i.   Define the problem

    ii.   Design the study

    iii.   Build the conceptual model

    iv.   Formulate inputs, assumptions and processes

    v.   Build, verify and validate the simulation model

    vi.   Experiment with the model

    vii.   Document and present the results

    viii.   Define the model life cycle

The stages are not to be followed in sequence as some stages may have to be done prior to others. For example, the data might need to be collected before defining the problem as data might throw anomalies which require attention that could be the problem.

Similar approach is taken in the article (Joanne Berry, 2011). In this simulation, the problem is defined in Section 1.3. All the other phases of building the model is explained in later sections of the thesis. This is the model that is followed in the thesis to obtain the result.

4.2   Factory layout: Main Factory

The company has 2 major sites for manufacturing in UK, one in Pontypool and the other in Stoke-on-Trent. This study is being conducted in the factory at Pontypool. In Pontypool, the company has 2 factories; one has the main production line and the other which manufactures sub-assembly parts which is called the GRP (Glass Reinforced Plastic) unit. The production of pre-fabricated arches and Brick Specials takes place in the main factory, and the manufacturing of the Brick-clad chimneys takes place both in the main factory and in the GRP factory where a sub-assembly part is made.

The layout of the main factory is shown in Figure 4.1.
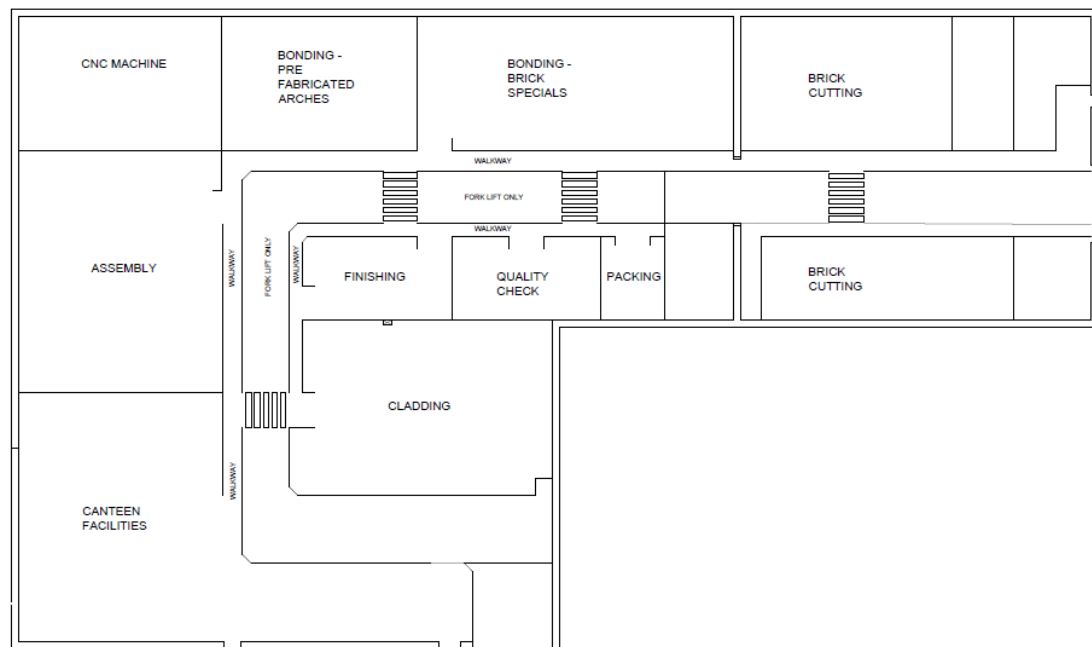
Figure 4.1: Plant layout: Main factory

For pre-fabricated arches, the process flows from Brick cutting to Bonding. Same applies for Brick Specials. The Kiln which is used to dry cut bricks is located in the Brick Cutting part of the process. Following the Bonding process, the products move to the holding bay to be checked for Quality and then to the Packing bay. Following packaging, the products are moved to the yard to be delivered to the customers.

For manufacturing of the Brick-clad chimneys, the process starts with the CNC Machine followed by the Assembly process. After the Assembly process, the assembled core of the chimney is transported to the GRP factory.

The layout of the GRP factory is shown in Figure 4.2.
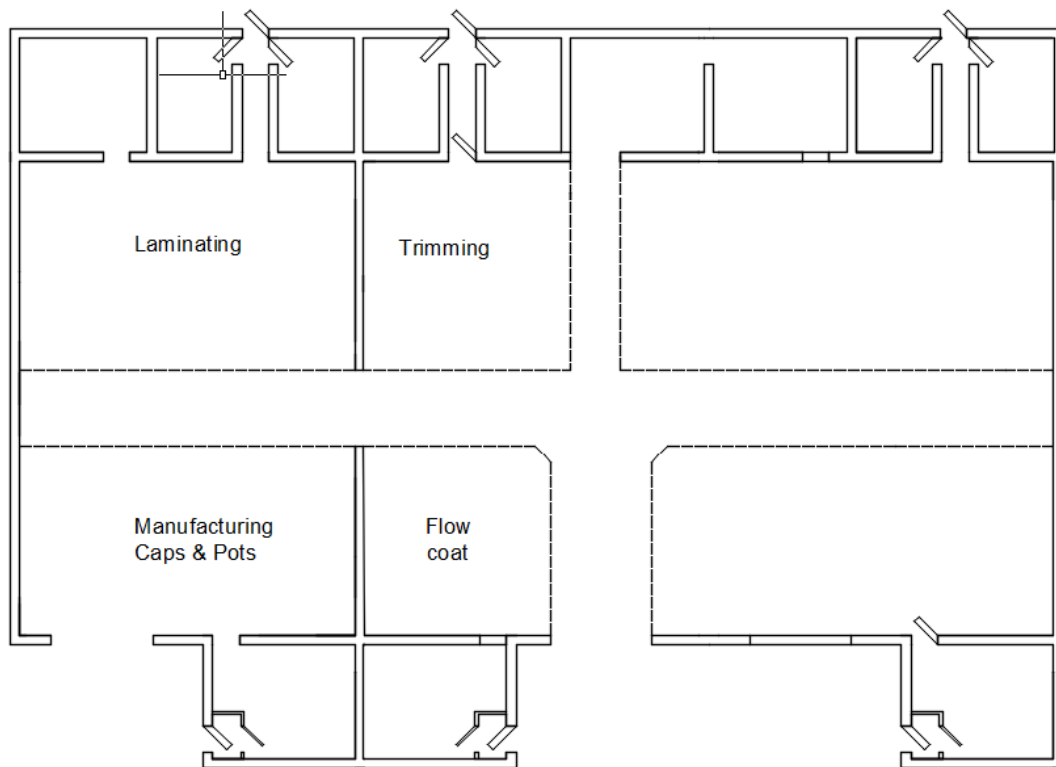
Figure 4.2: Plant layout: GRP factory

The laminating process and the trim & flow coat process takes place in the GRP factory. Also, this is the manufacturing unit for the Caps & Pots. They are manufactured and finished completely in this unit. Following this process, the chimney core and caps & pots are delivered to the main factory.

The rest of the process takes place in the main factory where brick slips are clad to the chimney, and when it is finished, quality checked and packed. Following packing, the chimneys are transported to the customers.

In the following section, assumptions used in the simulation model are discussed.

4.3 Assumptions

Following are the assumptions used in building the simulation model.

    i.   Parts arrival: The parts used in the model are used to control the orders processed per day. In reality, the parts are brought weekly with infinite capacity.

    ii.   Holding area capacity: The capacity of the holding area is assumed to be infinite for simulation purposes. This is not possible in practice with the existing floor space to store the work-in progress (WIP) beyond capacity.

    iii.   Number of machines: Machines in the simulation model are not representative of exact machines but models that represent processing the order. For example, the number of machines shown in the Assembly area is two, which means 2 chimneys could be assembled in the operation at the same time and not representative of 2 physical mechanical machines on the shop floor.

    iv.   Scale: The simulation model is created not to scale to the factory floor. It is changed to suit the model and express results.

    v.   Raw materials: Not all raw materials are represented in the system that is required to make the finished product. This is done not to make the model over-complicated. Just the raw materials required to produce the result for analysis purposes are modelled.

Human activities such as sickness, stopping to have a conversation with a colleague are unpredictable and random in nature. For this reason, the following assumption are made when building the Witness model.

    vi.   Labour resources are modelled as working at full capacity. Travel time from one location to another is not included.

    vii.   Holidays, sickness, time wasted on shop floor due to general conversation are also not included in the simulation model.

    viii.   Any non-conformance on products and time spent on resolving customer complaints are assumed to be zero or negligible.

    ix.   Break times are not modelled in the simulation as it is expected not to alter the results.

4.4 Building the Witness model

The simulation model for the manufacturing is shown in Figure 4.3. It shows the layout of the plant in the simulation model representing parts, machines, labour resources and layout.

In Figure 4.4, the model is shown with the process flow map which shows the movement of parts in the factory. The parts are processed using the machines. Once a process is completed, the parts are stored in a holding area before the next operation is started. These holding areas are represented by Buffers in the model which is represented as numbers. Before 2 different processes, the parts are held in a buffer which is shown by numbers. In Figure 4.3, Arch_storage is an example of a buffer.

The process map for the model is given in Figure 3.2: Production process map for arches, brick specials & brick-clad chimneys. The operations on the first column on Figure 3.2 represents actual operations in the factory. The second, third and fourth columns represent the process flow for each product. This is modelled below in Figure 4.3 and Figure 4.4. The factory is split into main factory, Brick Cutting and GRP. With reference to Figure 3.2, each operation is represented by a machine in the simulation model which is stationed in one part of the factory. This is explained in Table 4.1.

Operation (Figure 3.2)	Name of the Machine used in Witness	Location
Panel & Board cutting	CNC_Machine	Main Factory
Assembly	Assembly	
Bonding	Bonding_Arches Bonding	
Cladding	Cladding	
Finishing	Finishing	
Packing	Packing	

Brick Cutting	Slip_machine Bndng_saw_01 Bndng_saw_02 Arch_saw_01 Arch_saw_02 Chmny_saw	Brick Cutting
Laminating	Laminating	GRP Factory
Trim/Flow coat	Trim_coat	
GRPVRTM	Cap_n_Pots	

Table 4.1: Operations vs. Machine elements
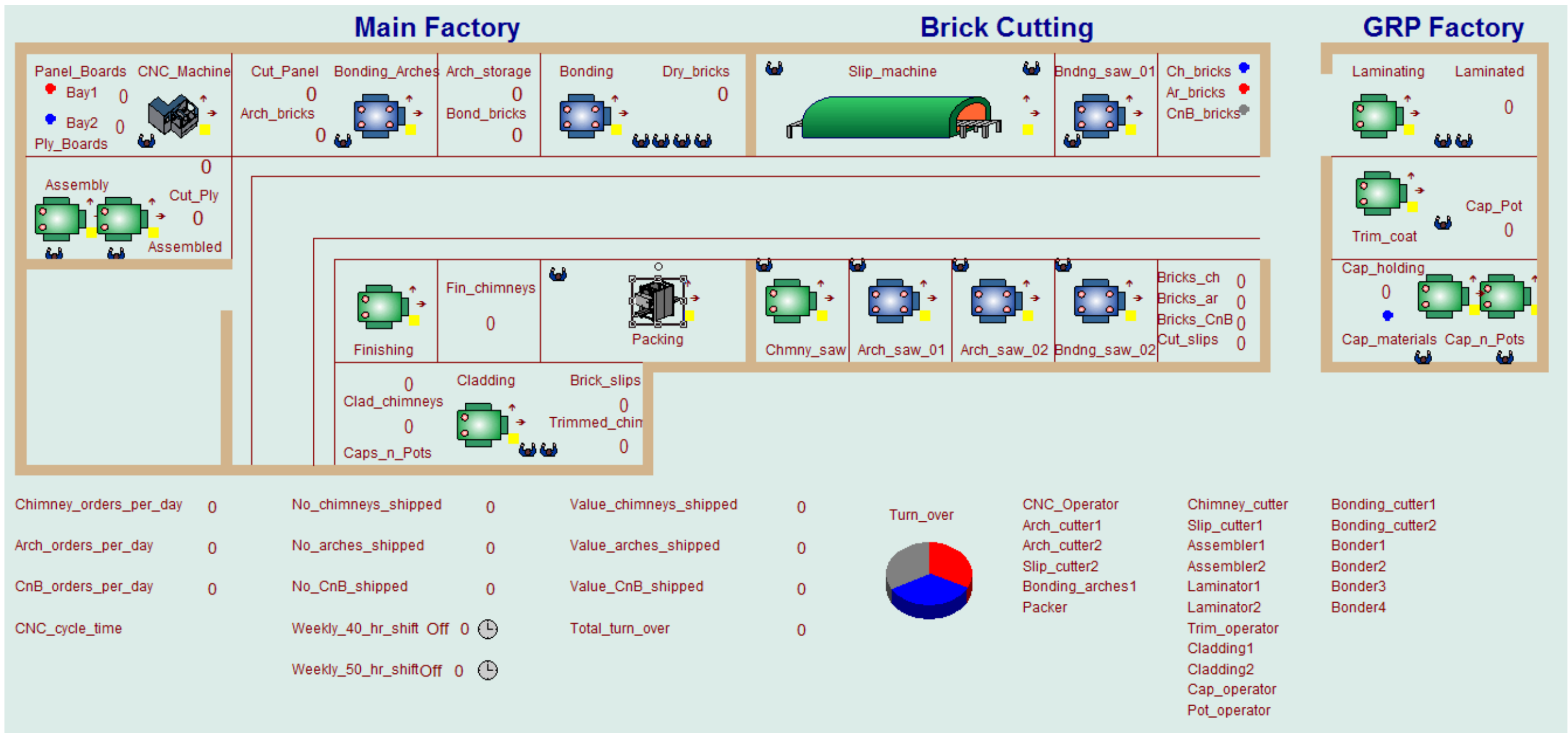
Figure 4.3: Simulation model - entire factory
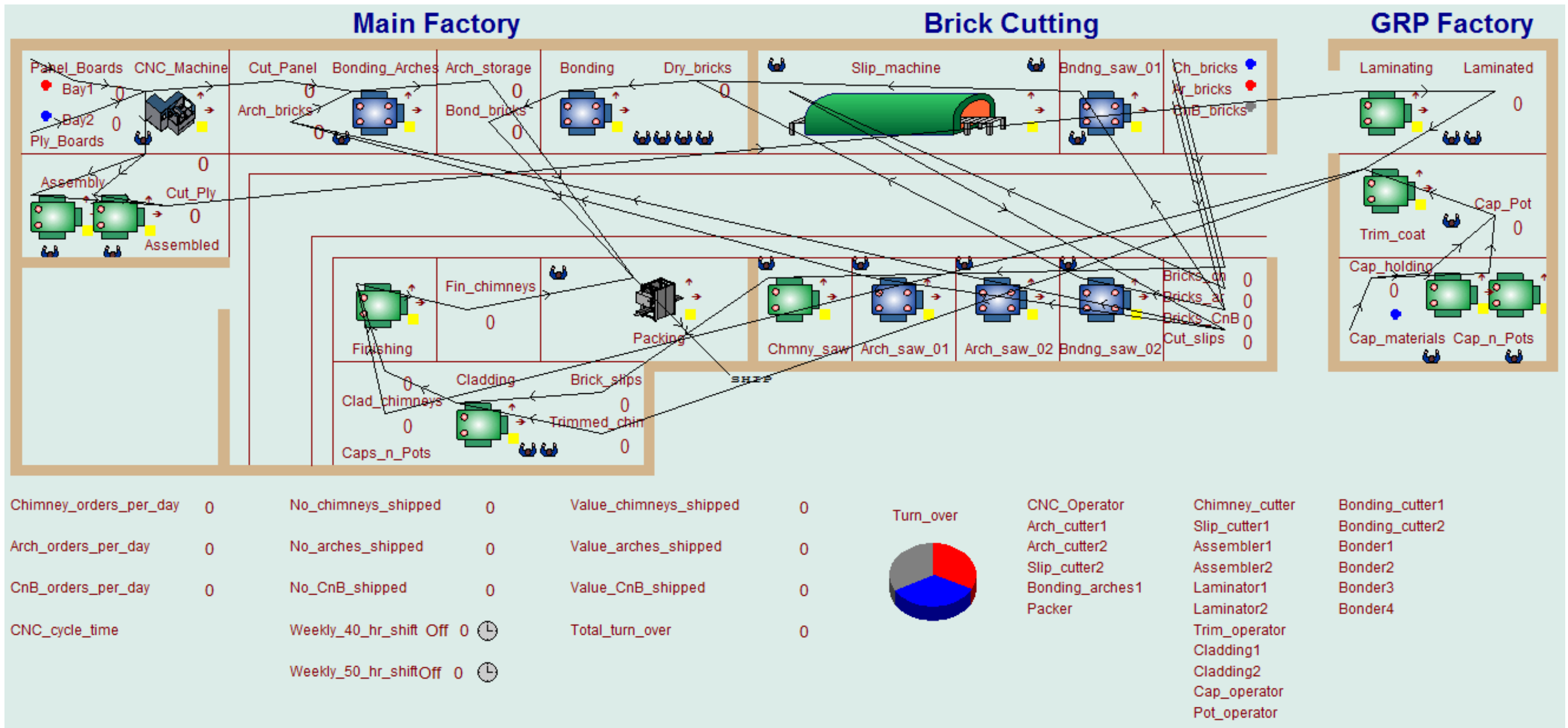
Figure 4.4: Simulation model - with part movements

4.4.1 Parts

Parts are the components that get processed in the model to create the finished products. They are representative of raw materials but as discussed in the Assumptions, not all raw materials are modelled. The parts modelled in the system are given below:

- **Ply_boards:** This is the part used to manufacture chimneys. It is represented as 'Ply_boards' in the model. The part is pushed into the buffer 'Bay2' from which the 'CNC_Machine' pulls the part for manufacturing. It is represented by blue in colour. The arrival profile for the part is controlled by the parameter 'Chimney_orders_per_day' which is given in Figure 4.5:

Figure 4.5: Ply_boards arrival profile

It can be seen that a lot size arrives at time zero, followed by the next lot size at intervals of 1440 minutes which is every 24 hours. The lot size is controlled by the variable 'Chimney_orders_per_day', value of which is given when the model is initialised.

- **Cap_materials:** This is used to manufacture Caps & Pots. It is pushed into the buffer 'Cap_holding' from where it is pulled into the machine 'Cap_n_Pots'. The material is represented by blue in colour. The arrival profile of the part is given in Figure 4.6:

Figure 4.6: Cap_material - arrival profile

It can be seen that the first lot size arrives at time zero, followed by the next lot size at time intervals of 24 hours (1440 minutes). This is controlled by the variable 'Chimney_orders_per_day' which is given in the model initialisation.

- **Panel_boards:** This part is used to manufacture pre-fabricated arches. It is pushed into the buffer Bay1 which is used by the CNC_Machine to manufacture arches. The material is represented by red in colour. The arrival profile of the part is given in Figure 4.7.
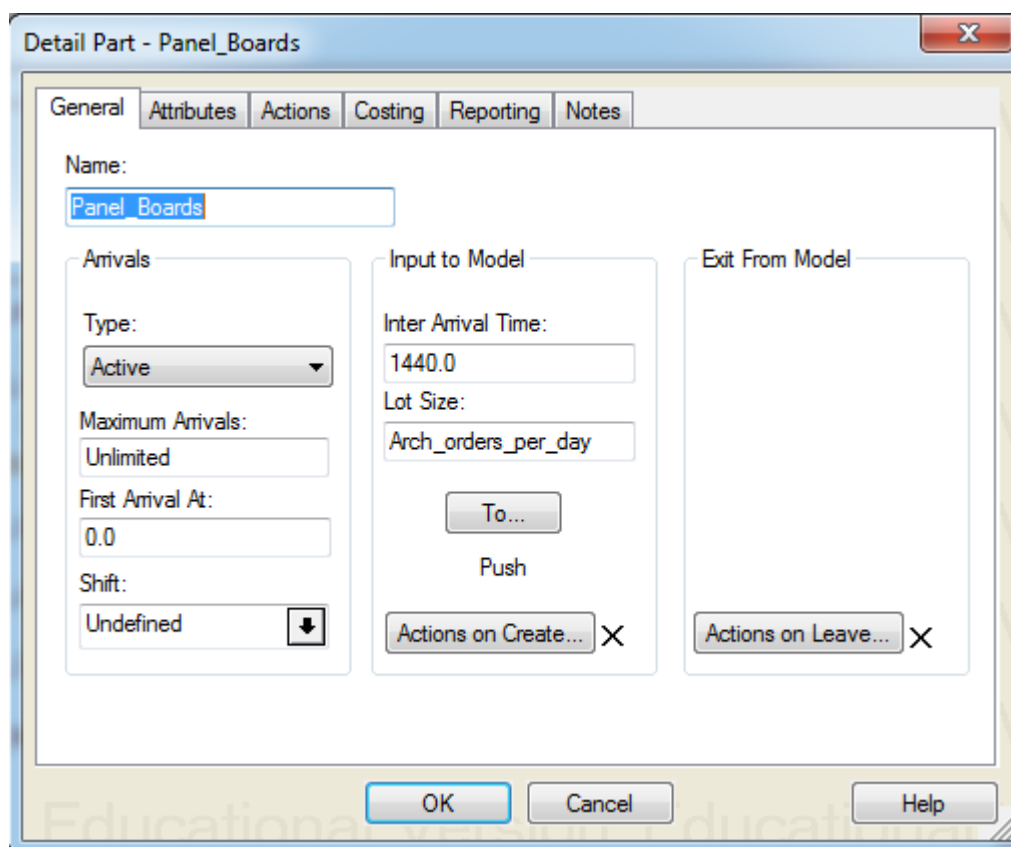
Figure 4.7: Panel_boards - arrival profile

The arrival time and inter arrival time are similar to other parts and is also controlled by the variable 'Chimeny_orders_per_day'. But the number of orders arrived per day is 35 compared to that of chimneys of 10.

- **Ch_bricks:** This is the bricks used to make chimney slips. The arrival profile is similar to other raw materials used for manufacturing chimneys.
- **Ar_bricks & CnB_bricks:** This is the bricks used to manufacture arches and brick specials. The first arrival is at time zero followed by inter arrivals at 24 hours with the lot size of 1000 for arches and 10 for brick specials respectively.

4.4.2 Buffers

Buffers are used in the model to represent work holding areas. For example, if a delay is present in starting a process after the previous process and the work needs to be held for a while, it is represented by a buffer in the system.

Buffers can be represented by parts of numbers. In this simulation model, buffers are represented by numbers which represent the number of parts held in the buffer at a particular point in time. For example, the work processed by the CNC Machine is completed and moved into a holding bay in the factory. This is then processed by the Assembly area depending upon the numbers of jobs in the queue. This is represented by the buffer 'Cut_Ply' in the model. The example of this buffer is given in Figure 4.8
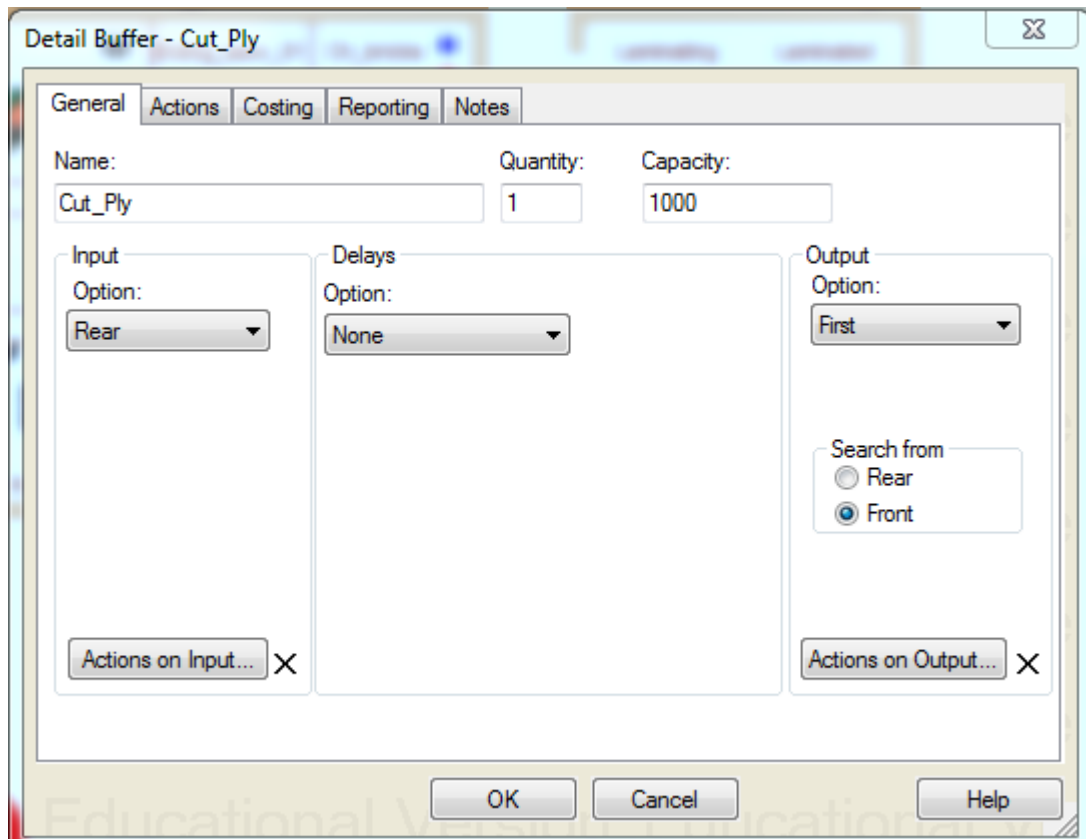
Figure 4.8: Buffer - 'Cut_Ply'

It can be seen from the detail above that the buffer has a maximum capacity of 1000 which means it can hold 1000 jobs in the buffer at one point of time.

Buffers are also used to model delay time. Some processes require a delay time (such as cooling time or curing time) after the process is completed and before the next process is started. An example would be chimneys that are laminated requires a delay of 8 hours before the next process is started. This is modelled in the simulation in buffers as the delay time shown in Figure 4.9.

Figure 4.9: Modelling delay time

The buffers used in the simulation model are given below:

- Arch_bricks
- Arch_storage
- Assembled
- Bay1
- Bay2
- Bond_bricks
- Brick_slips
- Bricks_ar
- Bricks_ch
- Cap_holding
- Cap_Pot
- Caps_n_Pots
- Clad_chimenys
- Cut_Panel
- Cut_Ply

- Cut_slips

- Dry_bricks

- Fin_chimneys

- Laminated

- Trimmed_chim

20 different buffers are used in the model to simulate the manufacturing processes in the factory.

4.4.3 Machines

Machines are representative of processes in the factory and not exact models of mechanical machines. For example, in the model, the machine 'Assembly' represents the Assembly operation in the factory and not a physical machine on the factory floor. The parameters required to model a machine are given in Figure 4.10.

Figure 4.10: Modelling a machine - CNC_Machine

The most important parameters of modelling a machine are:

- **Input**: It represents the path from which a part is pulled to the machine. Normally it is from a buffer.

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- **Cycle Time**: The cycle time is one of the most important parameters in a model. It represents the amount of time required to process the part in the machine. It can be given as a number or controlled by a function. In the above example for 'CNC_Machine', the cycle time is controlled by a function as the cycle time changes depending upon the type of product that is processed. The function used to control the machine is given in Figure 4.11.
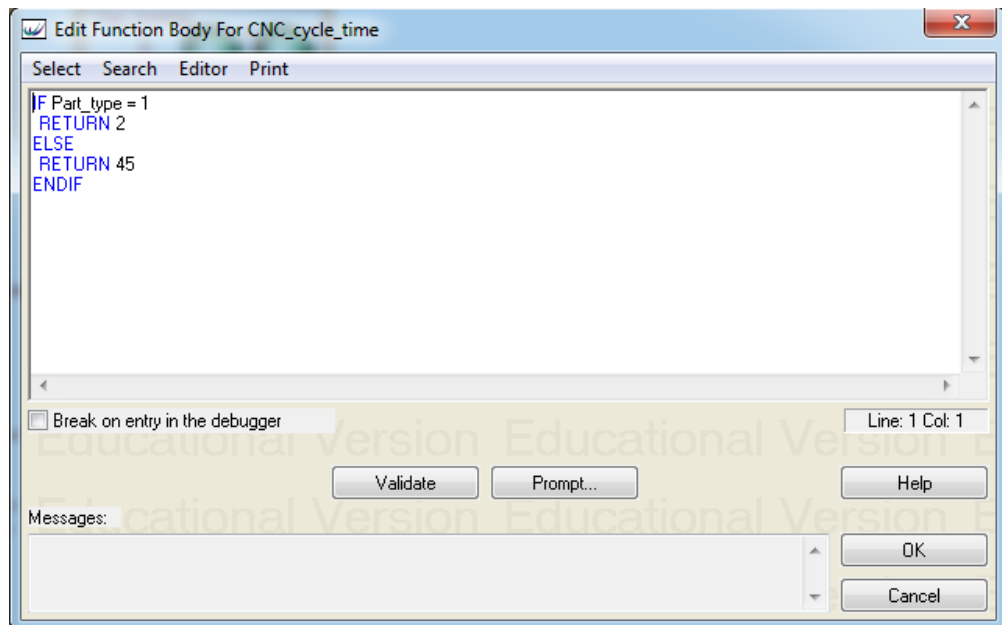
Figure 4.11: Cycle time function

This function sets the cycle time to be 2 minutes if 'Part_type' 1 is being processed, else to 45 minutes.

- **Labour Rule:** In this parameter, the labour resources can be specified on the machine. The machine can be modelled for one labour resource or 2 labour resources. This can be modelled in WITNESS using 'AND' or 'OR' function to tell the machine which combination of labour resources are to be used The example of Bonding machine is given in Figure 4.12:
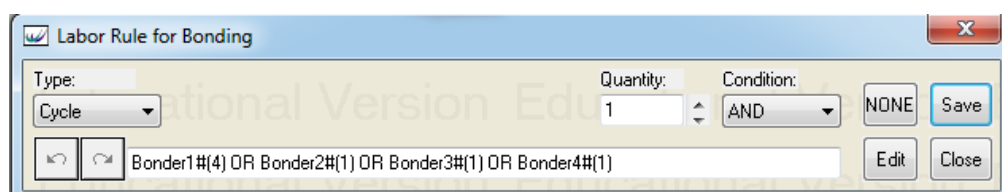
Figure 4.12: Labour rule for Bonding

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This shows that any of the 4 bonders are only required to operate the machine 'Bonding'.

- **Type:** There are 7 different types of machines that can be modelled using Witness which are given below:

  i. Single

  ii. Batch

  iii. Assembly

  iv. Production

  v. General

  vi. Multiple Cycle

  vii. Multiple Station

In this simulation model, only Single and Assembly machines are used. In a Single machine, there is one input and one output. In an Assembly machine, there are 2 or more part inputs and one output. This is used to represent an operation which assembles different parts to one. This is controlled by the input quantity. Following is an example of an Assembly machine as shown in Figure 4.13.
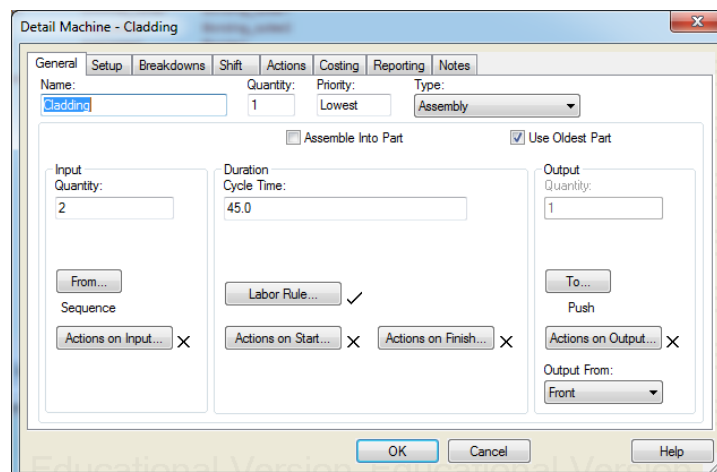
Figure 4.13: Assembly machine example

In the above machine, it can be seen that the input quantity required is given as 2 and the Type of the machine is selected as Assembly which indicates 2 parts are required by the machine to produce an output. This can be compared to Figure 4.10 which is a Single machine.

- **Output:** In this tab, the output parameters of the machine as specified. The output of a machine is generally to a buffer using the PUSH rule.

The different types of machines modelled in the simulation with its parameters are given in Table 4.2.

Machine	Type	Input quantity	Cycle time (min)	Labour resources	Output quantity
Arch_saw_01	Single	1	90	1	1
Arch_saw_02	Single	1	20	1	1
Assembly	Single	1	65	2	1
Bndng_saw_01	Single	1	30	1	1
Bndng_saw_02	Single	1	30	1	1
Bonding	Single	1	30	1	1
Bonding_Arches	Assembly	2	5	1	1
Cap_n_Pots	Single	1	60	2	1
Chmny_saw	Single	1	60	1	1
Cladding	Assembly	2	45	2	1
CNC_Machine	Single	1	2 or 45	1	1
Finishing	Assembly	2	20	1	1
Laminating	Single	1	45	2	1
Packing	Single	1	10	1	1
Slip_machine	Single	1	15	2	1
Trim_coat	Single	1	20	1	1

Table 4.2: Machines parameters in the simulation model

16 different operations are modelled using the machines in the simulation. Some machines are considered a shared resource between different products.

4.4.4 Labour resources

Labour resources are modelled in the simulation using the 'labor' parameter. Labour resources are allocated to each machine. The Table 4.3 shows the labour resources allocated to each product where a few resources are shared.

Brick-clad chimneys	Pre-fabricated arches	Brick specials
CNC_Operator		Bonding_cutter1
Slip_cutter1		Bonding_cutter2
Slip_cutter2		Bonder1
Chimney_cutter	Arch_cutter1	Bonder2
Assembler1	Arch_cutter2	Bonder3
Assembler2	Bonding_arches1	Bonder4
Laminator1		
Laminator2		
Trim_operator		
Cladding1		
Cladding2		
Cap_operator		
Pot_operator		
Packer		

Table 4.3: Labour resources

23 labour resources are modelled in the simulation, 3 of which are shared for 2 product lines, the Packer is a shared resource between all 3 products. The rest of the resources are dedicated resources to each particular product.

4.4.5 Shift pattern

The factory operates on a 40 hour/week shift pattern. In order to get accurate results from the simulation model, the model needs to represent the real-life situation. If shift patterns are not modelled into the simulation, it will not represent the actual results from the factory. The shift pattern used in the simulation is given in Figure 4.14 which is for a standard 40-hour work week Monday to Friday.

Figure 4.14: Weekly (40 hour) shift pattern

The Working Time represents the time the model is run and the Rest Time represents the non-working times. Period 1 to 5 represents Monday to Friday respectively with working time of 8 hours (represented as 480 minutes) and non-working time of 16 hours (960 minutes). Saturday and Sunday are non-working times represented by 2880 minutes (48 hours) in the model.

The total working time for the week is 2400 minutes and non-working time of 7680 minutes. To simulate a full working week, the running time should be 10080 minutes. A warm up time is also required while running the simulation to make sure enough parts are in the system before calculating the results so the model is not empty when running.

4.4.6 Input parameters

These are used to control the simulation model. The input parameters used in the model are given below.

i.   **Chimney_orders_per_day:** It is the number of orders per day received for brick-clad chimneys. This parameter tells the model how many chimneys needs to be produced per day. It is given as 10 on the initial model. An example of calculation of input parameters to find out the chimney orders per day is given in Appendix C: Order analysis for Brick-clad chimneys.

ii. **Arch_orders_per_day:** This parameter represents the number of arch orders that arrive in the factory per day. In the initial model, it is given as 35.

iii. **CnB_orders_per_day:** This parameter is modelled to input the number of batch order (100/batch) of Brick Specials that arrive in the factory for processing. The number of batch orders per day is given as 1000.

4.4.7 Output parameters

The outputs from the simulation model is captured using the output parameters. Below are the output parameters modelled in the simulation.

i.   **No_chimneys_shipped:** Represents the number of chimneys produced in the simulation time.

ii. **No_arches_shipped:** Captures the number of arches produced in the simulation time.

iii. **No_CnB_shipped:** Captures the number (batches of 100) of Brick Specials produced in the simulation time.

iv. **Value_chimneys_shipped:** This represents the '£' value (cumulative sum) of the total number of chimneys shipped during the simulation time at an average price of £535/chimney.

v.   **Value_arches_shipped:** This represents the cumulative sum of the value of the arches shipped (£55/arch) during the simulation time.

vi. **Value_CnB_shipped:** This represents the cumulative sum of the value of Brick Specials shipped (£105/batch of 100) during the simulation time.

vii. **Total_turn_over:** This calculates the total value of all 3 products shipped in the simulation time.

viii. **Turn_over:** This is a pie chart of the share (in £ value) of the 3 products shipped.

4.4.8 Rules in the Simulation model

In order for the model to replicate exactly what happens on the shop floor, certain rules are modelled in the simulation. The rules in the simulation model are given below.

i. **Model initialise actions:** This rule is run before the model started or at time 0. It is run only once at time zero, it sets or resets the values of certain parameters to what is specified. The data was collected from the factory based on the review of orders for 3 months. These orders were then averaged to find the number of orders per day per product. See Appendix C: Order analysis for Brick-clad chimneys for the calculation of Brick clad chimneys. The rule is given below.

> *Arch_orders_per_day = 35*
> *Chimney_orders_per_day = 10*
> *CnB_orders_per_day = 1000*
> *!*
> *No_chimneys_shipped = 0*
> *No_arches_shipped = 0*
> *No_CnB_shipped = 0*
> *!*
> *Value_chimneys_shipped = 0*
> *Value_arches_shipped = 0*
> *Value_CnB_shipped = 0*
> *Total_turn_over = 0*

ii. **Output rule:** This rule is used to calculate the output parameters when a part is leaving the model. It is modelled in the output rule of

the Packing machine. The rule is run every time a part leaves the Packing machine. The rule sets the value of all output parameters to zero if the simulation time is less than 10080 minutes (1 week) as this is the warm up time used in the model to make sure enough parts are there in all sections of the model before capturing results. For time greater than 10080, the rule increases the value of output parameters. The rule is given below.

```
IF TIME <= 10080
!
  No_arches_shipped = 0
  No_chimneys_shipped = 0
  No_CnB_shipped = 0
  Total_turn_over = 0
  Value_arches_shipped = 0
  Value_chimneys_shipped = 0
  Value_CnB_shipped = 0
!
ELSE
!
  IF TYPE = Ply_Boards OR TYPE = Ch_bricks OR TYPE =
  Cap_materials
!
    No_chimneys_shipped = No_chimneys_shipped + 1
    Value_chimneys_shipped = Value_chimneys_shipped + 535
    Total_turn_over = Total_turn_over + 535
!
  ENDIF
!
  IF TYPE = Panel_Boards
!
    No_arches_shipped = No_arches_shipped + 1
    Value_arches_shipped = Value_arches_shipped + 55
    Total_turn_over = Total_turn_over + 55
!
  ENDIF
!
```

IF TYPE = CnB_bricks

!

  No_CnB_shipped = No_CnB_shipped + 1

  Value_CnB_shipped = Value_CnB_shipped + 105

  Total_turn_over = Total_turn_over + 105

!

 ENDIF

!ENDIF

The full list of rules such as input, labour and output rules inside each machine in the simulation model is given in Appendix E: List of rules and variables used in DES model.

4.5 Chapter Summary

In this chapter, the simulation of models including Continuous and Discrete simulations have been introduced. The parameters required for the building of the simulation model has been discussed in detail with the factory layouts. Assumptions used in the model has been explained clearly. All the important components of the model have been explained along with the rules and parameters used to capture the outputs.   The model which has been developed will be used in the following chapter to conduct simulations of the process flow under different conditions.

5 Manual optimisation of resources

In this chapter, the Discrete Event Simulation (DES) model is optimised manually in an intuitive manner by changing the model parameters. Changes that could improve the productivity of the model were identified by using FIT manufacturing principles to allow the process to be more lean and agile. Critical analysis and evaluation of the simulation model were carried out intuitively using line balancing techniques to identify scenarios to maximise productivity. These scenarios were manually tested in the model to study the changes in the manufacturing process flow.

The DES model offers the opportunity to study the behaviour of the existing production process. Hence, the model was utilised conveniently by considering different parameters that would improve the process in such a way to get more out from the existing system without having to make more investment.

In other words, various model parameters are optimised using different line balancing solutions to find the optimal way of operating the plant with reduced costs and maximum output. The simulation model explained in the previous chapter is the basis of the experiments. Thus, it is even more critical to ensure that the simulation model developed is an exact replica of the real-life production lines that are operating at the factory and the results obtained using the model is validated before any experiments are carried out. In the next sub-section, the authenticity of the created DES model is validated.

5.1 DES model validation

The simulation model being validated is the initial model developed in Chapter 4.

Validation strategy: This model is run for a specified amount of time, the results are collected and compared against the actual values from the shop floor. If the values are found to be matching, the DES model can be considered valid and ready for conducting simulation experiments. The three important strategies that are used for validation are given below.

- **Conceptual validity:** This strategy looks at validating the model 'within the scope of the initial plan' against the real world. For this to happen, the purpose of the model needs to be specified initially (Semanco, Marton, 2013). For example, if a model is built to predict the breakdown pattern of a conveyor, and the simulation provides results which is in line with the outputs obtained from the conveyor but not exact breakdown patters, the model cannot be validated.

- **Operational validity:** This validity considers the operational side of the model. Operational validity is a data oriented strategy of comparing the output data against real life scenarios. This is set by the simulation engineer when building the model (Robinson, 1994). For example, if the objective of the simulation model is to increase the outputs within the existing manufacturing constraints, the output data is compared with the real-life plant to validate the model.

- **Believability:** As the term explains, believability is subjective rather than objective. It entails if the end user of simulation, in this case, the Production Management at the company has faith in the model and the suggested solutions (Opper, 1999). The end user may differ in their choice of solutions generated within the context of the KTP project. Different solutions for the selection of process parameters recommended by the simulation model is a prediction of production lines operating under the same conditions in a real-life scenario. This prediction must be believed by the end user depending on how close this result is to the real world. This is the concept of believability.

Tolerances: A tolerance of 5% is allowed in the results for validation. If the output results are found to be within ± 5%, the model can be considered valid. For example, if the expected output for a product per week is 100 and the model produces a result within the range of 95 -105, the model is acceptable.

Warmup time: While trying to obtain results from any model, a warm up time is essential. The parts enter the simulation at time 0. It gets processed at the first operation, goes to a buffer and then to the next operation. This process goes on till the last operation until the part is shipped (Mahajan, Ingalls, 2004).

In this way, the last operation is idle till the parts travel through the whole simulation model. For example, in the existing simulation model, for a part for chimney to reach the end stage of Packing, it takes 33 hours and 5 minutes. Until then, the Packing operation and the operator will be idle. This will be reflected on the simulation output as well.

But this is not the scenario in real practice. At the start of a week, every operation in the factory will have a part to process and will be busy. Thus, the results obtained from the simulation will be wrong if the model is run without a warmup time. As the maximum process time in this model is for Brick-clad chimneys (33 hours and 5 minutes), the warmup time is given as 1 week.

Figure 5.1 gives the results of the operator usage without a warmup time for a run time of 10080 minutes.
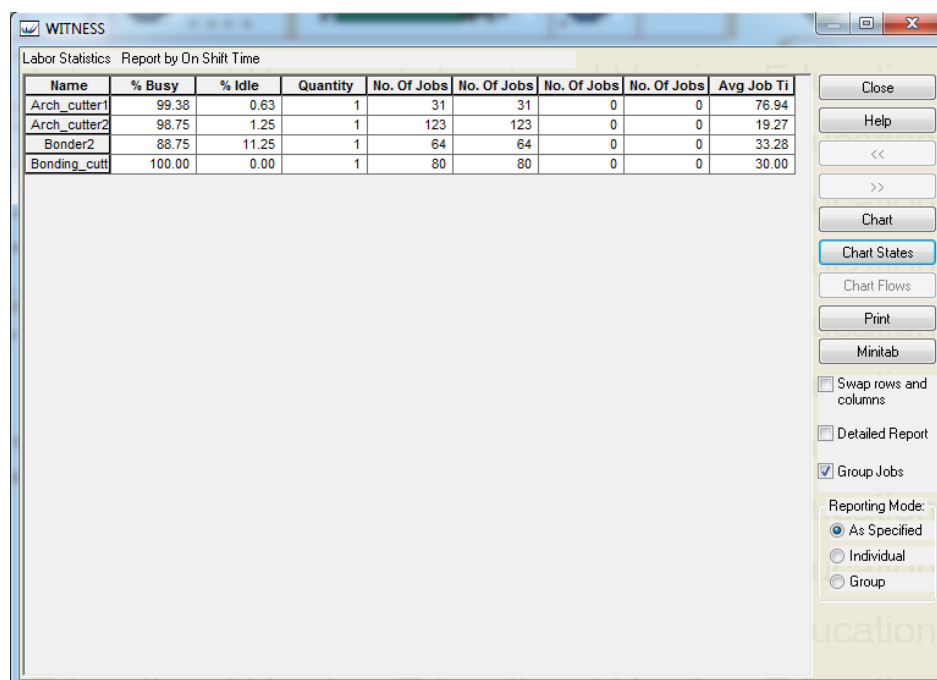
Figure 5.1: Report on shift time without warmup time

The results of the same simulation without changing any parameters with a warmup time of 10080 minutes (1 week) and run time of 10080 minutes is given in Figure 5.2.

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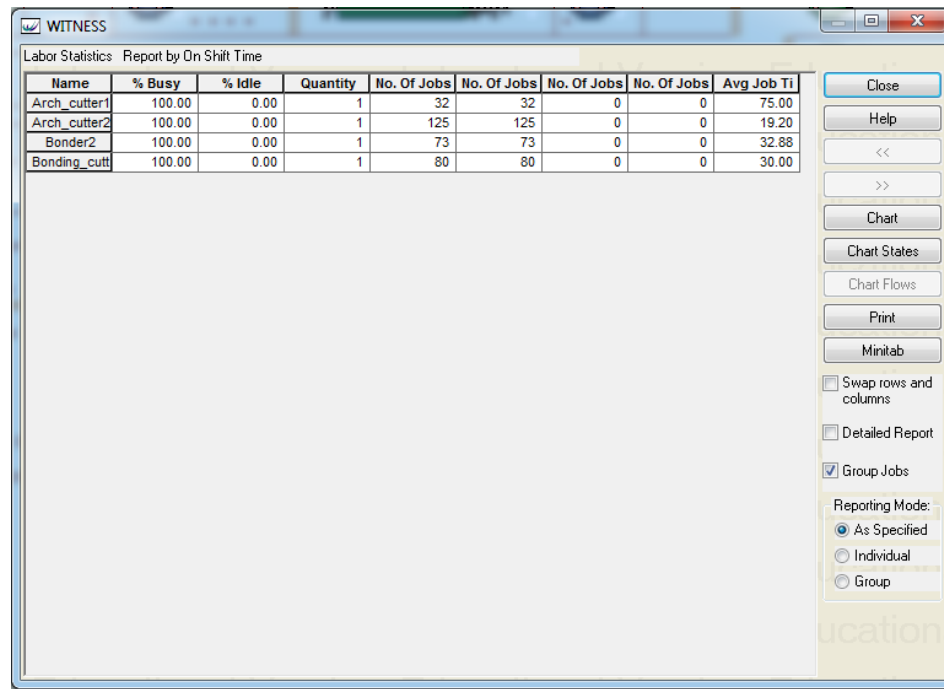
Figure 5.2: Report on shift time with warmup time

It can be seen from Figure 5.1 that the first 3 operators are not 100% busy over the simulation period. This is without the warmup time. But when including the warmup time, as it can be seen from Figure 5.2, all the operators are 100% busy which would be similar to the actual scenario. Thus, it is essential in this simulation to include a warmup time of 1 week (10080 minutes).

5.1.1 Results

The DES model is run for 20160 minutes (2 weeks) with a warmup time of 10080 minutes (1 week). The following are the input parameters:

- Arch_orders_per_day: This parameter represents the number of arch orders that arrive in the factory. This information is taken from the company data. It is set to 35 in the model.

- Chimney_orderes_per_day: On average, it is taken as 10 based on the company data.

- CnB_orders_per_day: Each order is represented in a batch of 100 of Brick Specials. The number of orders received per day is given as 100.

The results from the simulation model are given below.

No_chimneys_shipped	50
No_arches_shipped	59
No_CnB_shipped	131

Figure 5.3: Quantity of finished products

- **Number of chimneys produced:** This is obtained from the parameter No_chimnyes_shipped. For a 40-hour 5 day working week, with an input orders of 10/day, the total number of chimneys produced in a week is 50. This is the maximum capacity of the plant for the chimney production line and is within the range of outputs produced per week.

- **Number of arches produced:** With an order input of 35 per day, the output produced is 60 per week. The result obtained from the simulation model is 59 per week which is within the tolerance limit. Thus, this can be considered acceptable.

- **Quantity of Brick Specials produced:** A total of 131 jobs were completed for the week against an order quantity of 100 per day.

Another parameter used to measure and validate the outputs from the model is the turnover values of the products. This is given in Figure 5.4 for the simulation model.

Value_chimneys_shipped	26750
Value_arches_shipped	3245
Value_CnB_shipped	13755
Total_turn_over	43750

Figure 5.4: Turnover per product

The company turns over £25,000 - £30,000 for Brick-clad chimneys per week. The value obtained from the model is £26,750 which is within the expected range. The large range is due to the fact that, in the company, each order is customer specified which has a different price. Since this is not required to meet the objective of the simulation, an average value for the chimney is modelled which produces a definitive range. The value generated by this

product in a week is shown in Figure 5.3 in comparison with the other two products.

Figure 5.5: Turnover (Blue: chimneys, Green: Brick Specials, Red- Arches)

The value of arches produced per week is £3,245 and Brick Specials is £13,755. The total turnover for the week is approximately £43,750 from the model which is within the expected limit for the company. Thus overall, the turnover for the company from the above 3 products is circa £2,275,000. The overall turnover for the company is circa £3 million. The above 3 products contribute towards 75% of the total company turnover which is fairly accurate.

The utilisation of resources is also checked to validate the model. The different types of resources available are machine resources, labour resources and buffer quantities.

Machine Statistics   Report by On Shift Time
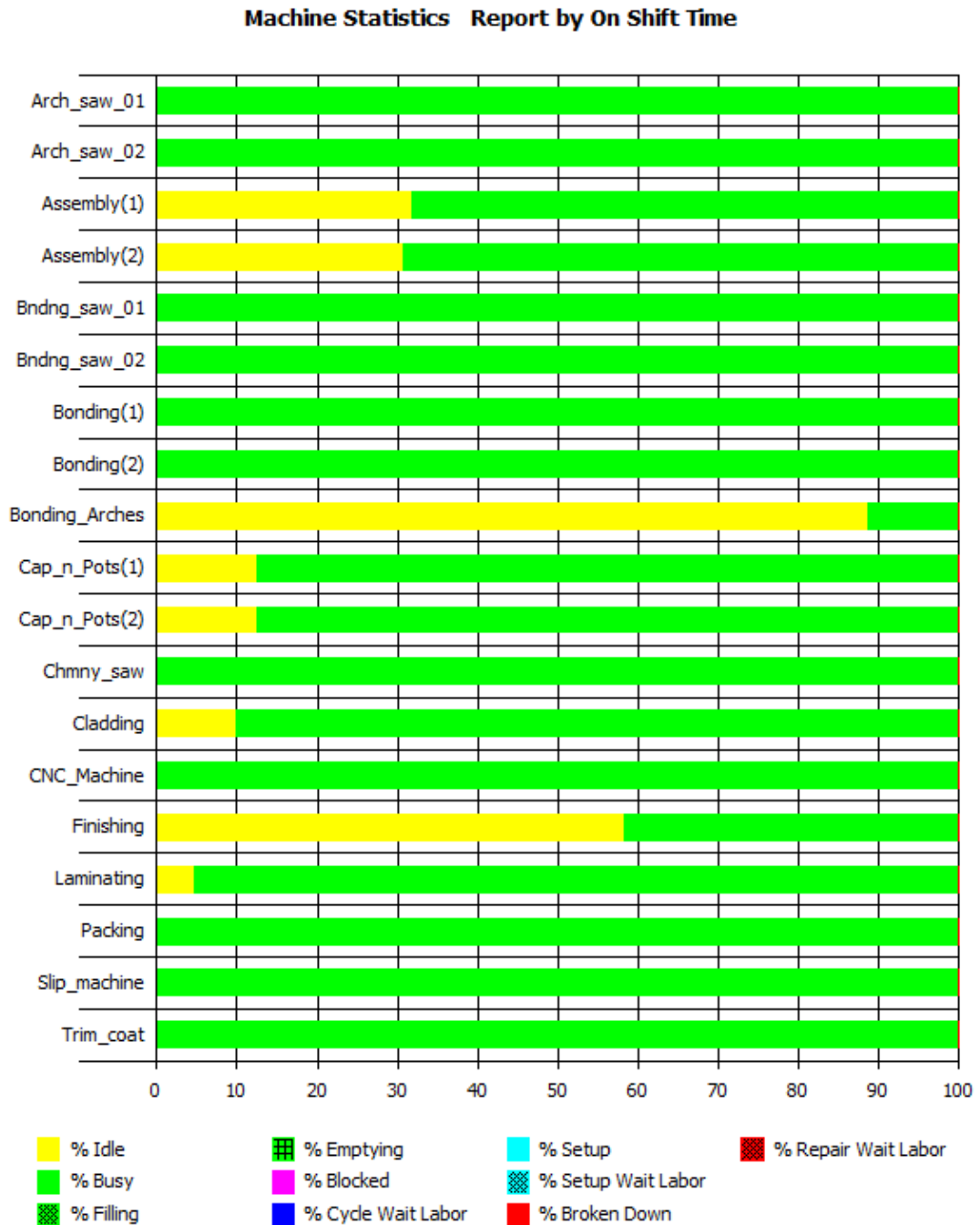
Figure 5.6: Machine statistics

The charts in Figure 5.6 show the utilisation of machines within the shift time. It can be seen that almost all the machines are 100% busy within the specified shift. The machines that are less busy are Bonding_Arches which is utilised only 11.38% which represents the real-life scenario at the company. Other underutilised machine resources are Finishing and Assembly. These are also representative of the real-world situation.

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The charts in Figure 5.7show the labour resource utilisation.

Labor Statistics   Report by On Shift Time
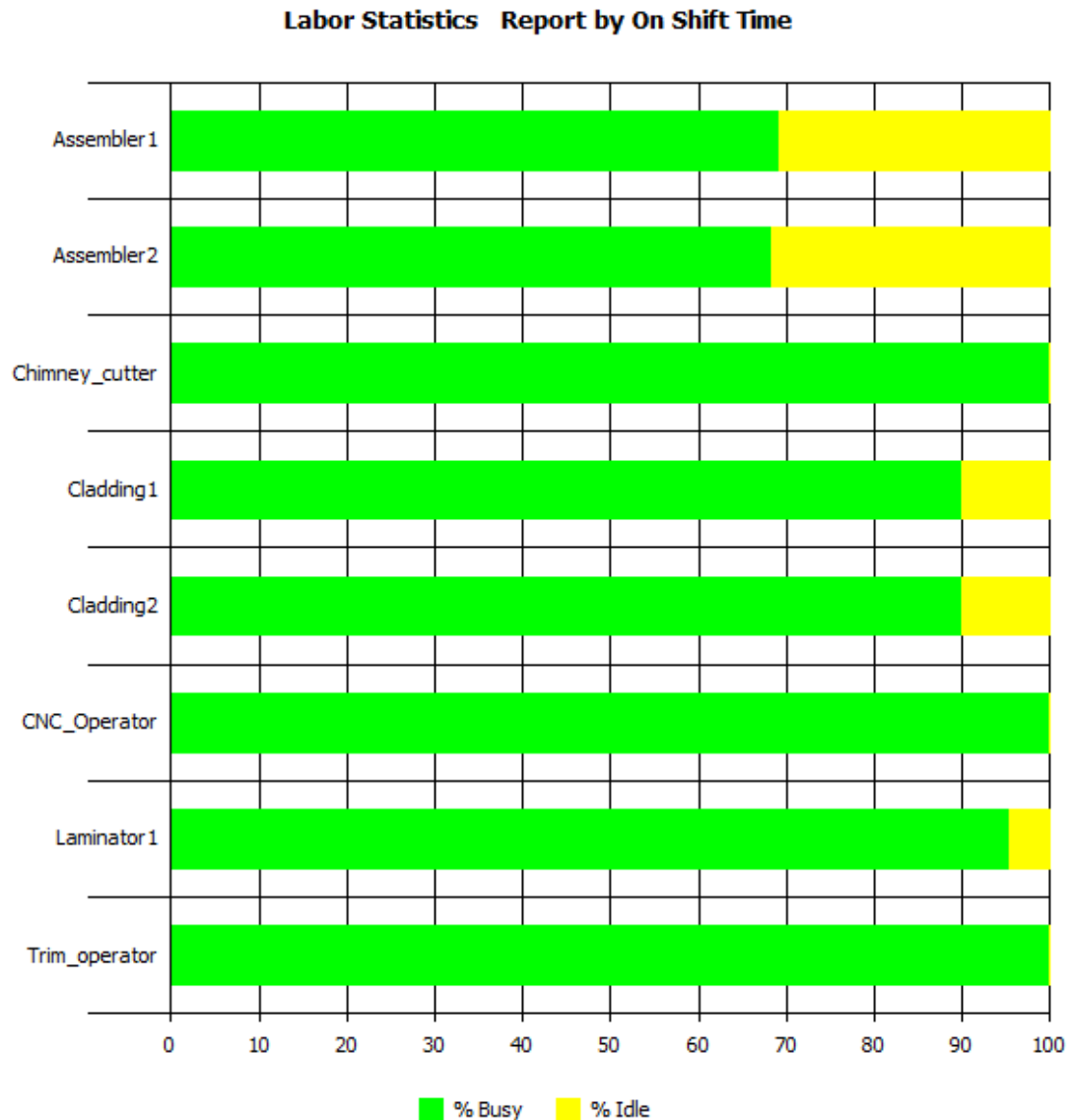
Figure 5.7: Labour resource utilisation for Brick-clad chimneys

The underutilised labour resources are Assembler1 and Assembler2. This is representative of the actual scenario in the factory. This is due to the fact that the factory operates in a 110% manning level to cover for holidays and absences. The assembly operators are modelled to cover for these. From the above, it can be inferred that the model is a true representative of the real-world situation.

In order to have a relative target of what could be achieved within the restricted time frame, the following 3 scenarios were selected.

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5.2 Scenario 01 – Initial results analysis and manual optimisation

In this section, the results from the model are analysed manually in an intuitive manner and changes are recommended in the model to improve the production output without changing the existing number of resources. This is done on the production line for each product.

5.2.1 Pre-fabricated arch production line

To carry out an initial analysis, the machines in the arch production line are analysed. The data used for analysis is given in Figure 5.8.

Machine Statistics Report by On Shift Time

Name	% Idle	% Busy	No. Of Oper
Arch_saw_01	0.00	100.00	27
Arch_saw_02	0.00	100.00	120
Bonding_Arches	88.63	11.38	54
Packing	0.00	100.00	240
Slip_machine	0.00	100.00	160

Figure 5.8: Pre-fabricated arches machine statistics

From the above table, it can be clearly inferred that all the operations are busy at 100% level except Bonding_Arches which is idle for 88% of time. This provides an improvement opportunity to get more out of the existing system. But to change the output, the reason for the machine being idle should be found out.
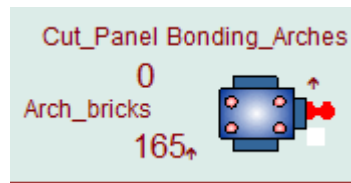
Figure 5.9: Bonding_Arches operation model

The Figure 5.9 shows the operation of Bonding_Arches. For the operation, 2 parts are required, one which is taken from Cut_Panel and other taken from Arch_bricks. The Figure 5.9 shows that the Cut_Panel is empty which explains the idle time of the operation. Further investigation suggests that the Cut_Panel is empty as the CNC_Machine is operating at full capacity. Thus, the CNC_Machine is the bottleneck in this process. It is envisaged that by increasing the resource allocation of the CNC_Machine in the process flow will improve the throughput of the pre-fabricated arch production line.

Suggested improvement: In this scenario, the suggested solution is to increase the number of working hours on the CNC_Machine and the operator to a 50-hour working week with 10 hours a day corresponding to a normal shift duration. The shift pattern is given in Figure 5.10.

Figure 5.10: 50 hour working shift details

This is not to be achieved by a single operator working 50 hours per week. The suggested improvement is to make the operation available for 50 hours a

week. This is achieved in the company by an operator starting 2 hours earlier than the normal 8 hour working shift, operating the machine for 2 hours and handing it over to the normal operative when the normal shift starts. The operator starting early would finish early as well with a total of 8 hours per day. This would give the capability of 10 hours per day for the utilisation of the machine which amounts to 50 hours per week.

5.2.2 Brick Specials production line

Analysis similar to the above section is carried out on the Brick Specials production line with the aim of optimising the production flow. The machine statistics of the production line and the labour resource usage is given in Figure 5.11.
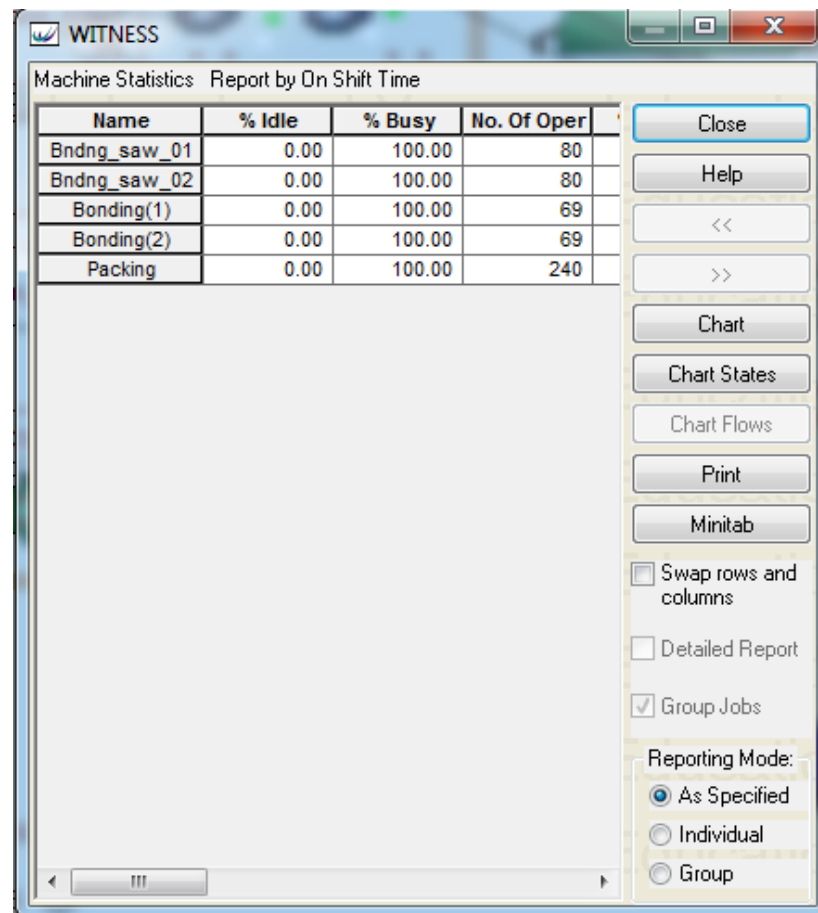
Figure 5.11: Brick Specials machine statistics

All the machines are utilised to the maximum capacity as it can be seen from the above statistics. The labour statistics are given in the Figure 5.11. From both the figures, it can be seen that the Packing operation is fully utilised with

240 operation. As this is a shared resource between 3 different production lines, it can be improved by increasing the shift pattern.
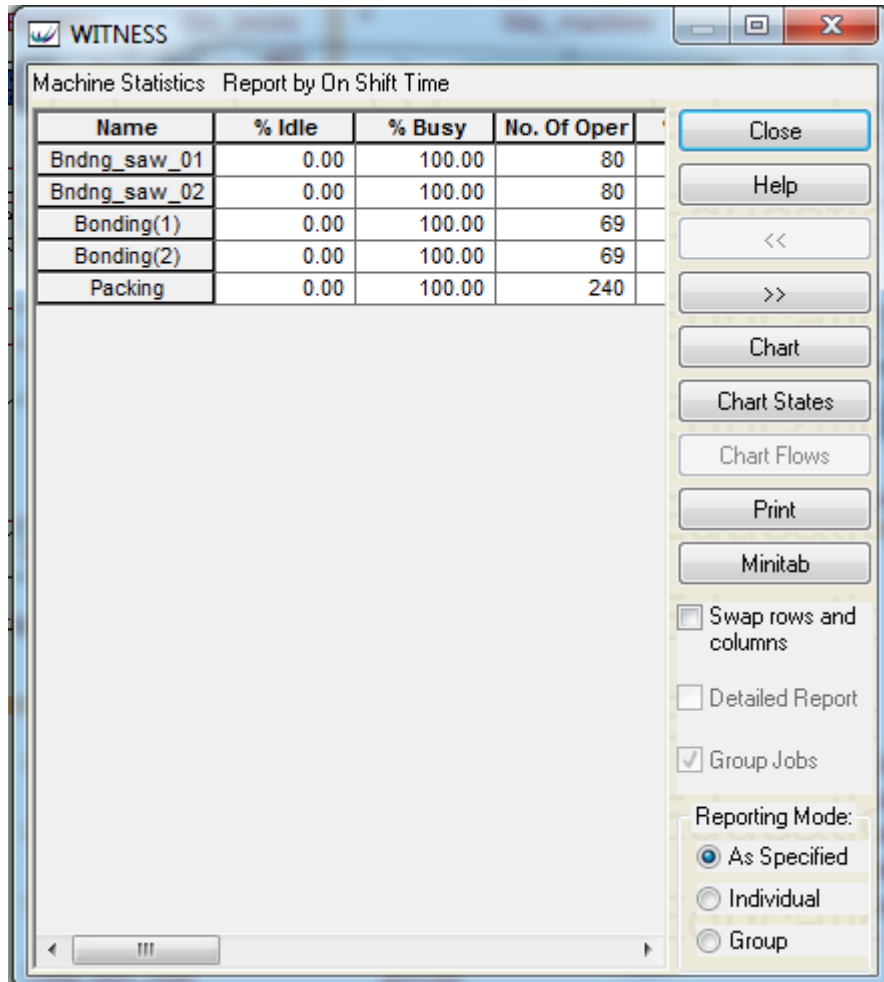
Figure 5.12: Brick specials labour statistics

Suggested improvement: Increasing the shift pattern for the packaging operation and operative to a 50 hours shift as this resource is shared between the 3 production lines. It is anticipated this would increase the production throughput.

5.2.3 Brick-clad chimney production line

The initial analysis of Brick-clad chimney production line is more critical as around 50% of the company turnover is from this product. Also, comparing the value-adding work force which excludes the management, fork truck drivers and so on is also circa 50%.

The simulation model is run for a week with a warmup time of 1 week. Results are collated and shown in Figure 5.13. Machines, buffers and labour resources are analysed.
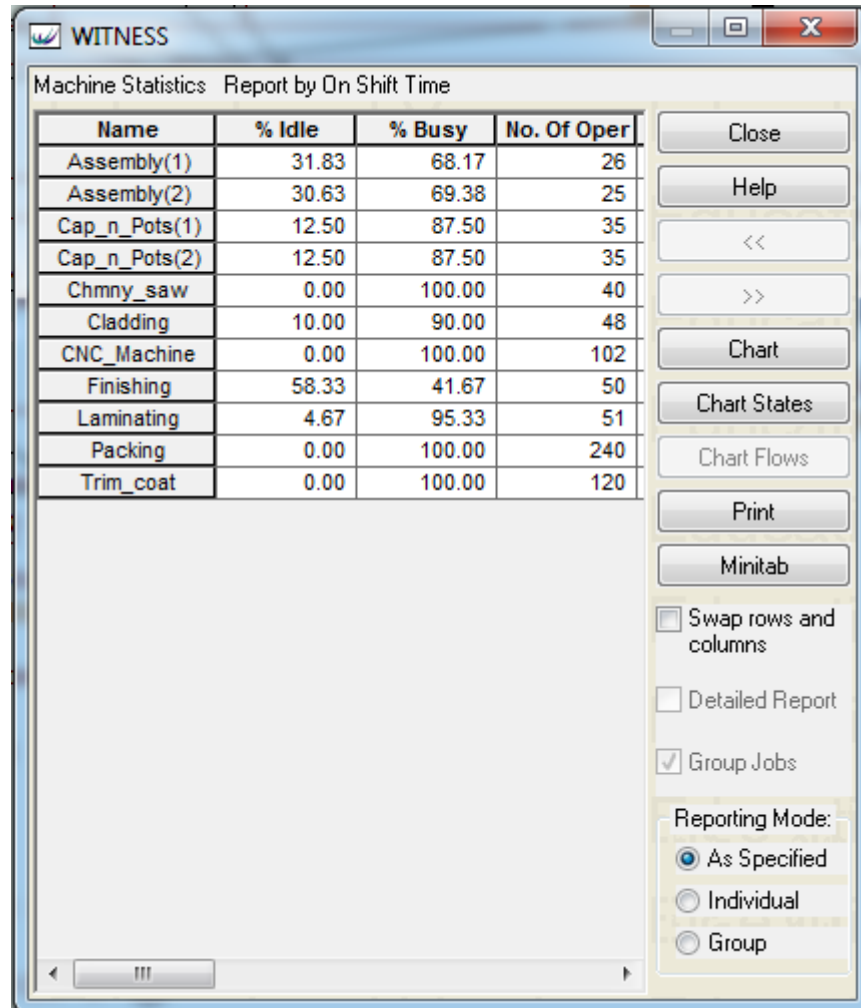
Figure 5.13: Brick-clad chimney machine statistics

From the Figure 5.13, it can be clearly seen that not all the operations are 100% busy. Assembly operations average about 70% busy time. Every other operation is utilised over 80% except for Finishing which is heavily underutilised at around 42%.

As the operation Finishing has spare capacity but it cannot be utilised to produce more chimneys. But the operator can be considered of having spare capacity and can be utilised elsewhere to increase the throughput.

The number of operations processed is a critical feature in analysing the line balancing. This provides information to determine over or under allocation of

resources in the production line. The total number of orders processed by each operation is given in Table 5.1. For example, Assembly is one operation represented by 2 machines for which the sum is given.

Operation	Number of operations
CNC Machine	51
Assembly	51
Laminating	51
Caps_n_Pots	70
Cladding	48
Finishing	50
Packing	50

Table 5.1: Brick-clad chimneys - total number of orders processed
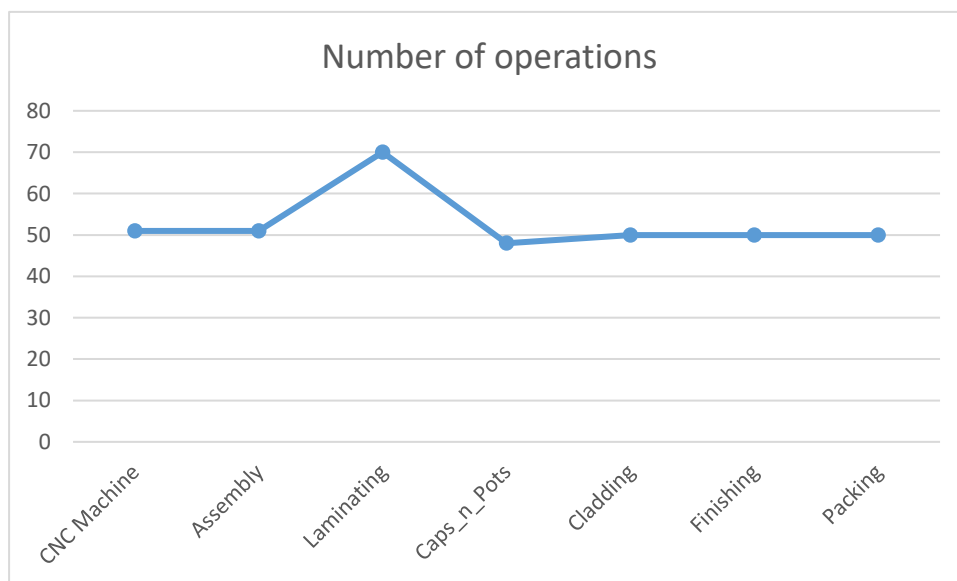
Figure 5.14: Brick-clad chimney line balancing

From the graph in Figure 5.14, it can be clearly seen that the operation Caps_n_Pots has over allocation of resources. As the average production per week is circa 50 chimneys, there is no need to produce 70 Caps_n_Pots as there will be a surplus production of 20 per week. Thus, this over allocation of resource could be re-distributed to optimise the production line. Also from Figure 5.13, Caps_n_Pots are running at only 87% utilisation with 13% idle

time. Thus, it may be viable to redistribute the resources elsewhere to maximise throughput. The labour resource usage must also be verified before making any decision which is given in Figure 5.15.
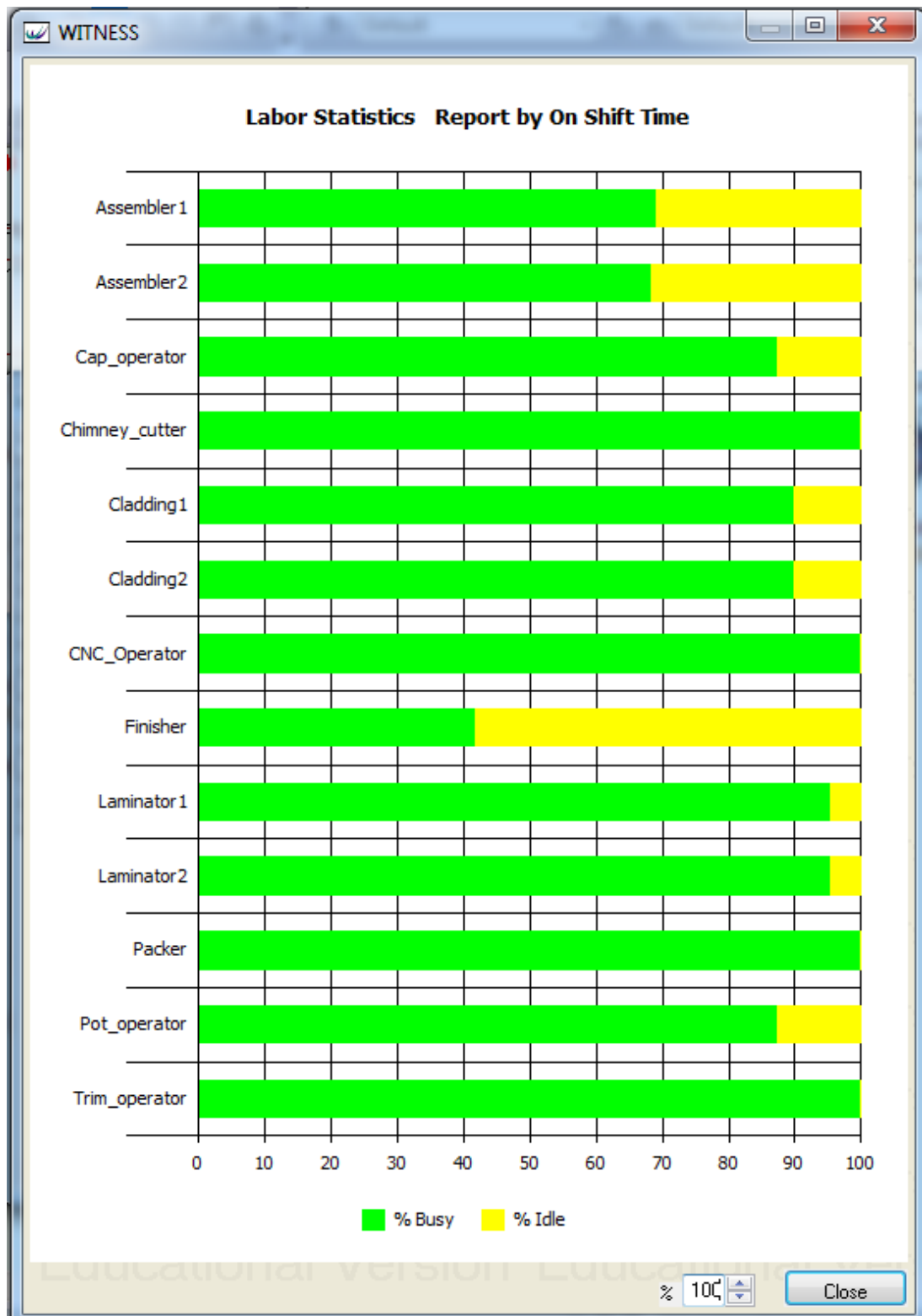
Figure 5.15: Brick-clad chimney - labour statistics

From the Figure 5.15, similar to the machine statistics, the operator in the Finishing operation is underutilised. Also, there is no requirement to over produce on Caps_n_Pots. Both of these could suggest redistribution of resources to produce more within the existing parameters.

Suggested improvement: Cross training the Finishing operative on Caps_n_Pots will enable the operator to do both jobs. Set the priority of the Finishing operation to be highest as it is in the critical path for the chimney production line. This will enable the company to reduce the workforce by 1 in the Cap_n_Pot production (currently 2 operatives) by utilising the underutilised resource in Finishing operation.

5.2.4 Suggested changes to the model for scenario 01

From the analysis of initial results in the previous sections, the following changes to the model are made to see changes in the model. The changes are identified using the FIT manufacturing principles of line balancing, bottleneck analysis and Takt time. They enable the company to be FIT by producing more with less resources.

i. **CNC Machine:** As this resource is shared between the Brick-clad chimneys and pre-fabricated arch production lines, it is essential to increase the number of working hours on this machine. From the analysis, this is identified as one of the bottlenecks in the model.

ii. **Packing:** This resource is shared between all the 3 product streams that are being modelled and is utilised at 100%. Comparing the number of operations that are pending to be processed on this machine, it is essential to increase the working time on this operation to reduce the bottleneck at this stage.

iii. **Line balancing by cross training:** As the finishing operation is underutilised and Caps_n_Pots produce more than what is required with 2 men, the line is not balanced. One operative in Caps_n_Pots can be replaced by cross-training the Finishing operative. This is expected to balance the line and create savings to the company by reducing the workforce by 1.

iv.   **Increasing the order input/day:** The simulation model is run at specific order inputs per day: 70 for arches, 10 for chimneys and 100 for Brick Specials which is limiting the model. This doesn't utilise the maximum manufacturing capability of the model which is against the FIT manufacturing principles. To utilise the maximum capacity, the model input values are increased imagining a scenario where the 'Order Book' is full with no limited orders per day. This also means in real world, a change in the planning way which is limited to the number or orders per day (for example, 10/day in chimneys). Thus, the input parameters are changed to 1000 to state the availability of unlimited orders in the pipeline.

5.2.5 Results

After the suggested changes to the DES model are made, the simulation model is run to the same amount of time as the initial model to ensure the comparison is between similar models. The results are given in Figure 5.16 and Table 5.2.

No_chimneys_shipped	51	Value_chimneys_shipped	27285
No_arches_shipped	64	Value_arches_shipped	3520
No_CnB_shipped	137	Value_CnB_shipped	14385
Weekly_40_hr_shift Off 6 🕒		Total_turn_over	45190
Weekly_50_hr_shift Off 6 🕒			

Figure 5.16: Results after Scenario 1

	Before scenario 1	**After scenario 2**	**% Change**
No_chimneys_shipped	50	51	2.0%
No_arches_shipped	59	64	8.5%
No_CnB_shipped	131	137	4.6%
Value_chimneys_shipped	£26,750	£27,285	2.0%
Value_arches_shipped	£3,245	£3,520	8.5%
Value_CnB_shipped	£13,755	£14,385	4.6%
Total_turn_over	£43,750	£45,190	3.3%

Table 5.2: Changes in results after Scenario 1

From the Table 5.2, it can be seen that the changes made to the model according the FIT manufacturing principles based on an intuitive approach has produced effective results and improved the simulation results. Each of the changes are discussed below.

i. **Number of chimneys shipped:** This has increased the results by 2% by a quantity of 1 per week. Although changes were made to reduce the labour resources by 1, there is an increase in throughput by 2% which is due to the increase in input parameters. Over the year, with an average price of £535/chimney, the turnover is expected to rise by £27,820. This is achieved by reducing the labour resources which also has a positive impact on the profit margin. With the current resources, this is considered the maximum capacity of the manufacturing model.

ii. **Number of arches shipped:** This has increased by a significant amount of 8.5%. In a real-life scenario, it is considered difficult to improve the performance of a manufacturing model by 8.5% by changing the shift pattern of 1 operation by 10 hours/week. The turnover for arches also increased by 8.5%, and over the year, this is projected to increase the sales by £14,300.

iii. **Number of Brick Specials shipped:** The total number of batches shipped increased by 4.6%. This has a significant impact on the lead times as more parts are processed in the same time. Thus, customers do not have to wait for the products as before. Over the year, this will produce an extra revenue of £32,760.

From the Figure 5.17 it can be seen that the packaging operation that was 100% busy and processed 240 jobs is now 84% busy while processing 252 operations.

The Caps_n_Pots compared to previous model has now time waiting for labour, with busy time around 80% compared to previous values of 87%. But in the optimised model, the total number of Caps_n_Pots produced is 64 compared to 70 from the previous model with one less operator. The demand per week is only 51. This clearly shows the potential savings that could be made.

WITNESS

Machine Statistics   Report by On Shift Time

Name	% Idle	% Busy	% Cycle Wait Labor	No. Of Oper
Assembly(1)	13.67	86.33	0.00	32
Assembly(2)	13.67	86.33	0.00	32
Cap_n_Pots(1)	0.00	81.67	18.33	33
Cap_n_Pots(2)	0.00	76.67	23.33	31
Chmny_saw	0.00	100.00	0.00	40
Cladding	12.50	87.50	0.00	47
CNC_Machine	0.00	100.00	0.00	128
Finishing	58.33	41.67	0.00	50
Laminating	0.00	100.00	0.00	53
Packing	16.00	84.00	0.00	252
Trim_coat	0.00	100.00	0.00	120

Figure 5.17: Scenario 1: Brick-clad chimney results

The changes to the number of products produced per week and line balancing graph is shown in Figure 5.18 against the number of operations on y-axis.
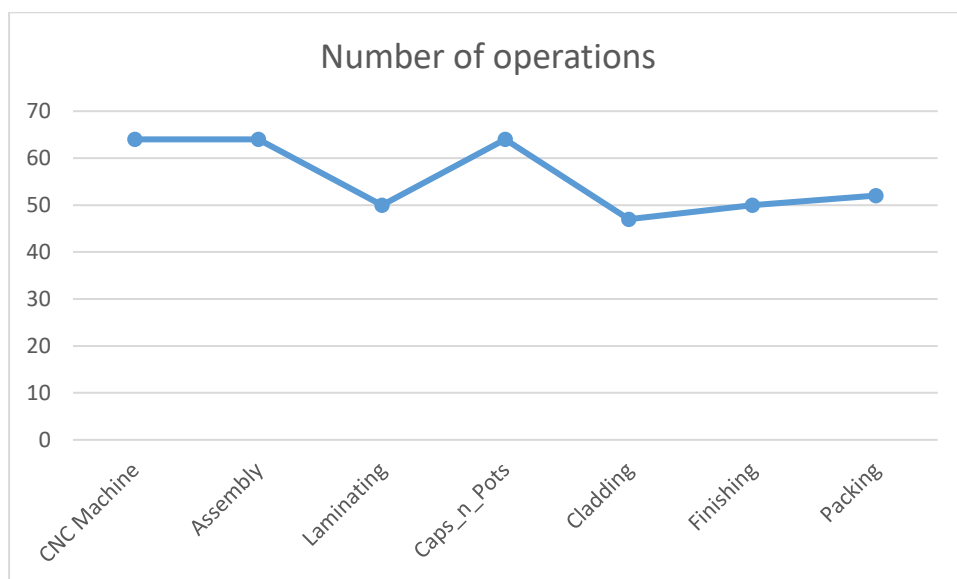
Figure 5.18: Scenario 1: Line balancing

The throughput of both CNC_Machine and Assembly has increased from 51 to 64 with the suggested changes. Laminating seems to be the new bottleneck in the model which limits the throughput further along the production line by producing only 51. From Figure 5.17, Cladding has 12.5% spare capacity, along the production line, Finishing and Packing also has spare capacity. Thus, the new bottleneck of Laminating can be addressed in scenario 2.

5.2.6 Validation of results

The suggestions for increasing the shift pattern of shared resources such as CNC Machine and Packaging were implemented in the factory. The cross training of the operators was also completed and implemented. This increased the throughput from the production lines as predicted.

But increasing the order quantity was not practically achieved as orders received per day depends upon the market conditions and buying decisions made by customers.

The results were obtained from the company following implementation of changes which is given in Table 5.3. The data from company has slight variation from the predicted result. This is due to the variations found in the order quantity as explained above. The results are within the 5% tolerance limit and hence through the process of Operational validity, the simulation results produced by the model has been verified.

	Before scenario 1	**After scenario 1 Simulation**	**Data from company**
No_chimneys_shipped	50	51	51
No_arches_shipped	59	64	63
No_CnB_shipped	131	137	136

Table 5.3: Scenario 01: Results validation

5.3 Chapter Summary

In this chapter, the DES model has been verified by comparing the behaviour and outputs from the model with the results from the shop floor. An initial analysis of the model has been carried out and improvements were suggested using the FIT manufacturing principles in an intuitive manner. The suggested changes increased the throughput of all 3 production lines, and the overall turnover for the company for the year could potentially be increased by circa £74,880 which is an increase by 3.3%.

It has been found that resources such as machines and labour that are shared between production lines may cause undue pressure on the production lines. Also, people with multiple skills who can carry out multiple operations have been found to improve productivity significantly.

The intuitively optimised model also showed new bottlenecks in the re-designed manufacturing system which will be addressed in scenario 2 as explained in the following chapter.

6   Automatic optimisation and experimentation

In the previous chapter, focus was on implementing the changes based on FIT manufacturing principles in terms of allocation of resources, especially labour resources and line balancing. Those changes did not require significant investment from the side of the company apart from introducing changes to the shift patterns and cross training.

In this chapter, the DES model is further refined using FIT manufacturing principles particularly those changes that require investment. As the production lines interact with each other and has shared resources, testing different scenarios and comparing the output values might become difficult (Law, 2010). Thus, to enable this, the Experimenter module in Witness software is used which uses an in-built optimisation algorithm to maximise the output parameter by testing the model at different user specified scenarios. The procedure for experimentation and optimisation is given below.

6.1   Experimentation and Optimisation procedure in Witness

Following are the steps taken in carrying out experiments and optimising parameters using Witness (Ford, 2010).

   i.   Open the Experimenter module in Witness from the Model menu.

   ii.   Specify in the model, the number of different scenarios to be run.

   iii. Input the parameters that correspond to the scenarios. For example, if the model is to optimise the production output by changing the labour force level, input parameter will be the labour force levels and output parameter will be the production output.

   iv. In the Model settings, specify the warmup and run length times.

   v.   Include the number of iterations required and run the model.

The model throws out results of different scenarios with the output parameter which helps the team to make an informed decision. The scenarios may or may not involve investments. In the following sections, potential improvement ideas are tested to improve the throughput of the production line.

6.2 Scenario 02: Pre-fabricated arches - maximum throughput with minimum investment

To further advance the manufacturing facility, the company requires to expand the current operational practices. It has been identified that the lead times for pre-fabricated arches are low compared to competitors. Thus, a decision needs to be made to maximise the throughput for the production lines. Three different options for optimising the production line will be discussed according to the level of investment required.

The reason for choosing the given 3 options were investment options suggested by the Production Management in the company to obtain maximum gain. This will be modelled in Witness on the existing manufacturing model and experimented to find the best solution.

In this scenario, 3 different options are considered which is expected to significantly improve the performance of the manufacturing model. The options are ranked according to the level of investment required. Following evaluation of the 3 options using the experimenter module in WITNESS, a decision can be made.

i. **Option 01 – Extra arch saw:** Invest in purchase of an extra Arch brick cutting saw which will produce more bricks for the arches and hence more turnover. This is considered a low investment option. With the extra saw, an extra operator will also be required.

ii. **Option 02 - Extra CNC machine:** This is a medium investment option with purchase of an extra CNC machine. A trained CNC operator will also be required. This option will also have an impact on the chimney production line as the CNC machine also serves the chimney production line.

iii. **Option 03 – Extra CNC machine + Slip machine:** This is a high investment option with the purchase of 2 extra machines which requires 3 extra operatives. But this option is also considered depending upon the return on investment.

The options are modelled in the Experimenter. A new function called Turn_over_function is created which return the value of total turnover as shown in Figure 6.1. The simulation attempts to maximise this value.

	Scenario Name	Parameter							Response
		Arch_cutter1 .Shift:Weekly_ 40_hr_shift .Quantity	Arch_saw_01 .Quantity	CNC_Machine .Quantity	CNC_Operator .Shift:Weekly_ 50_hr_shift .Quantity	Slip_cutter1 .Shift:Weekly_ 40_hr_shift .Quantity	Slip_cutter2 .Shift:Weekly_ 40_hr_shift .Quantity	Slip_machine .Quantity	Turn_over_fun ction
1	Extra arch Saw	2	2	1	1	1	1	1	
2	Extra CNC machine	1	1	2	2	1	1	1	
3	Extra slip machine + CNC machine	1	1	2	2	2	2	2	

Figure 6.1: Scenario 02: Input parameters

Three different scenarios are modelled with 7 input parameters which are used to model the scenarios. The output parameter is the Turn_over_function which is maximised.

Property	Value
Model Settings	
Warmup	10080
Run Length	20160
Replications	100
Random Number Control	
Alternate	False
Skip	50
Control Properties	
Maximum Results	100
Best Results	500

Figure 6.2: Scenario 02: model configuration

The model is configured using the values in Figure 6.2 to run for 20160 minutes (2 weeks) with a warmup time of 10080 minutes (1 week) for 100 replications. From initial analysis, this was found to be sufficient to produce stable results.

Simulation was run for a total duration of 1 minutes and 29 second with and average duration of 23 seconds. The results in Figure 6.3 were considered consistent as the mean and best values were matching for all 100 iterations with a standard deviation of zero.

Figure 6.3: Scenario 02: Variance data

The result of the scenario is given in Figure 6.4.

Figure 6.4: Scenario 02: Simulation results 01

Option 01 will increase turnover to £42,300, Option 02 to £44,715 and Option 03 to £44,690. The actual values may vary and can be found from the model.
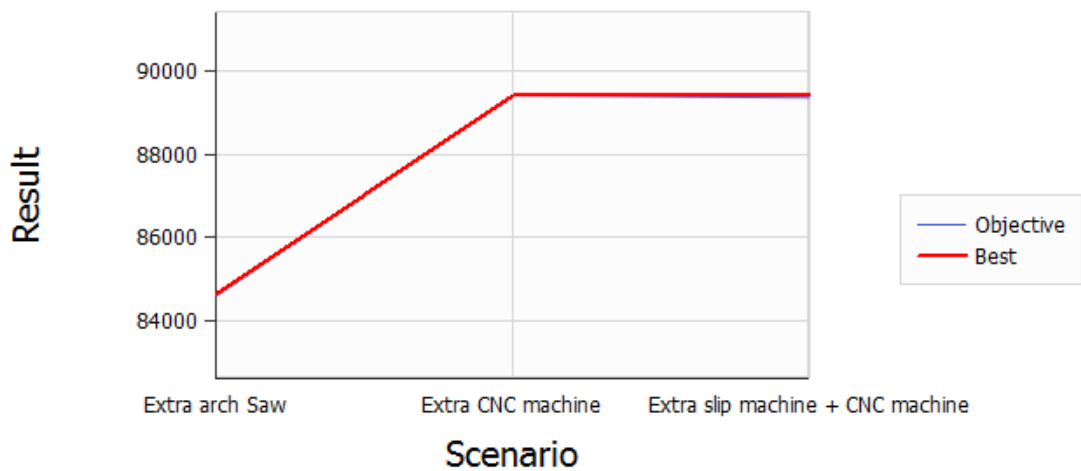
Figure 6.5: Scenario 02: Best scenario results (options vs. total turnover)

Box-Plot: Turn_over_function
Percentiles: Upper: 75.0 Lower: 25.0
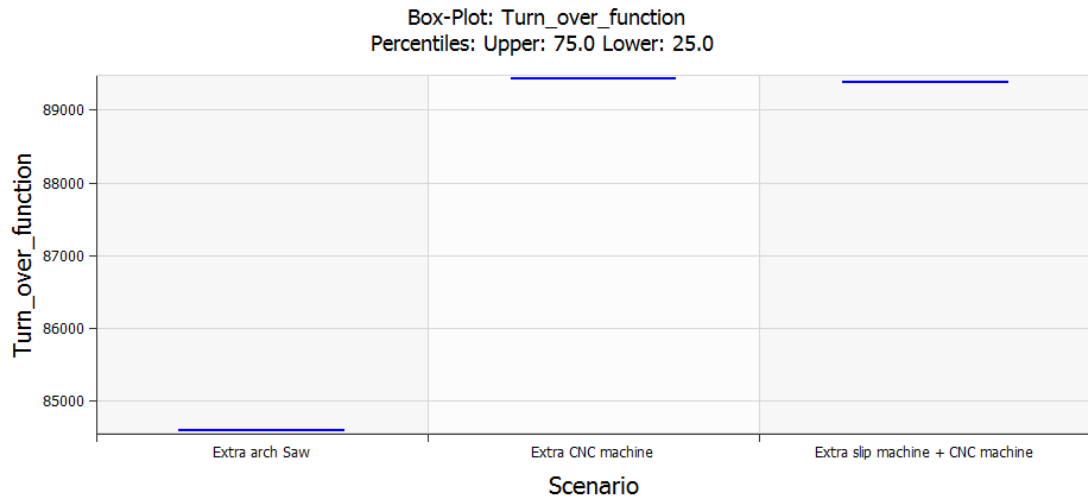
Figure 6.6: Scenario 02: Box plot results

From the data above, it can be concluded that the Option 02 of purchase of an extra CNC machine, which is a medium investment decision would increase the turnover by a larger margin than of the lower and higher investment options. The Box plot results suggest a percentile of 75 for Options 02 and 03 and a 25 percentile for Option 01. The confidence chart in Figure 6.7 also indicates a minimum value of 90% has been achieved whereby making the results reliable.

Confidence Chart: Turn_over_function
Scenario Name: Extra arch Saw

90%: 84600.00 - 84600.00

95%: 84600.00 - 84600.00

99%: 84600.00 - 84600.00
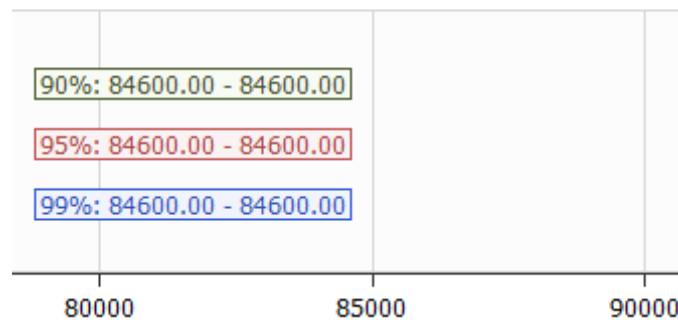
Figure 6.7: Scenario 02: Confidence chart

6.3 Scenario 03: Maximising cycle time efficiency for Brick-clad chimneys

From Figure 5.18, it was discussed in the previous chapter that the number of operations processed by the Laminating, Cladding and brick cutting were at the lowest level of 52 compared to the entire production line of 62 per

95

operation. Thus, it is necessary to investigate and optimise the production line to increase the number of chimneys shipped to a maximum.

The reason for choosing the 3 options are to investigate the benefits of implementing Lean manufacturing principles in the business. Implementation of the Lean principles were part of the KTP project objectives. The ideas were generated by reducing different wastes as discussed in Section 2.2.2 and this is shown in Figure 6.8.

Like the previous scenario experimented, 3 different options are modelled. As Laminating, Cladding and brick cutting are manual operations, investment in new machinery is not required. Changes needs to be made are related to reducing the cycle time or Takt time of the operations so they produce more per operation. The options are explained below based on the level of investment required.

    i.   **Option 01 – Reduce laminating cycle time:** As this is the initial bottleneck in the modified production line, reducing the cycle time for laminating might improve the results significantly. This is possible in real life scenario by implementing Lean manufacturing principles. The current cycle time is reduced from 45 minutes to 30 minutes. This is a low investment option for the company which requires no extra machine.

    ii.   **Option 02 – Reduce laminating & cladding cycle time:** Along with reducing laminating cycle time, reduce the cycle time of cladding from 45 minutes to 30 minutes. But in real life, this requires an additional labour resource which needs to be modelled. This is a medium investment option for the company which requires no extra machine.

    iii.   **Option 03: Reduce laminating and add resource in brick cutting:** The number of operations processed by the brick cutting for chimneys are at 40, thus this option also needs to be investigated to maximise the output of the processes. This requires apart from changes suggested in Option 01, an extra chimney brick cutting machine and labour resource. This is a high investment option for

the company which requires a new machine as well as an additional operator.

Lean manufacturing principles are used to reduce the cycle time for the above 3 options. Typical Lean tools used in Manufacturing are given below:

Figure 6.8: Lean 7 wastes (Sarhan, 2017)

From the value stream maps explained in Table 3.2, each one of the process is broken down into one of the above category. If it is categorised as waste, measures are taken either to reduce or eliminate that process. This way, the savings explained in the 3 proposed options could be achieved.

The options are modelled in the Experimenter module of Witness. All the options are practically achievable in the shop floor with changes in the structure of production. The input parameters and the configuration used in the model are given in Figure 6.9 and Figure 6.10.

Figure 6.9: Scenario 03: Input parameters

The experiment was run for 20160 minutes (2 weeks) with a warmup time of 10080 minutes (1 week) for 100 replications.

Figure 6.10: Scenario 03: Model configuration

The variance data in Figure 6.11 has a standard deviation of zero. The confidence chart in Figure 6.12 also indicates a minimum confidence level of 90% has been achieved which means the results obtained from the model are reliable.

Figure 6.11: Scenario 03: Variance data

98

Confidence Chart: Turn_over_function
Scenario Name: Option 01: Laminating

90%: 88520.00 - 88520.00

95%: 88520.00 - 88520.00

99%: 88520.00 - 88520.00

85000   90000   95000
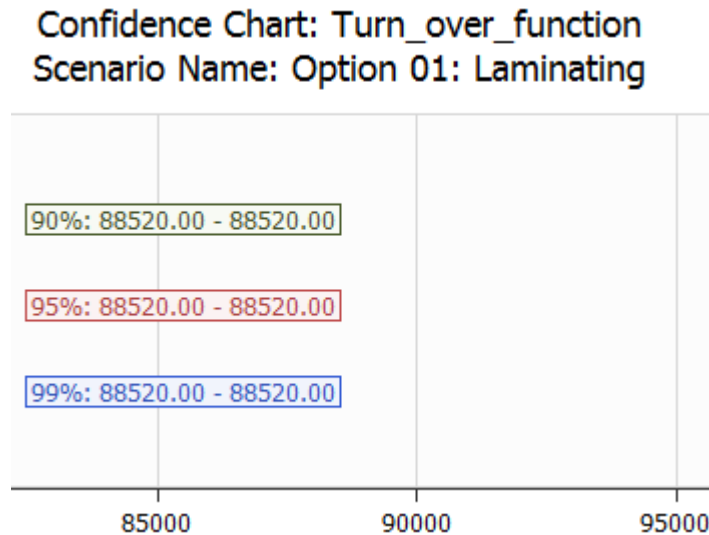
Figure 6.12: Scenario 04: Confidence chart

The model was run for a total time of 1 minute and 09 seconds with an average scenario duration of 23 seconds. The results of the experiments are given in Figure 6.13.

Experiment Duration:	00:01:09		Experiment Remaining:			

	Scenario	Laminating .Cycle Time	Cladding .Cycle Time	Cladding1 .Shift:Weekly_ 40_hr_shift .Quantity	Chimney_cutte r .Shift:Weekly_ 40_hr_shift	Chmny_saw .Quantity	Turn_over_fun ction
1	Option 01: Laminating	30.000	45.000	1	1	1	88520.000
2	Option 02: Laminating + Cladding	30.000	30.000	2	1	1	88040.000
3	Option 03: Laminating + Brick cutting	30.000	45.000	1	2	2	96710.000

Number of Scenarios: 3   Constrained: 3

Figure 6.13: Scenario 03: Results

It can be clearly seen from the above data that the option 03 of reducing the cycle time of laminating process along with adding an extra resource at brick cutting by introducing a new machine produced significant changes in the production output.

The total turnover is expected to increase to £96,710 for 2 weeks. But this is for the total of 2 weeks. Thus, the actual increase in turnover would be half of that – which is up to £48,355. In actual scenario, this may change by 10% because the minimum confidence level of the model is 90%.

The Figure 6.14 shows the response of the model against the objective.
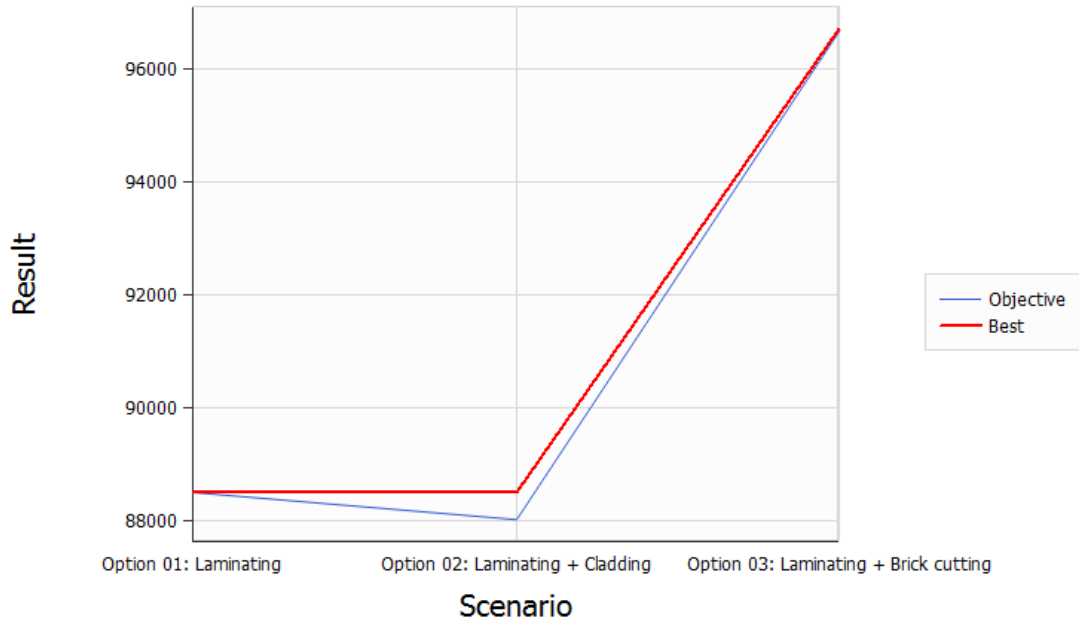
Figure 6.14: Scenario 03: Actual scenario vs. total turnover

The best results obtained from the simulation is found to be better than the set objective in the function. The Options 01 & 02 results were similar to each other, whereas the results of Option 03 were significantly higher than the others. In order to quantify the benefits of the suggested improvements the parameter analysis given in Figure 6.15 is conducted.

	Parameter	Value	Response Average	% Benefit	Number Of Scenarios
1	Laminating.CycleTime	30.000	88520.000	0.545	1
2	Laminating.CycleTime	30.000	88040.000	0.000	1
3	Laminating.CycleTime	30.000	96710.000	9.848	1
4	Cladding.CycleTime	45.000	88520.000	0.545	1
5	Cladding.CycleTime	30.000	88040.000	0.000	1
6	Cladding.CycleTime	45.000	96710.000	9.848	1
7	Cladding1.Shift:Weekly_40_hr_shift.Quantity	1.000	88520.000	0.545	1
8	Cladding1.Shift:Weekly_40_hr_shift.Quantity	2.000	88040.000	0.000	1
9	Cladding1.Shift:Weekly_40_hr_shift.Quantity	1.000	96710.000	9.848	1
10	Chimney_cutter.Shift:Weekly_40_hr_shift.Quantity	1.000	88520.000	0.545	1
11	Chimney_cutter.Shift:Weekly_40_hr_shift.Quantity	1.000	88040.000	0.000	1
12	Chimney_cutter.Shift:Weekly_40_hr_shift.Quantity	2.000	96710.000	9.848	1
13	Chmny_saw.Quantity	1.000	88520.000	0.545	1
14	Chmny_saw.Quantity	1.000	88040.000	0.000	1
15	Chmny_saw.Quantity	2.000	96710.000	9.848	1

Experiment Duration: 00:01:09   Experiment Remaining:
Number of Scenarios: 3   Constrained: 3

Figure 6.15: Scenario 03: Parameter analysis

From the parameter analysis, the maximum benefit can be seen with Option 03 with a percentage benefit of 9.848% which is significant in terms of turnover. Options 01 & 02 consistently seems to produce only a benefit of 0.545% which rules out these options.
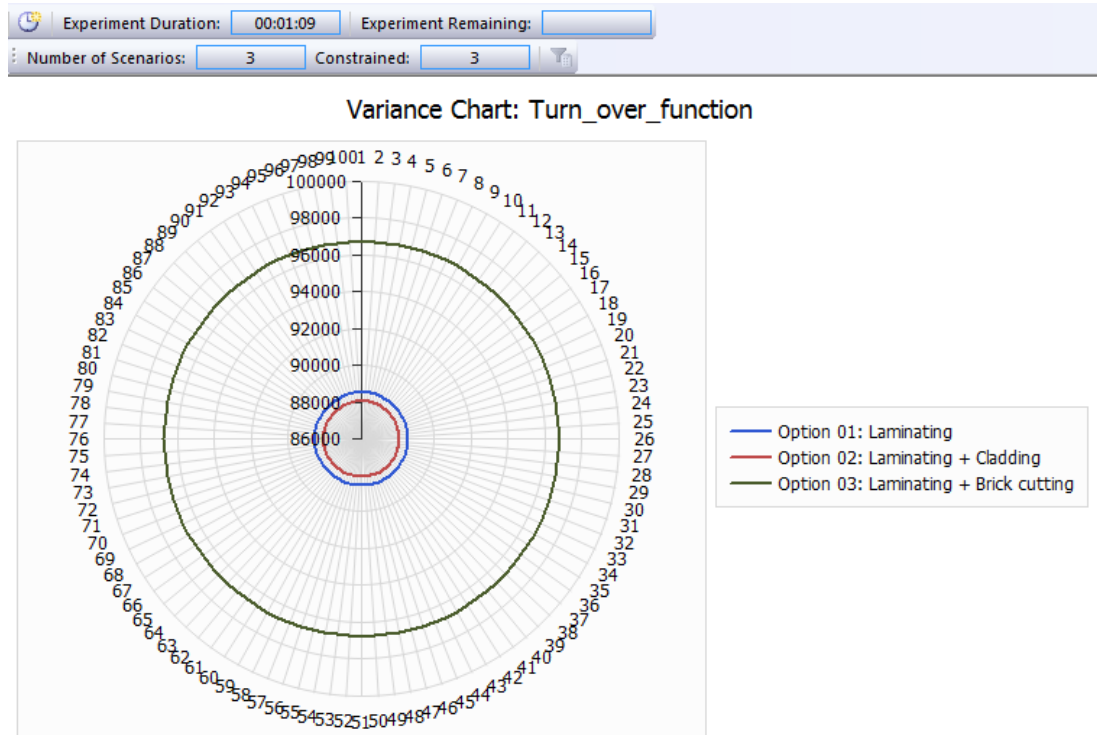
Figure 6.16: Scenario 03: Variance chart

The variance chart in Figure 6.16 also validates the improvement Option 03 over the other two options. Thus, it can be concluded that the Option 03 would produce a significant increase in turnover by 9.8%.

6.4 Validation of results

As the options explained in the scenarios require significant investment which requires time if it is to be implemented on the shop floor. Therefore, the suggested options could not be validated by data after implementing the changes from the shop floor.

Instead, the results were validated by discussion with the management and shop floor personnel using the Believability principle as explained in Section 5.1. The model results were seen to be sensible and considered feasible in

terms of improving the current production process without having to make any large investments.

Interestingly, comparing the results of the simulation model with the shop floor data threw out some anomalies. Following further investigation, it was found that the breakdown on machines on the shop floor had a significant impact on the productivity. This is investigated and discussed in Chapter 7.

6.5 Chapter Summary

The chapter discussed the use of Experimenter module within Witness which is used to model difficult and complex scenarios in the simulation. Two different scenarios were run on 2 different production lines using FIT manufacturing principles. The first scenario suggested an increase in turnover by 5.7% and the second suggested a further increase by 9.8%.

It has been shown that the maximum allocation of resources does not always mean maximum increase in productivity. On the contrary, lesser but smarter investment improved productivity by a higher margin.

Further, it has been found that increasing the efficiency of one production line does not always increase the overall efficiency if cross-functional relationships exist because increasing the efficiency of one production line is likely to cause a bottleneck on the inter-dependent operations.

In the following chapter, the DES model will be enhanced by including the inefficiencies in the production lines due to machine breakdown to further improve the production process.

7 Evaluation of the effect of breakdown of machines on productivity

This chapter investigates the effect of breakdown of machines on the shop floor on the productivity of the manufacturing process. From the previous chapter, while validating the results, some anomalies were noted which was found to be due to the breakdown of the machines on the shop floor.

The machines considered for the analysis are the machines from the Brick Cutting area. This was chosen because brick cutting is the most critical part of the manufacturing process. This is validated from previous analyses in Chapter 6 as majority of the processes are operating at maximum possible levels.

Another reason as suggested by Lu (L Lu, 2011) for investigating breakdowns was that there is evidence of correlation between machine downtime and production throughput.

7.1 Machine breakdown data collection

A system to capture breakdown was created on the shop floor using forms. When a machine was broken down, a downtime form was created which investigated the root cause analysis of the breakdown. This was carried out as part of this thesis. The template of the form is given in Figure 7.1 and the sample data in Table 7.1.

| MACHINE DOWNTIME REPORT |
| ISO 9001 |

Machine No. :		Date:
Time Reported:		
Description of fault:		
Raised due to : (delete not applicable) Internal Audit / Customer Complaint / Normal Working		
Reported by :		
Fault diagnostics and remedial action:		
Repair time start:	Repair time finish:	
Date:		
Action by :	Signature :	
Action to Prevent Recurrence:		
Action by :	To be completed by :	(date)
Corrective Action Completed		
Actioned by:	(signed)	(date)
Manager	(signed)	(date)
No. :	Date:	Audit No. :	(where relevant)

Doc. Ref.	Version	Previous Revision	Revision Date	Page
Machine Downtime Report	1.0	10/09/2015	30/10/2015	1 of 1
© Brick Fabrication Ltd.				

Figure 7.1: Machine downtime report

	Site	Pontypool															
	Type	Breakdown Monitoring System															
Month				Production				Maintenance				Time (Hours)		Associated Costs (£)			
	No	Machine No	Breakdown Code	Out		In		In		Out		Production	Maintenance	Material	Labour	Production	Total
				Date	Time	Date	Time	Date	Time	Date	Time						
Mar-14	1	3	4	04/03/2014	15:30	04/03/2014	16:00	04/03/2014	15:50	04/03/2014	16:00	0.5	0.17	£1.0	£1.3	£27.0	£29.3
	2	6	3a	05/03/2014	08:30	05/03/2014	09:00	05/03/2014	08:30	05/03/2014	09:00	0.5	0.5	£45.5	£3.8	£27.0	£76.3
	3	2	5	05/03/2014	09:00	24/03/2014		24/03/2014		24/03/2014		1.5	1.5	£44.5	£11.5	£81.0	£137.1
	4	3	7	21/03/2014		24/03/2014		24/03/2014	09:00	24/03/2014	09:10	3	0.17	£0.0	£1.3	£162.0	£163.3
		2	3b					31/03/2014	09:20	31/03/2014	13:30						
	5	6	9	24/03/2014		25/03/2014		25/03/2014	08:30	25/03/2014	08:40	8	0.17	£0.0	£1.3	£432.0	£433.3
Total												13.5	2.51	£91.0	£19.3	£729.0	£839.3
Apr-14	1	6	10	10/04/2014	14:20	10/04/2014	15:00					0.66				£35.6	£35.6
	2	2	9	23/04/2014	14:00	24/04/2014	09:00	24/04/2014	08:00	24/04/2014	08:30	4	0.5		£3.8	£216.0	£219.8
	3	3	10	23/04/2014	14:30	24/04/2014	09:00	24/04/2014	08:30	24/04/2014	08:45	3.5	0.25		£1.9	£189.0	£190.9
	4	3	6	24/04/2014	15:00	24/04/2014	15:30	24/04/2014	15:00	24/04/2014	15:30	0.5	0.5		£3.8	£27.0	£30.8
Total												8.66	1.25		£9.6	£467.6	£477.3
May-14	1	2	7	02/05/2014	06:00	06/05/2014	09:00	06/05/2014	14:00	06/05/2014	15:50	19	1.83	£0.0	£14.1	£1,026.0	£1,040.1
	2	2	3b	07/05/2014	07:30	13/05/2014	14:20	13/05/2014	08:30	13/05/2014	09:45	38	1.25	£65.0	£9.6	£2,052.0	£2,126.6
	3	6	10	07/05/2014	08:00	07/05/2014	10:00	07/05/2014	08:15	07/05/2014	09:35	2	1.33	£0.0	£10.2	£108.0	£118.2
	4	4	10	13/05/2014	14:20	14/05/2014	14:30	14/05/2014	09:05	14/05/2014	12:00	8.16	3	£0.0	£23.1	£440.6	£463.7
	5	6	10	19/05/2014	07:00	20/05/2014	09:15	20/05/2014	08:45	20/05/2014	09:15	10	0.5	£0.0	£3.8	£540.0	£543.8
Total												77.16	7.91	£65.0	£60.8	£4,166.6	£4,292.5
Jun-14	1	4	3b	06/062014	14:30	09/06/2014	14:30	06/06/2014	14:30	09/06/2014	12:00	8	0.5	£1.4	£3.8	£432.0	£437.2
	2	3	3a	13/06/2014	10:55	13/06/2014	11:20	13/06/2014	10:55	13/06/2014	11:20	0.41	0.41	£4.2	£8.1	£22.1	£34.4
	3	5	3b	16/06/2014	14:00	18/06/2014	14:00	16/06/2014	14:00	18/06/2014	14:00	16	5	£24.0	£38.5	£864.0	£926.5
	4	5	10	25/06/2014	14:00	25/06/2014	14:40	25/06/2014	14:00	25/06/2014	14:40	0.67	0.67	£0.0	£5.2	£36.2	£41.3
	5	2	4, 6	26/06/2014	06:00	26/06/2014	09:00	26/06/2014	08:00	26/06/2014	08:40	3	0.67	£75.0	£5.2	£162.0	£242.2
Total												28.08	7.25	£104.6	£60.7	£1,516.3	£1,681.6
Jul-14												0	0	£0.0	£0.0	£0.0	£0.0
Aug-14	1	6	4, 10	26/08/2014	08:15	26/08/2014	09:15	26/08/2014	08:15	26/08/2014	09:15	1	1	£29.0	£7.7	£54.0	£90.7
	2	3	3b, 5, 10	27/08/2014	14:30	27/08/2014	16:05	27/08/2014	14:30	27/08/2014	16:05	1.58	1.58	£12.1	£12.2	£85.3	£109.6
	3	4	3a	27/08/2014	14:15	27/08/2014	14:30	27/08/2014	14:15	27/08/2014	14:30	0.25	0.25	£4.0	£1.9	£13.5	£19.4
Total												2.83	2.83	£45.1	£21.8	£152.8	£219.7
Sep-14	1	1	3b	05/09/2014	12:30	08/09/2014	10:00	05/09/2014	12:30	08/09/2014	09:14	4	3.45	£40.0	£26.5	£216.0	£282.5
	2	6	3a	09/09/2014	14:40	09/09/2014	15:05	09/09/2014	14:40	09/09/2014	15:05	0.42	0.42	£4.2	£3.2	£22.7	£30.1
Total												4.42	3.87	£44.2	£29.8	£238.7	£312.6
Oct-14	1	1	3a	10/10/2014	11:30	10/10/2014	12:00	10/10/2014	11:30	10/10/2014	12:00	0.5	0.5	£4.2	£3.8	£27.0	£35.0
	2	2	9	13/10/2014	08:15	13/10/2014	08:30	13/10/2014	08:15	13/10/2014	08:30	0.25	0.25	£1.2	£1.9	£13.5	£16.6
	3	4	10	16/10/2014	14:30												
	4	2	10	30/10/2014	12:00	31/10/2014	11:00	30/10/2014	12:00	31/10/2014	11:00	8	8	£0.0	£61.5	£432.0	£493.5
Total												8.75	8.75	£5.4	£67.3	£472.5	£545.2

Table 7.1: Machine downtime statistics

The data in Table 7.1 shows the breakdown statistics of machines within the cutting room. Machines were numbered 1 to 6. The correlation of the machine numbers to the machines on the DES model is given in Table 7.2.

Machine number	DES model machine
1	Arch_saw_01
2	Arch_saw_02
3	Bndng_saw_01
4	Bndng_saw_02
5	Chmny_saw
6	Slip_Machine

Table 7.2: Machine numbers

A code was created for each type of breakdown as this would help classify each breakdown and analyse the breakdown data. The codes created are given in Table 7.3.

No	Breakdown type		Breakdown Code
	Main	**Sub**	
1	Blade Change	350 mm Hard Blade	1a
		350 mm Soft Blade	1b
		450 mm Block Saw	1c
		650 mm Deco Machine	1d
2	Blade stuck to shaft		2
3	Bearing Failure	Trolley Wheels	3a
		Cutting Spindle	3b
4	Cutting head spring breakage		4
5	Start/Stop buttons failure		5
6	Loss of tension on belts		6
7	Rust handle		7
8	Motor failure		8
9	Changing Water pipes		9
10	Other		10

Table 7.3: Breakdown codes

This data was used to identify and predict the breakdown patterns in the simulation model. The breakdown data added to the simulation model is described in the following section.

7.2 Scenario 04: DES modelling of breakdown patterns

Following analysis of the data, breakdown pattern for the machines were found and modelled in the simulation. The frequency of breakdown of machines against the breakdown code was found and is given in Table 7.4 together with the repair time.

The probability of breakdowns is assumed to be linear and not following a distribution. This is considered as the objective is to find the overall impact of the breakdown over a prolonged period of time and not the particular spike or fall on the model's performance as a result of a particular breakdown. Thus, the time at which the breakdown occurs is irrelevant as long as the total time the machine was not working remains the same over the period of entire simulation. This is why the modelling is carried out as explained below.

DES model machine	Breakdown code	Frequency of breakdown	Repair time (minutes)
Arch_saw_01	-	-	-
Arch_saw_02	05	3000 minutes	60
Bndng_saw_01	-	-	-
Bndng_saw_02	02	2880 minutes	30
Chmny_saw	-	-	-
Slip_Machine	01	50 operations	90

Table 7.4: Breakdown pattern per machine

From this table, only one saw per production line is modelled for breakdowns. This is since the breakdown frequency is double for each saw. But the simulation model is only run for a week. Thus, the breakdown frequency is

halved for both the saw's that supply the same production line and is modelled only for one saw.

Thus, Arch cutting saws are modelled to breakdown at a frequency of 3000 minutes of operating time. They have a breakdown code of 05 which is failure of start/stop buttons. This is due to the fact that the operating conditions in the cutting room are wet and filled with abrasive brick dust. The repair time to replace the start/stop buttons is 60 minutes.

This is modelled in the simulation. The breakdown mode is selected as 'Busy Time' with the repair time of 60 minutes. No labour is modelled to do the repair as the Maintenance technician is not modelled in the simulation. The data used for the modelling of the breakdown pattern for Arch_saw is given in Figure 7.2.

Figure 7.2: Arch_saw_02 breakdown pattern

For the Slip machine, the change of blades was a frequent issue that slowed the production down. Although this is not a breakdown of the machine, this is modelled as it is found to slow the production down. The data used for the modelling of the breakdown pattern for Slip_machine is given below. The data shows that the change needs to happen after 50 operations and require a change time of 90 minutes.

Figure 7.3: Slip_machine breakdown pattern

The breakdown of Bonding saw which supplies the Brick special production line was found to happen due to blade getting stuck on shaft for a cycle time of 2880 minutes of operational time. The repair time is 30 minutes. This is taken in proportion to 2 machines and modelled in a single machine like the Arch_saw 02. The modelling data used in the software for Bonding_saw is givenin Figure 7.4.

Figure 7.4: Bndng_saw_01 breakdown pattern

Following modelling of the breakdown patterns, the simulation model is run for a simulation time on 20160 minutes (2 weeks) with a warmup time of 10080 minutes (1 week) similar to all previous simulations in order to make comparison. The results of the simulation are given in the following section.

7.3 Results

Following the implementation of scenario 04 in the simulation model, there has been slight decrease in the output in terms of the number of finished products shipped. The results are given in Table 7.5.

	Initial model	After Scenario 3	% change	After Scenario 4	% change
No_chimneys_shipped	50	74	48%	70	40%
No_arches_shipped	59	113	92%	110	86%
No_CnB_shipped	131	113	-14%	105	-20%

Table 7.5: Results of breakdown modelling

This also will have an impact on the total turnover and profit margin. This implies the significance of introducing preventive maintenance strategies into the production process. But any decision on preventive maintenance should be offset against costs.

7.4 Proactive and reactive strategies to tackle machine breakdowns

The research into breakdown patterns highlighted the need to improve the process by introducing 2 different strategies. The first was to have a proactive strategy to implement a preventive maintenance schedule. The second was to have a reactive strategy of having a spare machine on the shop floor, so that in case there was a breakdown, the company could react quickly by utilising the spare machine.

For the proactive strategy, the preventive maintenance schedule could fall during the production time. As the factory operates on a 40-hour work week which consists 8 hour working day, maintenance could be carried out during off-shifts such as evenings or weekends. This would minimise the impact of breakdown of machinery on the productivity. Although, machines go through preventive maintenance this cannot be a guarantee that the machines will not

breakdown. If the machine breaks down, the effect on production will be significant.

The second reactive strategy is purchase and installation of a spare machine in case of breakdown of a machine. This is only possible if all the machines used in production are of same type as only one spare is required. This solution is not universal and might not be easily adopted for all manufacturing processes. However, this has been made possible in this scenario considered. In case of a machine breakdown, the operators could quickly use the spare machine while the broken-down machine is repaired without any loss of production.

Of the two strategies described above, the best option needs to be found for the manufacturing process considered in this study. For this, a cost study was carried out between the two strategies. Labour costs, cost of a new machine (modelled in depreciation per year) and the cost of breakdown repairs per year ere compared between the 2 options.

The cost comparison is given in Table 7.6. The estimates were made by the company based on previous data for over a period of 8 months which costs them losses of £8,368.20. Based on this figure, the yearly breakdown costs will amount to a sum of £12,552.30.

	Proactive strategy - Preventive maintenance schedule	Reactive strategy - Spare machine
Labour costs	£15,000	0
Machine cost	0	£1,000
Breakdown repair cost	£628	£12,552
Total costs/year	**£15,628**	**£13,552**

Table 7.6: Analysis of proactive and reactive maintenance strategies

To have a proactive maintenance schedule, a maintenance operator is required who should at least be employed for 30 hours a week. This is calculated roughly as £15,000 per year which includes the cost of National Insurance and tax contribution by the company. This figure is an estimate made by the company based on previous data. By having a proactive schedule does not guarantee 100% elimination of breakdowns. There will be a minimal amount (around 20%) which is expected to cost the company circa £628 per year. Thus, the total cost of having a proactive maintenance schedule is expected to be around £15,628 per year.

But the reactive maintenance strategy of having a spare machine is expected to cost only £13,552 per year. The cost of a new machine is circa £5,000 with a life expectancy of 5 years. Thus, the depreciation is modelled per year as £1,000 on a linear rate. The total cost of breakdown repairs is around £12,552 a year from company data. This totals to £13,552/year. This option is viable in this scenario as all the machines in the cutting room are of the same type which makes it possible to replace with a spare machine.

It can be found that a preventive maintenance schedule is not always the best option in any scenario. Reactive maintenance is found to be the cost-effective solution at this stage. There is expected to be a savings of around £2,000 per year when compared to the proactive strategy.

7.5 Validation of results

The results were validated by comparing against potential and actual targets achieved on the shop floor for periods of time when there was a breakdown. It was found that the breakdown of machinery did impact negatively on production.

A cost analysis of the 2 options, one to have a proactive preventive maintenance schedule or to have a reactive alternate machine breakdown strategy were discussed. Due to cost effectiveness, the reactive strategy was preferred by the company.

7.6 Chapter summary

This chapter evaluated the effect of machine breakdowns on the production efficiency. It was found that machine breakdowns did impact the production efficiency negatively. This has been validated using the DES model and the results were compared with actual data from the shop floor.

Reactive and proactive strategies were compared against each other to find the best option in the current scenario. It has been found that the proactive strategy of having a maintenance schedule is not always the best option. Instead, the reactive strategy of having a spare machine was found to be a more cost-effective solution in this particular case.

8 Results & Discussion

The study started with the initial simulation model. This produced a turnover of £43,750 per week which was validated from the company KPI's. Overall one manual, meaning intuitive, and 2 automatic scenarios were carried out to increase the throughput from the production line of 3 different products. The parameters being monitored for outputs were the number of products shipped and the turnover per product which increased the leanness and agility of the manufacturing model.

The results of the number of products shipped per product is given in Table 8.1 for the 3 simulations.

	Initial model	After Scenario 1	After Scenario 2	After Scenario 3	% change
No_chimneys_shipped	50	51	51	74	48.0%
No_arches_shipped	59	64	124	113	91.5%
No_CnB_shipped	131	137	125	113	-13.7%

Table 8.1: Results: Number of products shipped

After the first stage of scenario following a manual intuitive approach, the number of products produced for all the products increased. However, the improvements were restricted by a threshold which the intuitive method was unable to break. There is no change in the number of chimneys shipped on scenario 2 compared to scenario 1 as the latter is about maximising the throughput for arches and cut and bond bricks. But following Scenarios 02 & 03, which uses an automatic approach based on the in-built Witness optimiser, the number of chimneys increased by 48% and of arches by 91.5%. But the number of Brick Specials decreased by 13.7% as shown in Figure 8.1. This is due to the inter-dependence of production lines. Another reason for this

decrease is the shared resources such as Packing being over used by the other two products.

This change is considered acceptable as the changes to the other production lines are significantly higher. There is a cost associated with the increase in throughput as scenarios 02 and 03 relied on some investment. This needs to be considered while implementing the changes.
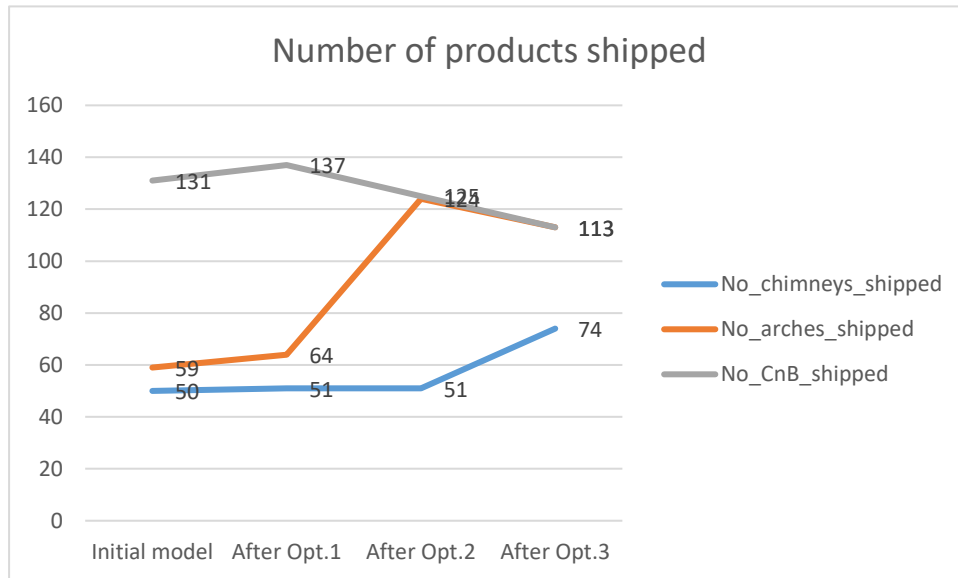
Figure 8.1 Results: Number of products shipped trend:

The trends in the graph also shows significant improvements in the model which achieves the objective of simulation. This needs to be compared with financial objectives and costs of implementing these changes.

Scenario 1 is implemented and verified albeit operational validity. Results of scenarios 2 and 3 were presented to the company to act upon. As scenarios 2 and 3 involves significant investment and time, the implementation was not completed within the time frame of this project.

8.1 Increase in turnover

The increase in turnover against the initial objectives after the 3 scenarios are given in Table 8.2.

	Initial model	**After Scenaro 1**	**After Scenario 2**	**After Scenario 3**	**% change**
Value_chimneys_shipped	£26,750	£27,285	£27,285	£39,590	48.0%
Value_arches_shipped	£3,245	£3,520	£6,820	£6,215	91.5%
Value_CnB_shipped	£13,755	£14,385	£13,125	£11,865	-13.7%
Total_turn_over	£43,750	£45,190	£47,230	£57,670	31.8%

Table 8.2: Results: Increase in turnover, % change accounts for scenario 03 only

$$\%\text{change} = \frac{(Value\ after\ scenario\ 3 - Value\ at\ initial\ model)}{Value\ at\ initial\ model} \times 100$$

After the 3 scenarios, the turnover of the entire company has increased by 31.8% by a value of £57,670 per week from the initial model which is initial model against scenario 3. The majority of this is contributed by the increase in the chimney production line. The highest percentage change is noted in the arch production line. Pie charts in Figure 8.2 and Figure 8.3 show the turnover produced by each product before and after the improvements.
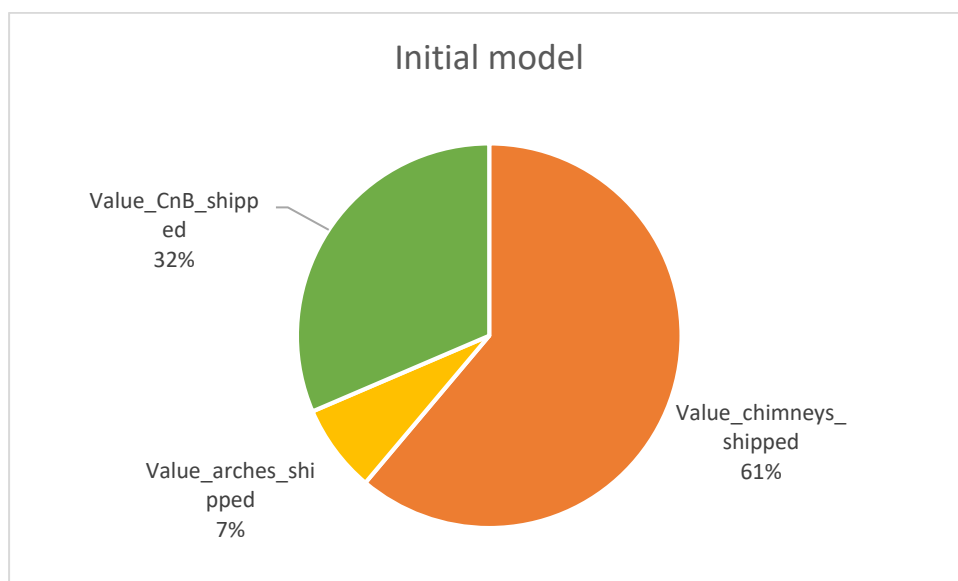
Figure 8.2: Initial model turnover ratio

As shown in Figure 8.2, in the initial model, 61% of the turnover was from the chimney production line, followed by Brick Specials as 32%. Arches only contributed towards 7% of the turnover.
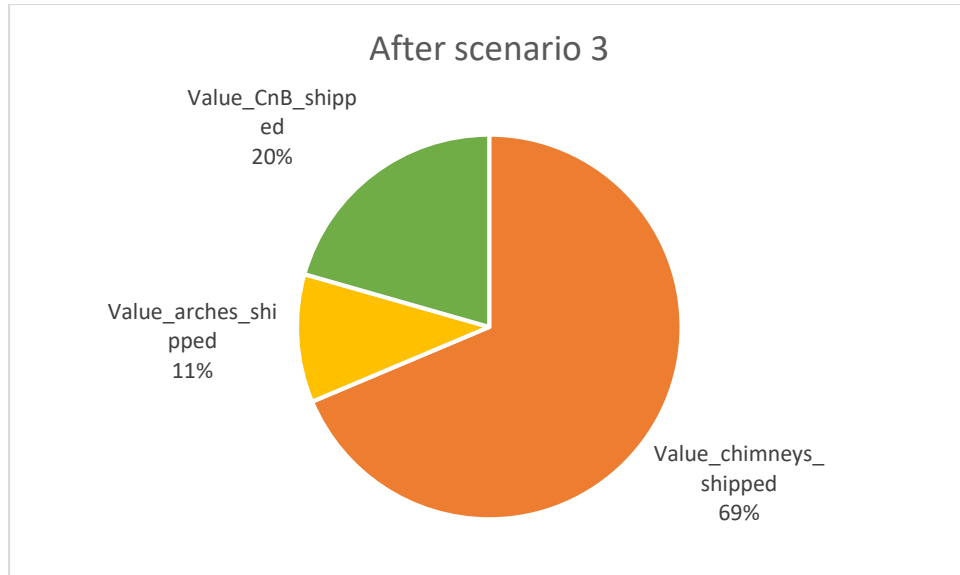
Figure 8.3: Optimised model turnover ratio

As shown in Figure 8.3, after the final scenario, turnover from chimneys increased to 69%. Brick specials contribution towards turnover reduced to 20% and also in value. Arches turnover increased significantly both in value and percentage to 11%.

8.2 Impact on gross profit

As a result of the improvements made to the production process through DES modelling the company turnover per week increased from £43,750 to £57,670 after final stage of optimisation. This amounts to an increase in £13,920 in turnover per week, which is approximately £696,000 a year considering 50 full working weeks.

However, the suggested changes in the model has costs associated with it. This needs to be accounted for to investigate the profitability of the changes. The suggested changes and costs are given in Table 8.3.

	Suggested changes	*Costs*
Scenario 01	Increase CNC shift by 10 hours/week	£5,000
	Increase Packing shift by 10 hours/week	£5,000
	Cross-train finishing operative	£0
	Reduce cap & pot operative by 1	-£15,000
	Increase order quantity	£0
Scenario 02	Purchase additional CNC Machine	£100,000
	Additional CNC Operative	£30,000
Scenario 03	Reduce laminating cycle time	£25,000
	Additional brick cutting machine	£10,000
	Additional brick cutting operative	£20,000
	Increase buffer capacity & consumables	£250,000
	Total Costs	**£430,000**

Table 8.3: Cost of implementing changes

From the above, scenario 01 does not cost anything but saves the company £5,000 per year in addition to the increased turnover. But scenarios 02 & 03 are costly and implementing the recommended changes amounting to a

combined £185,000 pounds. This is due to the significant investment required to make those changes.

In addition, as the number of products produced is nearly doubled, the cost of raw materials also increases. Overheads such as electricity, maintenance costs will also increase. More space on the shop floor is required to store these additional product quantities. This amounts to a significant £250,000 increase in costs.

The total cost of implementing and maintaining the suggested improvements amount to £430,000. This can be offset against a projected savings of £696,000. Thus, an increase in gross profit of £266,000 is predicted by the recommended changes of implementing the FIT manufacturing principles in the manufacturing industry.

8.3 Chapter summary

The results have shown potential savings and gains in the production process modelling following various scenarios by implementing FIT manufacturing principles and Discrete Event Simulation. It has been shown that the number of products shipped per week has nearly doubled giving an increase in the turnover. But the suggested improvements have costs associated with it. This needs to be offset to find the profitability of the changes. Overall, it has been found that the gross profit is expected to improve by £266,000 per year if the recommended changes are to be implemented.

9 Conclusions

The aim of the study was to improve the performance of the current manufacturing process through the application of FIT manufacturing principles. This has been achieved successfully using Discrete Event Simulation (DES) modelling and simulation with the help of the software Witness. The simulation models suggested a significant improvement in the throughput of the manufacturing plant and an overall £266,000 in gross profits per year.

It has been found that the resources such as machines and labour that are shared between production lines may cause undue pressure on the production line. Also, maximum allocation of resources does not always mean maximum increase in productivity. On the contrary, lesser but smarter investment improved productivity by a higher margin. People with multiple skills who can carry out multiple operations have been found to improve productivity significantly. It has also been found that increasing the efficiency of one production line might not always increase the overall efficiency if cross-functional relationships exists, as increasing the efficiency of one production line is likely to cause a bottleneck on the inter-dependent operations.

Breakdown of machinery has been found to impact the production negatively. In contrary to the belief that preventive maintenance is the effective solution, it has been found that a reactive maintenance strategy of having a spare machine is more cost effective in this case. This option is viable in the current manufacturing model, but not always on all scenarios.

The study has demonstrated the significance of implementing FIT manufacturing principles in the manufacturing industry. DES has been a very useful tool to validate proposed changes which are complex mathematical models. DES has been used to test different FIT scenarios without any investment in plant and machinery.

The company could expect the following benefits by implementing FIT manufacturing principles in their production facility:

- Improve the gross profit margin by £266,000 per year.

- Reduce the lead time of existing products, thus improving customer satisfaction.

- Increase the turnover per year.

- Balance the production time using Takt time.

- Optimise labour and machine resources and reduce operating costs.

- Increase sustainability and agility of the manufacturing processes.

Overall, FIT manufacturing principles have been very effective in improving the operational efficiency of a manufacturing plant. Although the recommended changes have been validated through simulation and Believability in general, in practice they should be tested and validated using any DES tool and on the shop floor before significant investments are made.

9.1 Contributions to knowledge

The contributions made to the existing knowledge of FIT manufacturing and DES are as follows.

- Maximum allocation of resources does not always mean maximum increase in productivity. On the contrary, lesser but smarter investment improved productivity by a higher margin.

- Multi skilled operatives that are trained to operate between different production lines can significantly increase productivity with minimal investment.

- Shared resources such as machines and labour are critical points on the production line which are subject to undue pressure during the process flow and may cause bottlenecks.

- Increasing the productivity of one production line might not always increase the overall productivity if cross-functional relationships exist.

- Reactive maintenance practices such as having a spare machinery was found more cost effective, in this case, than a proactive option of having a preventive maintenance schedule in this scenario.

- Promoting the application of DES & FIT manufacturing in brick cutting and fabricating industry by use of Witness Experimenter and Optimisation tools.

- Valuable information and simulation model for Cardiff University knowledge base to support existing teaching material and research.

- As a legacy of this research, the company has embedded the capability and work done on process mapping, value-stream mapping and FIT manufacturing principles.

- As a contribution to knowledge, five different conference papers were published which are listed in Appendix F: Published papers.

The process of data collection, simulation modelling, experimentation and the analysis of results could be used as a procedure and guide to similar types of manufacturing processes.

The list of papers publishes as part of this study are given in Appendix F.

9.2 Future work

This research has opened another set of questions which require further investigation, a few of which are given below.

- Three optimisations were carried out to find the optimal use of resources within a manufacturing plant. But each optimisation stage opens another set of possibilities. Hence, one should know how to define the convergence of results and when to stop the process.

- The existing model is an example of a complex manufacturing environment. This could be used to test and develop other manufacturing principles.

- A further study is required to investigate the effectiveness of proactive maintenance schedules against reactive maintenance due to machine breakdown with options such as spare machinery or sub-contract options is required to find the optimal solution or framework which will work in all scenarios.

- Research could also be carried out on modelling the effect of human behaviour on production throughput based on different distribution patterns.

The recommendations above are not limited to and could be expanded depending upon the application. Further advancement and existential evidence is required to prove and accept the principle of FIT manufacturing, for which widespread research is essential.

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Appendix A: Gross Value Added (GVA) Estimation

The following Table A.1 can be used to measure the GVA for the manufacturing system.

Factor	Basic measure: units per direct operator hour
Defect/scrap reduction	% = defective units/total units
On-time delivery improvement	% of products delivered on time
Improved space utilisation	£ per m^2 = sales turnover/area
Increase in stock turns	Number of turns = Sales turnover of the product/value of (raw materials + WIP + finished goods)
Gross value added per person	£/person = (output value – input value)/ number of employees
Overall equipment effectiveness	% = Availability % × Performance % × Quality %
Increased turnover	£ = New turnover – old turnover

Table A.1: GVA estimation (A.J. Thomas R. B., July 2008)

Appendix B: FIT-Sigma Process, Tools and Techniques

The following Table B.1 explains the FIT-Sigma processes, tools and techniques that can be used in the industry while implementing FIT manufacturing.

PLAN	MEASURE	ANALYSE	SOLVE	EXECUTE	EMBED
Strategic Review	Quickscan	Quickscan	Obtain Solutions (for Variation reduction Performance achievement Efficiency Improvement)	Solution Implementation Design and Planning	Create cultural change
Fiscal Analysis	Value Stream Mapping	Identify Inhibitors to System Performance Enhancement (ToC)			Develop Procedures
Quickscan[1]	Identification of system constraints		Select most effective solution	Implementation Team Selection	Train Staff
Big Picture Mapping		Cause and Effect Analysis (CLD)		Project Management	
	Pareto Analysis		Check solution on upstream and downstream operations		Develop Ongoing Discipline of Application
Project Definition (Set Lean Sigma Objectives)	Activity Sampling			Execute Solution	
		Value Stream Mapping		Evaluate Solution Effectiveness	Monitor control system to check for performance
Project Selection	Industrial Engineering		Test solutions		
		QFD (Wants and Hows)			
Resource Selection	Scrap / Throughput Analysis		Check solution integrity	Agree on solution performance, can it be improved?	Revisit area for next stage of improvement
		Industrial Engineering			
Project Team Selection	OEE		Agree on Solution		
		Critical Path Analysis			Do it again!
Problem Definition	SPC		TRIZ		
		Experimental Design			
Project Planning	Critical Path Analysis		Computer Aided Engineering		
		Fault Tree Analysis			
Project Risk Analysis & Contingency Planning			Simulation		
			What-if Analysis		
Cost Benefit Analysis					

Table B.1: FIT Sigma process, tools and techniques

Appendix C: Order analysis for Brick-clad chimneys

The analysis of the orderbook for Brick-clad chimneys were carried out for a period of 3 months with the objective of finding the average price and orders received per day as shown in Table C.1. As the size of the chimneys vary per order, a 'units worth' value for each chimney is calculated, 1 being the average size. Any size less than the average is given a unit worth of less than 1 and vice versa.

Chimneys Units Worth	Chimneys made to order	Chimneys made for other purposes	Total chimneys produced	Total units value of chimneys	Sales Price	Avg. Unit Price
0.5	12	3	15	6	£5,720	£953
1	217	4	221	217	£122,346	£564
1.25	2	0	2	2.5	£1,510	£604
1.5	82	0	82	123	£61,167	£497
2	13	0	13	26	£10,684	£411
2.5	1	0	1	2.5	£1,619	£648
3	8	0	8	24	£14,884	£620
Total	**335**	**7**	**342**	**401**	**£217,930**	**£543**

Table C.1: Chimney order analysis

It was calculated that the average number of chimneys made per day is 7 with an average price of £543/chimney. But in the simulation, the value considered is £535 due to the decision from the company to reduce a percentage of the profit margin in the simulation.

Appendix D: Value-stream map for pre-fabricated arches

The value-stream map (VSM) exercise helps map the value-added activities for a production line. It also provides an excellent format for identifying and making changes to the existing production line to improve the performance. The VSM of the pre-fabricated arch production line is given in Table D.1.

Pre-fabricated arches								
Ref No.	Activity Description	Dept	Time (mins)	Operation	Transport	Inspection	Store	Delay
1	Transport bricks to Slip machine	Brick cutting	5		5			
2	Cut slips		10	10				
3	Label the job		1	1				
4	Stretch wrap cut slips		2	2				
5	Move to storage area		2		2			
6	Move to super saw		2		2			
7	Locate the template to cut bricks		3			3		
8	Cut the slips to shape in super saw		60	60				
9	Move to kiln		2		2			
10	Drying in kiln		30	30				
11	Move from kiln to storage		2		2			
12	Cooling off time		20	20				
13	Transport to bonding area		5		5			
14	Check - job number, size etc.	Panel cutting	2			2		
15	Set the machine to cut required size		5			5		
16	Cut the ply board on panel saw		10	10				
17	Mark on cut ply using template		3	3				
18	Cut to shape on band saw		5	5				

19	Palletise cut panel boards		2				2	
20	Move bricks to bonding area	Bonding	2		2			
21	Move cut panel boards to bonding area		2		2			
22	Glue arches		7	7				
23	Move to storage area		2		2			
24	Curing time		60	60				
25	Stack on pallet		2				2	
26	Packing	Packing	5	5				
27	Ship to yard		5		5			
			256	**213**	**29**	**10**	**4**	**0**
			213					
			83%					

Table D.1: VSM of pre-fabricated arches

It can be seen clearly that 83% of activities in the pre-fabricated arch production line are value adding.

Appendix E: List of rules and variables used in DES model

The list of rules used for each machine on the simulation model is given in Table E.1.

Machine	Input Rule	Labour Rule	Output Rule
Arch_saw_01	PULL from Cut_slips	Arch_cutter1#1	PUSH to Arch_bricks
Arch_saw_02	PULL from Cut_slips	Arch_cutter2#1	PUSH to Arch_bricks
Assembly	PULL from Cut_Ply(1)	Assembler1#1 OR Assembler2#1	PUSH to Assembled(1)
Bndng_saw_01	PULL from Bricks_CnB	Bonding_cutter1#1	PUSH to Dry_bricks
Bndng_saw_02	PULL from Bricks_CnB	Bonding_cutter2#1	PUSH to Dry_bricks
Bonding	PULL from Dry_bricks	Bonder1#1 AND Bonder2#1 OR Bonder3#1 AND Bonder4#1	PUSH to Bond_bricks
Bonding_Arches	SEQUENCE /Wait Cut_Panel(1)#(1), Arch_bricks(1)#(1)	Bonding_arches1#1	PUSH to Arch_storage
Cap_n_Pots	PULL from Cap_holding	Cap_operator#1 OR Finisher#1	PUSH to Cap_Pot(1)
Chmny_saw	PULL from Bricks_ch	Chimney_cutter#1	PUSH to Brick_slips(1)
Cladding	SEQUENCE /Wait Brick_slips#(1), Trimmed_chim#(1)	Cladding1#1 AND Cladding2#1	PUSH to Clad_chimneys(1)
CNC_Machine	SEQUENCE /Next Bay1#(1), Bay2(1)#(1)	CNC_Operator#1	PUSH Panel_Boards to Cut_Panel,Ply_Boards to Cut_Ply
Finishing	SEQUENCE /Wait Clad_chimneys#(1), Caps_n_Pots#(1)	Finisher#1	PUSH to Fin_chimneys(1)
Laminating	PULL from Assembled(1)	Laminator1#1 AND Laminator2#1	PUSH to Laminated(1)
Packing	SEQUENCE /Next Fin_chimneys(1)#(1), Arch_storage(1)#(1), Bond_bricks(1)#(1)	Packer#1	PUSH to SHIP
Slip_machine	PULL from Bricks_ar	Slip_cutter1#1 AND Slip_cutter2#1	PUSH to Cut_slips
Trim_coat	SEQUENCE /Next Laminated(1)#(2), Cap_Pot(1)#(1)	Trim_operator#1	PUSH Ply_Boards to Trimmed_chim,Cap_materials to Caps_n_Pots

Table E.1: Rules used in machine models

Appendix F: Published papers

The following papers were published as part of the project.

1. Achieving sustainability in small to medium sized manufacturing enterprises through Educational awareness; SDM'15 Second International Conference on Sustainable Design and Manufacturing, Seville, Spain; April 2015; Alan Davis, Michael Packianather, John White, Sajith Soman.

2. Identifying inefficiencies in a process flow and rectifying it through discrete event simulation and FIT manufacturing techniques; ICIDM16 International Conference on Innovative Design and Manufacturing, Auckland, New Zealand; Jan 2016; Alan Davis, Michael Packianather, John White, Sajith Soman, Williams H.J.

3. Achieving sustainability in SME Manufacturing Operations via the use of Flexible Integrated Technology and Product Symbiosis; SDM'16 Third International Conference on Sustainable Design and Manufacturing, Crete, Greece; April 2016; Alan Davis, Michael Packianather, John White, Sajith Soman.

4. Data mining techniques applied to a manufacturing SME; 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16; Michael S Packianather, Alan Davies, Sam Harraden, Sajith Soman, John White.

5. Manufacturing process flow improvements using simulation and sustainable manufacturing; World Automation Congress (WAC), 2016; Michael S Packianather, Alan Davies, Mohamed AlNemr AlZarooni, Sajith Soman, John White.