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An Exploration of the Relationship between Maintenance Performance and Resource Productivity

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Abstract

As a consequence of their relative magnitude with respect to overall organisational expenditure, potential sources for significant cost savings involve maintenance costs, raw material costs and energy consumption. Previously conducted but inconclusive research indicates that there may be a relationship between maintenance activities and resource productivity. If this is the case, knowledge of such a relationship may unveil opportunities for direct productivity enhancement. Moreover, it may also serve as an aid in making improved measurements of the true value of the maintenance function. This in turn may enable practitioners to recognize when resource reallocation may be required to achieve greater levels of productivity.

The objective of this research is to explore the relationship between maintenance activities and resource productivity. It aims in part to assess if opportunities for productivity enhancement exist as a result of such a relationship. It also aims to establish if resource productivity can serve as a representative measure of maintenance performance. This study is based on rigorously proven theoretical propositions which are tested empirically on data procured from a metallurgical plant in South Africa.

The conclusion of this study is that the maintenance function enables equipment to process resources productively. Resource productivity may thus have the propensity to serve as an encompassing and cost effective measure of maintenance performance. In terms of its potential in this regard, decreases in resource productivity may offer valuable signals which indicate that corrective action is warranted.

In terms of productivity enhancement, this study elucidates the fact that machinery should always be kept in the best operating condition possible. When machinery malfunctions are discovered, it should be repaired in a timely manner to prevent unnecessary wastage from occurring.

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Chapter 1

Introduction

1.1 Background

Several authors have recently given credence to the current pressure for organisations to become more efficient (see for instance Tsang (2002), Hanula (2002) and Kumar *et al.* (2013)). Tsang (2002) explains that the emerging trend to adopt operational strategies such as JIT, Lean Manufacturing and Six Sigma demonstrates the global economy's growing need for quick response and for waste prevention.

Because of their relative magnitude with respect to overall organisational expenditure, potential sources for significant cost savings involve maintenance costs, resource costs and energy consumption. Regarding maintenance expenditure, Parida and Kumar (2009) report that maintenance costs frequently account for the largest category of costs in production firms. They also suggest that reducing unplanned maintenance costs by \$1 million can be as effective for companies as increasing sales by \$3 million. Moreover, Coetzee (1997; 1998) points out that because production processes are becoming more subject to an increased level of mechanisation, maintenance costs are on the rise. As for resource consumption, a recent report by the UN indicates that between US\$2.9 trillion and US\$3.7 trillion a year can be saved globally if wasted resources can be recovered (Von Weizsäcker *et al.*, 2014).

A review of the literature reveals that little attention has been given to the relationship between maintenance activities and resource productivity. Immense benefit may possibly manifest from exploring this relationship:

1. If this relationship remains unexplored, a potentially powerful means of productivity control may be forfeited. Abdul Raouf (2004) argues that decreased levels of productivity results when equipment failure rates increase. His rationale is that failing equipment often causes irreparable damage to raw materials, delays in production and decreases in quality. Thus, productivity may potentially be enhanced by controlling rates of failure by the implementation of more effective maintenance techniques. Research into the matter may unveil this possibility.

2. From an industry perspective, Norman (1997) and Kumar *et al.* (2013) explain why it is imperative to measure the total value of maintenance. Managers require proof of the value of maintenance in order to recognise that resource reallocation may be necessary to achieve greater levels of productivity. Research performed by Khan and Darrab (2010) indicates that maintenance activities may have large unaccounted effects on raw material productivity. As such, the total value of maintenance may be drastically underestimated at present.

1.2 Problem Statement and Research Purpose

Resource productivity may have a relationship with maintenance activities which may be exploited for purposes of productivity enhancement and for purposes of making improved measurements of the value of maintenance. It appears that no conclusive research in this regard has been published.

The purpose of this theoretical and empirical study is to explore the relationship between maintenance activities and resource productivity. The purpose of this exploratory research is threefold:

1. Firstly, this research aims to establish with statistical rigour if a relationship exists between maintenance activities and resource productivity. If a relationship does exist, it aims to establish the nature of the relationship.

2. Secondly, it aims to identify if opportunities for productivity enhancement exist as a result of such a relationship.

3. Thirdly, it aims to establish if resource productivity may be used as a measure of maintenance performance.

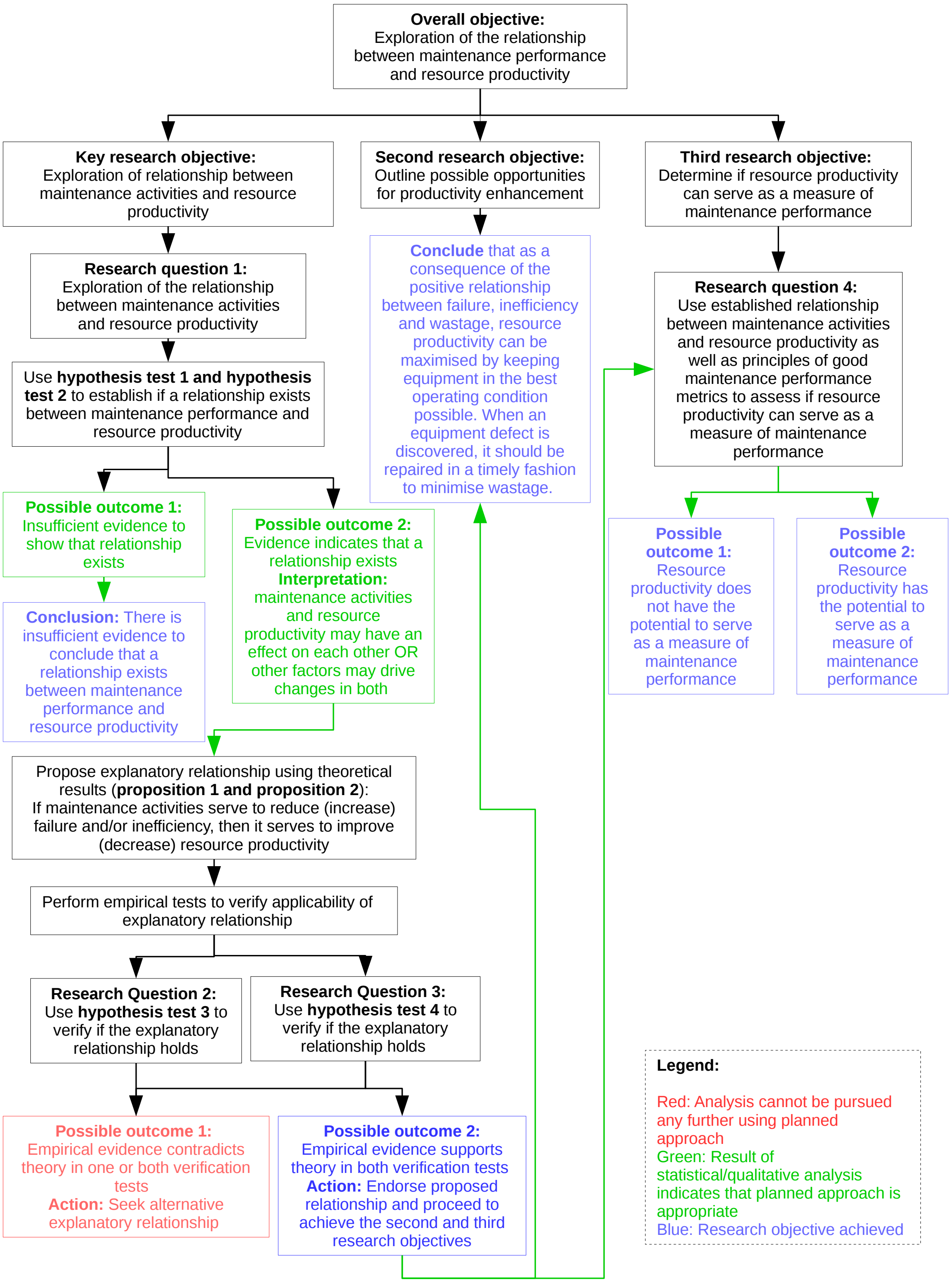
Data for this study is collected from a metallurgical plant in South Africa.

1.3 Research Questions

Figure 1.1 provides a schematic flowchart which indicates how the research questions listed below are used to achieve the objectives of this study.

The key objective of this study is to establish if a relationship exists between maintenance activities and resource productivity. If it is determined that a relationship is likely not to exist, then this research effort serves to demonstrate that there may not be any merit in undertaking further studies regarding the relationship between maintenance activities and resource productivity. If a relationship is found to exist, further effort can be undertaken to describe the relationship. To achieve this objective, the first research question makes use of statistical results to test if a relationship exists and theoretical results to postulate a description of the relationship. The result obtained is of crucial importance here because the description of the relationship is required to achieve the second and third research objectives.

The scientific method requires that empirical evidence be supplied to demonstrate the applicability of theory in practice. Thus, upon postulation of the nature of the aforesaid relationship, it is imperative to verify its validity.



Overall objective: Exploration of the relationship between maintenance performance and resource productivity

Key research objective: Exploration of relationship between maintenance activities and resource productivity

Research question 1: Exploration of the relationship between maintenance activities and resource productivity

Use **hypothesis test 1 and hypothesis test 2** to establish if a relationship exists between maintenance performance and resource productivity

Possible outcome 1: Insufficient evidence to show that relationship exists

Conclusion: There is insufficient evidence to conclude that a relationship exists between maintenance performance and resource productivity

Possible outcome 2: Evidence indicates that a relationship exists **Interpretation:** maintenance activities and resource productivity may have an effect on each other OR other factors may drive changes in both

Propose explanatory relationship using theoretical results (**proposition 1 and proposition 2**): If maintenance activities serve to reduce (increase) failure and/or inefficiency, then it serves to improve (decrease) resource productivity

Perform empirical tests to verify applicability of explanatory relationship

Research Question 2: Use **hypothesis test 3** to verify if the explanatory relationship holds

Research Question 3: Use **hypothesis test 4** to verify if the explanatory relationship holds

Possible outcome 1: Empirical evidence contradicts theory in one or both verification tests **Action:** Seek alternative explanatory relationship

Possible outcome 2: Empirical evidence supports theory in both verification tests **Action:** Endorse proposed relationship and proceed to achieve the second and third research objectives

Second research objective: Outline possible opportunities for productivity enhancement

Conclude that as a consequence of the positive relationship between failure, inefficiency and wastage, resource productivity can be maximised by keeping equipment in the best operating condition possible. When an equipment defect is discovered, it should be repaired in a timely fashion to minimise wastage.

Third research objective: Determine if resource productivity can serve as a measure of maintenance performance

Research question 4: Use established relationship between maintenance activities and resource productivity as well as principles of good maintenance performance metrics to assess if resource productivity can serve as a measure of maintenance performance

Possible outcome 1: Resource productivity does not have the potential to serve as a measure of maintenance performance

Possible outcome 2: Resource productivity has the potential to serve as a measure of maintenance performance

Legend:

Red: Analysis cannot be pursued any further using planned approach
Green: Result of statistical/qualitative analysis indicates that planned approach is appropriate
Blue: Research objective achieved

Figure 1.1: Plan for achievement of research objectives

The verification tests conducted in the second and third research questions are based on two perspectives of the output of the maintenance function. When considering a single machine at a time, the purpose of the maintenance function can be construed as ensuring adequate equipment capability (Muchiri and Pintelon, 2011; Pintelon and van Puyveld, 2006). Thus, one possible verification test is based on reports of defective machinery. On the other hand, when considering all the equipment in a production plant simultaneously, the output of the maintenance function can be construed to be the total production capacity which results (Coetzee, 2006; Coetzee, 2013). A second verification test is thus based on observations of total production capacity.

The second and third research objectives are aimed at establishing if the relationship deduced in the first research question can be used for productivity improvement and for maintenance performance measurement. Achieving the second research objective simply requires analysis of the results of the first three research questions. To achieve the third research objective, the fourth research question is used in conjunction with the results of the others to establish if resource productivity has the potential to serve as a measure of maintenance performance.

The research questions follow:

1. Do maintenance activities have an effect on the probability distribution of resource productivity and if so, what effects is it likely to have?
2. Is the postulated relationship between maintenance activities and resource productivity consistent with the relationship between production capacity and resource productivity as reflected by the sample data?
3. Does the sample data reflect that resource productivity decreases before defects in machinery are reported?
4. Does resource productivity have the potential to serve as a measure of maintenance performance?

1.4 Hypotheses and Propositions

The following hypotheses serve as the foundation for answering the foregoing research questions. The first two hypotheses correspond to the first research question and the third and fourth hypotheses correspond to the second and third research questions respectively.

Hypothesis 1 *Modifications in maintenance activities are related to changes in the average rates of resource consumption.*

Hypothesis 2 *Modifications in maintenance activities are related to changes in the variance of rates of resource consumption.*

Hypothesis 3 *Resource consumption rates have a negative monotonic correlation with production capacity.*

Hypothesis 4 *Increases in resource consumption rates are related to the manifestation of defects in machinery.*

The key feature of this research is to explore the relationship between maintenance activities and resource productivity. To this end, the purview of the first research question is to establish what effect, if any, maintenance activities have on the probability distribution of resource productivity. The answer to this research question depends on the use of the tests of the first two hypotheses to establish if a relationship exists. It then relies on some additional theoretical results to outline the potential nature of the relationship.

The following theoretical results (proven in section 3.2.2) potentially relate maintenance activities (through their effect on failure and inefficiency) to resource productivity. Loosely interpreted, the first proposition to follow states that failure and inefficiency necessarily lead to wastage. The second proposition suggests that greater levels of inefficiency and failure increases the risk of further failure.

Proposition 1 *In any production process, for any batch of essential inputs which the production process can process, wastage arises in the production process if and only if failure or inefficiency are prevalent in the production process.*

Proposition 2 *Ceteris paribus, in any production process which can only process a finite amount of input before failing, the likelihood of failure can only increase or remain the same as the production process processes more input.*

1.5 Importance of Research

For the metallurgical plant under study, a detailed investigation of cost data is performed making relevant adjustments for implemented production formulae modifications. The analysis reveals that just by using the standard production formulae, if relative resource consumption can be reduced to the lower quartile of relative resource consumption experienced since 2007, savings in excess of R48 million a year can be realised in terms of 2013 prices. This translates into an increase in operating profits of more than 44% for the company in question. Given that resource utilisation is often assumed to remain proportional to output (Khan and Darrab, 2010), this analysis exemplifies the extent to which resource productivity can fluctuate during the course of production (see appendix A for graphs of resource productivity ratios).

If maintenance performance has a relationship with resource productivity, this research will shed light on the true value of well planned maintenance policies. Knowledge of the relationship will then enable practitioners to deliberately execute maintenance techniques to achieve the immense cost savings alluded to above.

1.6 Methodology

The study design is described briefly in the subsections below. A more detailed description of the design can be found in Chapter 4.

1.6.1 Hypothesis Test 1

Hypothesis 1 is restated below:

> Modifications in maintenance activities are related to changes in the average rates of resource consumption.

Hypothesis 1 is tested by means of regression analyses and an overall binomial test on 3 maintenance regimes and 16 essential resources from the metallurgical plant under study.

1.6.2 Hypothesis Test 2

Hypothesis 2 is reprinted below:

> Modifications in maintenance activities are related to changes in the variance of rates of resource consumption.

Hypothesis 2 is tested on 16 essential resources from the metallurgical plant under study over 3 maintenance regimes by using a battery of Brown-Forsythe tests and an overall binomial test.

1.6.3 Hypothesis Test 3

Hypothesis 3 is copied below for ease of reference:

> Resource consumption rates have a negative monotonic correlation with production capacity.

This hypothesis is tested using Spearman's ranked correlation test and an overall binomial test.

1.6.4 Hypothesis Test 4

Hypothesis 4 is reprinted below:

> Increases in resource consumption rates are related to the manifestation of defects in machinery.

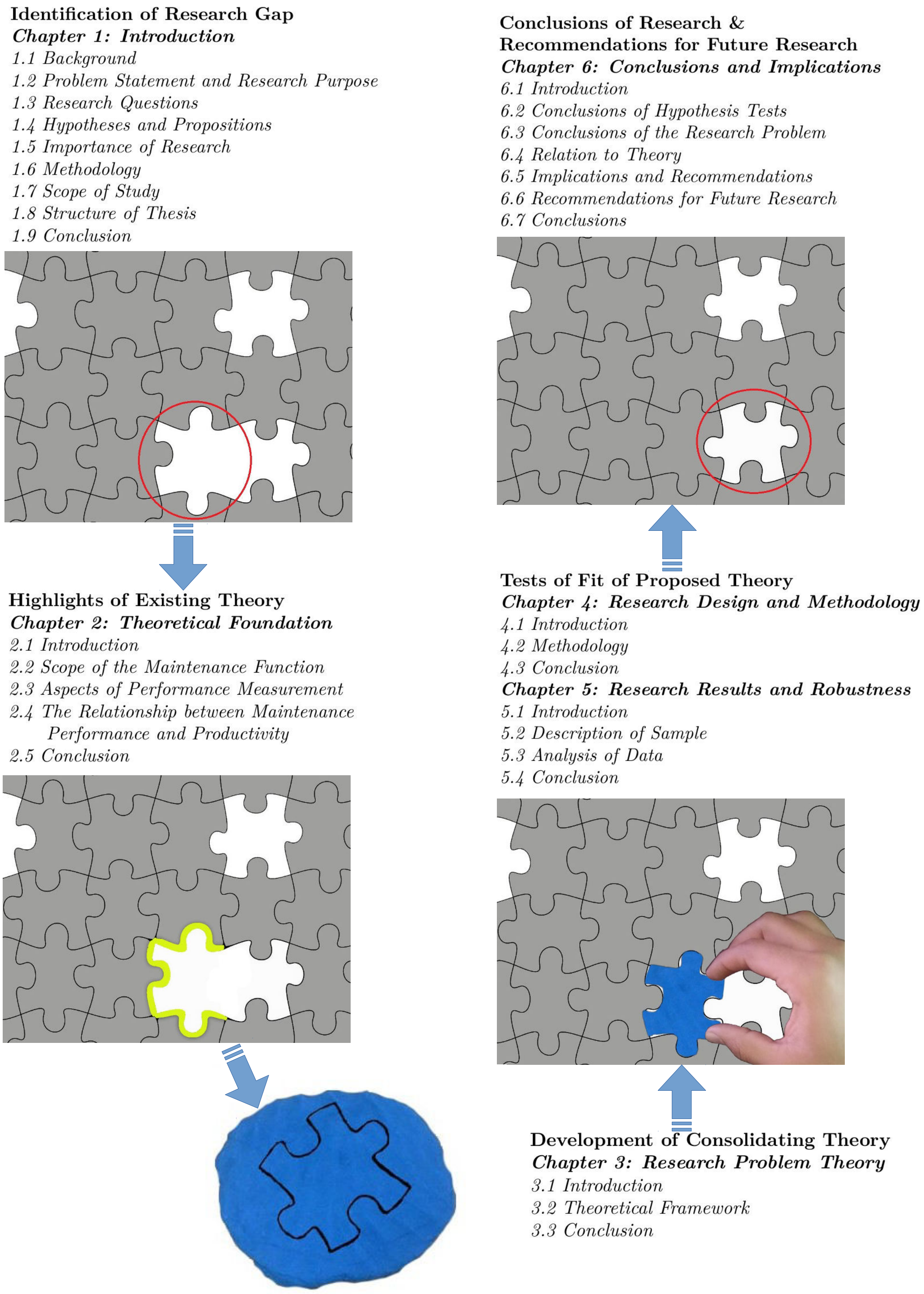
Hypothesis 4 is tested using a Chi-squared test of independence between increases in rates of resource consumption and reports of machinery defects.

1.7 Scope and Limitations of Study

This study is designed so that its conclusions are potentially universally applicable. The statistical data is sampled from a company which has been selected on the basis that it is complex enough to be representative of production operations world wide. The theoretical results available are encompassing, promising and can be rigorously proven.

This study is however limited in that its postulations are tested on sample data which arises from a single company only. More experimentation is thus required to give credence to the conclusions of this research.

1.8 Structure of Thesis



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1.9 Conclusion

This study emerges from a research gap which concerns the global need for companies to use resources more efficiently. Amongst other key motivating factors, global competition forces companies to reduce costs and increase product quality or alternatively risk bankruptcy (Kumar *et al.*, 2013). A recent report issued by the UN indicates that there is as yet tremendous potential for productivity enhancement (Von Weizsäcker *et al.*, 2014). A preliminary investigation of the metallurgical company under study reveals that resource productivity tends to fluctuate drastically over time (see section 1.5 and appendix A for details). If resource productivity can be stabilised at improved levels, immense gains in organisational profitability can be realised.

Previously conducted but inconclusive research indicates that there may be a relationship between maintenance activities and resource productivity. If this is the case, knowledge of such a relationship may unveil opportunities for direct productivity enhancement. Moreover, it may also serve as an aid in making improved measurements of the true value of the maintenance function. This in turn may enable practitioners to recognise when resource reallocation is required to achieve greater levels of productivity (Norman, 1997; Kumar *et al.*, 2013). In response to these promising observations, it is the objective of this study to explore the relationship between maintenance performance and resource productivity.

Chapter 2

Theoretical Foundation

2.1 Introduction

In summary, the objectives of this study pertain to the exploration of the relationship between maintenance performance and resource productivity. In order to examine the existing body of knowledge on the matter, the following databases were searched for documents containing the keywords *productivity* and *maintenance*:

1. Elsevier
2. Emerald
3. IEEE
4. Proquest

Few studies appearing in literature have been conducted on the topic of interest. From the 233 articles which surfaced from the literature search, 5 are relevant to the topic at hand. However, only 2 of these articles are reports resulting from actual research work. Moreover, the research that has been conducted is inconclusive. This fact is elucidated in section 2.4.

To ensure that an encompassing review of the literature is conducted, a further search of the databases includes a search for review articles in maintenance theory. These articles make almost no mention of research pertaining to the relationship between maintenance performance and resource productivity. Providentially though, much material is available on maintenance performance measurement.

This literature review is constructed as follows: In the next section, the contemporary opinions on the scope of the maintenance function is summarised. Thereafter, the concept of performance measurement is explored with respect to maintenance performance measurement and productivity measurement. Articles which relate the concepts of maintenance performance and resource productivity are then discussed. Finally, a conclusion is drawn.

2.2 Scope of the Maintenance Function

To develop an appropriate interpretation of the concept of maintenance performance, it is essential to establish the scope of activities which the maintenance function must fulfil. There are a range of mutually overlapping definitions in this regard.

Muchiri and Pintelon (2011) and Pintelon and van Puyveld (2006) who are often cited in literature favour the definitions of the British Standards Institute (BSI) and the Asset Management Council (previously known as the Maintenance Engineering Society of Australia or MESA). The definition outlined by the former (BSI, 1984) is:

> A combination of all technical and associated administrative activities required to keep equipment, installations and other physical assets in the desired operating condition or to restore them to this condition

while the definition outlined by the latter (MESA, 1995) is:

> The engineering decisions and associated actions, necessary and sufficient for attainment of specified equipment capability

Both definitions above make reference to the desired operating condition or capability of physical assets. This terminology should be clarified.

In the philosophy of MESA (1995), equipment capability gives rise to relevant functionality which enables the production of output. Accordingly, Tsang *et al.* (1999) suggest that equipment capability should be interpreted according to the rate of quality production equipment enables. Their definition follows:

> Capability is the ability to perform a specific function within a range of performance levels that may relate to capacity, rate, quality and responsiveness.

Kumar *et al.* (2013) suggest that the contemporary view of maintenance from the perspective of production managers is to enable production to take place. Along these lines, Coetzee (1998) defines the maintenance function as a supporting service which facilitates production. In later work, it is suggested that the generation of production capacity is in essence the fundamental output of the maintenance function (Coetzee, 2006; Coetzee, 2013). The scope of the maintenance function as outlined by Coetzee (1998) follows:

> The objective of the maintenance function is to support the production process with adequate levels of availability, reliability, operability and safety at acceptable levels of cost.

As is clear, the definitions of the scope of the maintenance function are generally consistent.

Regarding the boundaries of the relevant disciplines, it is apparent that the maintenance function serves the production process during the operating life of machinery. Tsang *et al.* (1999) suggest that when the maintenance function is extended to include acquisitions and disposals of assets, the function should be referred to as Physical Asset Management which includes Maintenance Management as one of its constituents.

Finally, is important to note that there is a general trend in literature which suggests that, in its operations, the maintenance function must support the strategic intent of organisations (Kumar *et al.*, 2013).

2.3 Aspects of Performance Measurement

In the words of Tomlingson (2004), lack of evaluation invites guesswork, frustration and a failed improvement effort. Meekings (2005) states that performance measurement has evolved from pointless historical evaluations to where it has now progressed. It is now understood that performance measurement has the following useful dimensions:

1. Performance measurement is about attaining insight and making predictions. Utilizing measurements enables improvement to be pursued.
2. Measures offer feedback and as such offer intrinsic motivation to personnel.
3. Performance measurement relates to systemic thinking, fundamental structural change and organisational learning. Measures enable all relevant teams in a company to align their goals with overall organisational objectives.

The aforesaid aspects of performance measurement are clearly manifest in the contemporary view of maintenance performance measurement and productivity measurement. Moreover, several useful techniques such as the Balanced Scorecard Approach proposed by Kaplan and Norton (1995) and the Quality Function Deployment method suggested by Akoa (1994) are also relevant to performance measurement in general (Hannula, 2000; Kumar *et al.*, 2013). Many of these themes are revisited in the subsections that follow.

2.3.1 Purpose and Implementation of Maintenance Performance Measurement

Kutucuoglu *et al.* (2001) state that it is now generally understood in academia that maintenance is not merely a cost centre but rather a means to increase organisation wide profits. Arts *et al.* (1998) explain that the purpose of maintenance performance measurement is to guide increases in productivity, to ensure process safety, to meet environmental standards and to assist in the reduction of maintenance costs. In addition, Parida and Kumar (2006) state that maintenance performance measurement enables companies to measure the value created by maintenance in terms of all business aspects including health and safety.

In line with the dimensions of performance measurement stipulated in the foregoing section, Kutucuoglu *et al.* (2001) state that as with all other company departments, it is essential to ensure that the objectives of the maintenance department are in line with other corporate objectives. By measuring maintenance performance, it can be ensured that the efforts of various departments are not in conflict. This is especially important for the maintenance function as it is multidisciplinary in nature (Parida and Kumar, 2009). However, Kutucuoglu *et al.* (2001) state that in industry, it is as yet necessary to achieve total harmony between the objectives of the maintenance function and corporate strategic objectives.

2.3.2 Definition of Maintenance Performance Measurement

To bridge the gap between academic discourse and its implementation in industry, Parida and Chattopadhyay (2007) define maintenance performance measurement in terms of the total value of maintenance:

> [Maintenance Performance Measurement is] the multi-disciplinary process of measuring and justifying the value created by maintenance investments, and meeting the organisation's stockholders' requirements viewed strategically from the overall business perspective.

The importance of measuring the total value of maintenance is indeed acknowledged in academia. However, work such as that of Alsyouf (2007) and Khan and Darrab (2010) demonstrates that the total value of maintenance may still not be completely understood. This topic which is pertinent to this research is discussed further in section 2.4.

2.3.3 Characteristics of Good Maintenance Performance Metrics

To achieve the objectives of this research work, the fourth research question listed in section 1.3 entails an assessment of resource productivity as a measure of maintenance performance. The following theory regarding elements of good maintenance performance measures is thus pertinent in the context of this research.

Armitage (1970) proposes the following criteria for good maintenance performance metrics. Alsyouf (2006) reiterates the need for maintenance performance metrics to meet these specific standards.

1. The metrics should reflect the aspects of maintenance performance which are of interest. These aspects should be aligned with organisational objectives.
2. The metrics should be relatively easy and inexpensive to calculate.
3. The metrics should have a well defined interpretation.
4. The metrics should indicate when remedial action is necessary and should preferably indicate what remedial action should be taken in these events.

5. When any action is undertaken which affects maintenance performance, the metrics should reflect all the consequences of such actions.

Armitage (1970) notes that while each of these characteristics in isolation are important, he ascribes particular importance to the first and fourth standards aforementioned. It is clear why this should be the case given the widely accepted strategic importance of the maintenance function. Maskell (1991) and Besterfield *et al.* (2002) emphasise the importance of the second and third standards. They argue along the lines of pragmatism: if maintenance performance metrics are too complex to calculate or interpret, they simply will not be used in industry. The fifth standard is of great importance as well because performance standards should be used to guide management in planning and decision making (Kumar *et al.*, 2013).

Although Armitage (1970) suggests that it is difficult for any single maintenance performance metric to satisfy all these standards, these standards are each important in their own right. They will therefore be used in this research work to assess resource productivity as a measure of maintenance performance.

2.3.4 Purpose and Implementation of Productivity Measurement

Productivity may be perceived as a measure of the engineering efficiency of production (Dumovic, 2008). The standard structure of the definition of productivity in literature follows (Hannula, 2000):

> Productivity is a relationship (usually a ratio or an index) between output (goods and/or services) produced by a given organisational system and quantities of input (resources) utilised by the system to produce that output.

Much research has been undertaken with respect to productivity measurement. Mohanty (1992) summarises its features as follows. These characteristics largely resemble those which pertain to maintenance performance measurement.

1. Productivity measurement is essential in ensuring that productivity improvement programmes are driven on course and enable organisational learning to take place.

2. Productivity improvement programmes require a top down approach with measures selected with an overall organisational perspective borne in mind. This is meant to ensure that effort undertaken within various departments of a company do not conflict.

Mohanty (1992) states that the application of productivity measures in industry is not commensurate with the total research effort. Hannula (2000) explains that financial measures can serve to reveal the effects of actions already taken whereas operational measures such as productivity measurement serve to describe the drivers of future performance. However, in industry, the most commonly used measurements are financial measures. These are reported long after policies are implemented and offer little utility in identifying and remedying the causes of poor performance.

Hannula (2000) distinguishes between total productivity measures and partial productivity measures. He surmises that the primary focus in literature is on partial productivity measures. Due to its complexity, total productivity measures usually do not feature in industry.

Partial productivity measures may be categorised into five distinct sets (Vora, 1992; Hannula, 2000):

1. Capital productivity measures
2. Labour productivity measures
3. Material productivity measures
4. Energy productivity measures
5. Space productivity measures

Vora (1992) reports on the results of a survey regarding the use of productivity measurement in the Midwestern USA. He concludes that measures of material, energy and space productivity are scarcely utilised by upper and middle management as performance indicators.

2.3.5 Maintenance Productivity

Measuring maintenance performance is both an extremely important and complex activity (Kumar *et al.*, 2013). To facilitate maintenance performance measurement, several authors have considered making use of the concept of maintenance productivity (Visser, 1995; Norman, 1997; Löfsten, 2000). The major foundation of maintenance productivity measurement is that the maintenance function can be construed as a system on its own. The inputs of this system may include labour, materials, spares, tools, information and money and the outputs of the system may include the volume, quality and cost of production, as well as safety of the operation (Tsang, 2002).

Maintenance productivity indicators are devised by formulating ratios of inputs and outputs of the maintenance function. Löfsten (2000) for instance presents a partial productivity measure determined by the value of corrective maintenance costs and downtime costs per quantity of production. Other measures such as Overall Equipment Effectiveness (OEE) are also utilised (Norman, 1997).

Measuring maintenance productivity however may not necessarily simplify the measurement of maintenance performance. Not only does the maintenance function possess several types of outputs, but it is also multidisciplinary in nature (Parida and Kumar, 2009). In the following section, attention is drawn to an encompassing concept which may shed more light on maintenance performance: considering the maintenance function as a key driver of the productivity of production systems.

2.4 The Relationship Between Maintenance Performance and Productivity

The articles in this section are those which pertain directly to this study. These appear to constitute the majority of the research effort which draws a relationship between maintenance performance and resource productivity. The relevant literature is considered here in chronological order.

In the words of Wells (2004), there is an intrinsic relationship between productivity, reliability and maintenance. The primary dividends from effective maintenance are reduced total operating costs, on-time delivery and consistent product quality. Wells (2004) refers to an in-operation research study regarding two newspaper presses where one implemented a systemic maintenance policy whereas the other continued to make use of a reactive maintenance policy. The former press enjoyed production of 20% more copies per hour and experienced 40% less waste.

Abdul Raouf (2004) argues along similar lines suggesting that there exists a relationship between maintenance, productivity and safety. Problems with machinery leads to damage of materials, inconvenience to workers, production interruptions, quality deteriorations and injury to personnel. He postulates that when the maintenance function performs well, it serves to reduce equipment failure and so improves productivity and safety.

Productivity measurement of the entire production process presents itself as a potential metric of maintenance performance. In order to make this point, Alsyouf (2007) draws attention to the definition of profitability as given by the American Productivity and Quality Centre. The intention is to create a conceptual framework with the aim of demonstrating the benefits of planned maintenance. Profitability is defined as the product of productivity and price recovery. Production organisations are thus perceived to effect two important conversions:

1. Raw materials are transformed into output
2. Output is thereafter transformed into financial assets through economic transactions

Here, the production process is perceived to be a transformative process which converts inputs into outputs. Maintenance is considered to be a key driver in this process and its performance can thus be measured by the productivity of the production process as a whole.

Alsyouf's (2007) intention is to use productivity of the overall production system as a basis for demonstrating the benefits of planned maintenance on production performance. However, his focus is only on improvements that planned maintenance makes on the rate of output generation and the quality rate. In his writing, he makes the assumption that raw material productivity and energy productivity are constant during production. He therefore ignores the possibility that increases in profitability may be achieved by reducing the utilisation of production resources other than time alone. In particular, he ignores the possibility that increases in profitability may result from reduced raw material and energy consumption per unit quantity of quality output.

In response to the work of Alsyouf (2007), Khan and Darrab (2010) performed research at a company over the period of a year to determine if varying the number of maintenance activities and quality hours has an effect on raw material productivity. In their study, raw material productivity is measured by the sum total mass (in tonnes) of raw materials utilised per tonne of output produced. While their data indicates that there may exist a positive relation in the company between resource productivity and the number of maintenance activities conducted, there are a few problems with their research:

1. Firstly, output is defined as the total mass of goods produced regardless of whether it meets quality standards or not. As such, they spuriously conclude that implementing more quality inspections reduces raw material productivity.
2. Secondly, they make use of only twelve data points from which they conduct a regression analysis and draw their conclusions. Furthermore, they tacitly assume in their use of regression analysis that the relationship between the number of maintenance activities, quality hours and resource productivity is necessarily linear in form.

It is thus possible that increasing the intensity of maintenance activities increases raw material productivity. However, because of the lack of evidence brought forth, the result remains inconclusive.

Most recently, Burgoon *et al.* (2012) theorise in a trade journal about the benefits of well planned maintenance practice in terms of energy utilisation. In essence, they suggest that inadequately maintained equipment results in the wastage of energy. They hypothesise that well planned maintenance strategies can lead to better performing machines, ultimately reducing energy usage and lowering overall operating costs.

Burgoon et al. (2012) also recommend that energy utilisation data should be used for predictive purposes. They emphasise that the implementation of machine monitoring strategies can be used to ensure that equipment is not subjected to undue stress. As such, the operating life of machinery can be lengthened.

2.5 Conclusion

A contemporary view of the scope of the maintenance function is to ensure adequate equipment capability. From a broader perspective, its purpose is to ensure adequate production capacity at acceptable levels of cost. Because the maintenance function is essential in supporting production, its measurement is crucial. Kumar *et al.* (2013) summarise the need for maintenance performance measurement as follows:

1. It enables companies to re-evaluate and revise their maintenance policies and techniques
2. It serves as a guide for the revision of resource allocation
3. It enables companies to justify investment in new maintenance techniques

4. It assists in developing an understanding of the true value created by maintenance as well as the effect that the maintenance function has on other functions and stakeholders

If resource productivity bears a relation to maintenance performance, there may be more to the total value of maintenance than is currently appreciated in academia and in industry. However, very little research has been conducted to connect these concepts. Moreover, existing literature is either unsubstantiated by research or it remains inconclusive due to insufficient evidence. This potentially demonstrates that the proposed research area does indeed constitute an important research gap.

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Chapter 3

Research Problem Theory

3.1 Introduction

In this chapter, the necessary framework for this study is formalised and all essential terminology are disambiguated by use of rigorous definitions. Furthermore, crucial results required for establishing the nature of the relationship between maintenance activities and resource productivity are presented.

The main section to follow is broken up into two subsections. In the first subsection, the framework of the study is outlined using an array of definitions. Appropriate measures for maintenance performance and resource productivity are stipulated. Finally, the concepts: inefficiency, failure and wastage are defined. These are potentially required to relate maintenance activities (through their effect on failure and inefficiency) to resource productivity. In the second subsection, two important propositions are presented and proven. From these results, two main conclusions can be derived:

1. The first result in essence states that failure and inefficiency are inextricably related to wastage. This implies that if maintenance activities serve to reduce the rates of failure and inefficiency, then they serve to reduce the rate of resource consumption.

2. The second result loosely implies that inefficiency and failure increases the probability of further failure. This suggests that current maintenance performance has a tendency to affect resource productivity in the present and the future.

3.2 Theoretical Framework

3.2.1 Definitions

The following definitions are sufficient to outline the framework of this study.

Definition 1 *(Production Process) A production process constitutes a set of components which are utilised to transform a given set of inputs into a single type of output which possesses particular characteristics.*

Remark 1 *The term production process here refers to a transformative process. It is a special case of the concept of a system as is commonly defined in Systems Theory. Moreover, the term production process as defined above encompasses far more types of systems than those intended for production of tangible products only. A system used to render a service may for instance constitute a production process.*

Remark 2 *Both energy and time are considered to constitute part of the inputs of production processes. These, along with relevant raw materials, are referred to as resources, production resources, process resources, inputs or process inputs.*

Remark 3 *In the context of a production or service environment, the characteristics which output must possess constitutes its quality specifications. In this context, people and equipment are considered to comprise the components of production processes.*

Remark 4 *In order for the concept of a production process to be applied in practice, if a production plant is capable of producing more than a single type of output, the production plant should be considered to constitute several production processes (one for each type of output it can produce). Only those components relevant in producing each specific type of output should be construed to form part of each individual production process.*

With respect to the broad definition of a production process above, the concept of resource productivity can now be addressed in accordance with its standard form as per Hannula (2000).

Definition 2 *(Resource Productivity) The productivity level of any production resource is given by the quantity of input utilized per unit quantity of output produced.*

The concept of maintenance performance is formalised subject to contemporary views of the purpose of the maintenance function (see section 2.2 for a complete discussion).

Definition 3 *(Maintenance Performance) Maintenance performance is the extent to which the maintenance function (which comprises a set of maintenance activities) serves its purpose in the process of production.*

Given that the maintenance function is considered from an individual machine capability perspective (Muchiri and Pintelon, 2011; Pintelon and van Puyveld, 2006) and a plant wide perspective (Coetzee, 2006; Coetzee, 2013), two measures are ascribed to it. When considering the former perspective, maintenance performance is measured in accordance with the presiding level of equipment capability at a particular point in time. In the latter perspective, maintenance performance is established by measuring the total production capacity generated by the maintenance function over a selected time period.

Theoretical results pertinent to this study are stipulated at the end of this section. In order to express these results free from obscurity, optimal resource productivity must be defined very carefully. A potential confounding factor in the measurement of resource productivity is that input consumption per unit quantity of output often depends on the batch size of inputs processed. Use of the following concept enables this factor to be taken into consideration so that the results of interest can be expressed coherently.

Definition 4 *(Class of Production Processes) A class of production processes is the set of all possible production processes which are capable of processing a given batch of inputs to produce a specific type of output which possesses prespecified (quality) characteristics.*

Remark 5 *Because of the nature of the reference to processing capability in the foregoing definition, each production process may be categorised into several classes of production processes.*

Definition 5 *(Essential Input) An essential input in a production process is an input without which a production process is incapable of producing output with the required (quality) characteristics.*

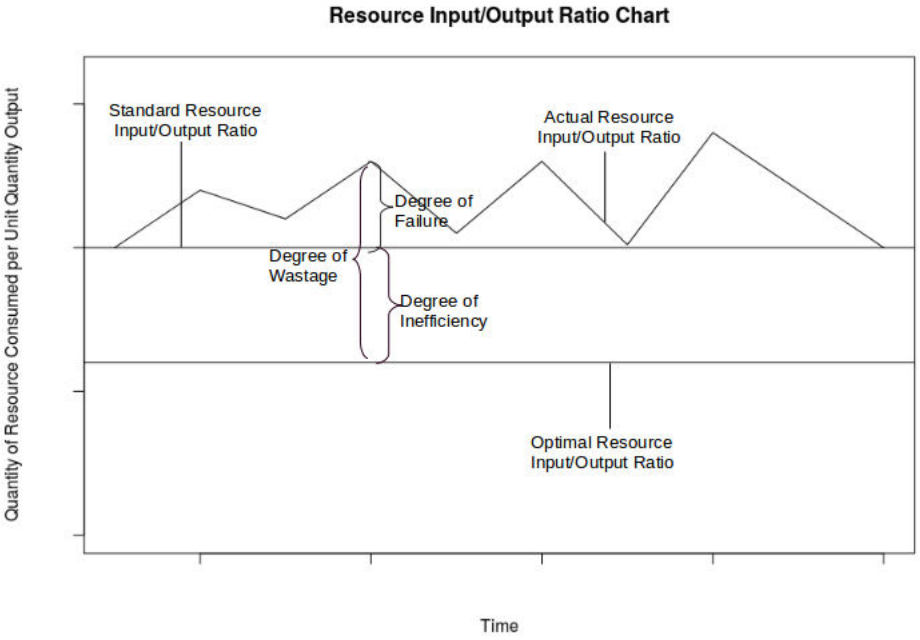

Figure 3.1: Illustration of Definitions

In order to define the concepts of failure, inefficiency and wastage, three important reference points are used. Figure 3.1 gives a very simplified illustrative representation of these reference points. Note that in practice, these reference points need not remain constant in value over time.

1. The optimal input/output ratio represents the absolute minimum resource utilisation from all possible production processes which produce the output of interest.
2. The standard input/output ratio is the minimum ratio that a production process can produce at when all of its components operate at full capability. The standard input/output ratio is limited by the design of the production process.
3. The actual input/output ratio represents the resource usage experienced by the production process when in operation. During operation, components of the production process may deviate from full capability.

Definition 6 *(Optimal Resource Input/Output Ratio) For each essential input in a production process, the optimal input/output ratio is the minimum level of input utilisation per unit quantity of output from all classes which the process belongs to, over all batches of input which the processes in those classes are capable of processing.*

Definition 7 *(Standard Resource Input/Output Ratio) For each essential input in each batch of inputs which a production process can process, the standard input/output ratio is the amount of input per unit quantity of output which the process must consume at minimum to process all the other inputs in the batch into output when every component in the production process is fully functional.*

Definition 8 *(Actual Resource Input/Output Ratio) When a batch of essential inputs is processed using a production process, for each input which is processed, the actual input/output ratio is the quantity of input utilised per unit quantity of output produced.*

Definition 9 *(Inefficiency of a Production Process) For each batch of essential inputs which a production process can process, a process is said to be inefficient if its standard resource input/output ratio exceeds its optimal resource input/output ratio with respect to any of its essential inputs. For each essential input, the degree of inefficiency refers to the difference between the standard input/output ratio and the optimal input/output ratio.*

Remark 6 *It is possible that a process may be inefficient in processing one batch size but may be perfectly efficient in processing another.*

Definition 10 *(Failure) For each batch of essential inputs which a production process can process, a process is said to be subject to failure if its actual resource input/output ratio exceeds its standard resource input/output ratio with respect to any of its essential inputs. For each essential input, the degree of failure refers to the difference between the actual input/output ratio and the standard input/output ratio.*

Remark 7 *The definition of failure above is far more mathematically tractable than the definitions of failure usually presented in Reliability Theory. Furthermore, it is in fact a generalization of such definitions. In Reliability Theory, failure is construed as the the loss of component functionality (see for instance Ascher and Feingold (1984)). Here however, failure is said to occur whenever more resources are required to produce a particular quantity of output than would be required under standard operating conditions.*

To reconcile these concepts, it should be borne in mind that loss of relevant equipment functionality implies loss of output (MESA, 1995). The presence of failure here implies that productivity is reduced. When loss of equipment functionality occurs, it can be said that failure (as used in this context) has occurred.

This definition of failure is certainly broader in scope than that from Reliability Theory. While it includes loss of component functionality, it also encompasses other instances where resources may be wasted. If employees decrease their rate of work or if shrinkage occurs in stock, this definition will indicate that failure has occurred. This is certainly reasonable as employees are considered here to be components of the production process.

Definition 11 *(Wastage) For each batch of essential inputs which a production process can process, wastage is said to occur if the actual resource input/output ratio exceeds the optimal resource input/output ratio with respect to any of the essential inputs. For each essential input, the degree of wastage refers to the difference between the actual input/output ratio and the optimal input/output ratio.*

3.2.2 Propositions

The following results are pertinent to this research.

Proposition 1 *In any production process, for any batch of essential inputs which the production process can process, wastage arises in the production process if and only if failure or inefficiency are prevalent in the production process.*

Proof.
The proof this proposition follows directly from the definitions above.

Consider any batch of n types of inputs which the production process is capable of processing; $n \in \mathbb{N}$. For this batch of inputs, let O_k be the optimal input/output ratio for input k, let S_k be the standard input/output ratio for input k and let A_k be the actual input/output ratio for input k; $O_k, S_k, A_k \in (0, \infty)$ $\forall k \in \{1, 2, ..., n\}$.

Forward Implication: For any batch of inputs which a production process can process, if wastage exists in the production process, then failure and/or inefficiency are prevalent in the process.

Assume that wastage is prevalent in the production process. Then by definition, $\exists i \in \{1, 2, ..., n\}$ such that $A_i > O_i$.

Now, assume for the sake of argument that $A_i = S_i$ (i.e. the production process is not subject to failure as a result of resource i) and $S_i = O_i$ (i.e. the production process is not subject to inefficiency as a result of resource i).

But it is known that $A_i > O_i \Rightarrow A_i \neq S_i$ *or* $S_i \neq O_i$ *or* $A_i \neq S_i$ *and* $S_i \neq O_i$.

Now, by definition, $A_i \geq S_i$ and $S_i \geq O_i$. Thus:
if $A_i \neq S_i \Rightarrow A_i > S_i$ (failure is prevalent)
if $S_i \neq O_i \Rightarrow S_i > O_i$ (inefficiency is prevalent)
if $A_i \neq S_i$ *and* $S_i \neq O_i \Rightarrow A_i > S_i > O_i$ (failure and inefficiency are prevalent)

Thus, it can be concluded that if wastage exists in the production process, then failure and/or inefficiency are prevalent in the process.

Reverse Implication: For any batch of inputs which a production process can process, if failure and/or inefficiency are prevalent in the process, then wastage is prevalent in the process.

By definition, $A_k \geq S_k \geq O_k \ \forall k$.

If inefficiency is prevalent in the production process, $\exists i \in \{1, 2, ..., n\}$ such that $S_i > O_i \Rightarrow A_i > O_i$ (i.e. wastage is prevalent in the process).
If failure is prevalent in the production process, $\exists i \in \{1, 2, ..., n\}$ such that
$A_i > S_i \Rightarrow A_i > O_i$ (i.e. wastage is prevalent in the process).

Thus, it can be concluded that if failure and/or inefficiency are prevalent in the process, then wastage is prevalent in the process. ■

Proposition 2 *Ceteris Paribus, in any production process which can only process a finite amount of input before failing, the likelihood of failure can only increase or remain the same as the production process processes more input.*

Proof. A rigorous proof of this theorem would require the use of Advanced Calculus. As the more technical parts of this proof are not essential for this discussion, only its most important elements are noted here.

Consider any production process which processes n types of input to produce a particular type of output; $n \in \mathbb{N}$. Let x_i be the total amount of input i which has been processed up until this point in time; $i \in \{1, 2, ..., n\}$; $0 \leq x_i < \infty \ \forall i$.

Let the sample space be Ω so that $(x_1, x_2, ..., x_n) \in \Omega$. Let the probability measure of failure be given by P. Then, the probability of failure is given by $F : \Omega \mapsto [0, 1]$ such that $F(x_1, x_2, ..., x_n) = \int_{\{[0,x_1],[0,x_2],...,[0,x_n]\}} dP$.

As F is non-negative over Ω, F increases monotonically over Ω. Thus, the probability of failure cannot decrease as the system processes more input. ■

Corollary 1 *For any two production processes which produce the same type of output with equivalent quality characteristics using the same types of input and* *having produced the same quantity of output while having experienced the same degree of failure, the less efficient production process is subject to an equal or greater likelihood of failure than the more efficient production process.*

Proof. For a particular total quantity of output which is produced, the more efficient production process would have processed fewer inputs than a less efficient production process. As a consequence of the latter proposition, the probability of failure of the production process which has processed more inputs is at least as large as the probability of failure of a system which has processed less inputs. Therefore, the less efficient production process is either equally likely or more likely to fail than the more efficient production process. ■

Similarly, it can be shown that failure affects the likelihood of future failure.

3.3 Conclusion

Besides the establishment of the overall framework of this study, theoretical propositions have been outlined in this chapter which have the potential to be used to describe the relationship between maintenance activities and resource productivity.

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Chapter 4

Research Design and Methodology

4.1 Introduction

The purpose of this research is reprinted below for the sake of easy reference.

The objective of this theoretical and empirical study is to explore the relationship between maintenance activities and resource productivity. The purpose of this exploratory research is threefold:

1. Firstly, this research aims to establish with statistical rigour if a relationship exists between maintenance activities and resource productivity. If a relationship does exist, it aims to establish the nature of the relationship.
2. Secondly, it aims to identify if optimization opportunities exist as a result of such a relationship.
3. Thirdly, it aims to establish if resource productivity may be used as a measure of maintenance performance.

The research questions (stipulated in section 1.2) which address the aforesaid objectives depend heavily on the results of a series of hypothesis tests. The primary aim of this chapter is to describe the logic and design of these hypothesis tests in sufficient detail so that they can be executed and interpreted with the necessary understanding. A detailed description of the company under study is also provided.

4.2 Methodology

A metallurgical organisation in South Africa has been selected for this study. In terms of the objectives of this research work, the company possesses the following essential characteristics:

1. Firstly, to conduct the hypothesis tests, a lot of data is required. As part of its policy, the organisation possesses well maintained information

systems which store data relating to production, resource utilisation and maintenance parameters. This data is readily available for exporting. Furthermore, the company also keeps daily records of resource consumption and production output. Input utilisation and production output can be collated over corresponding time frames to develop the resource productivity ratios required to conduct the hypothesis tests.

2. Secondly, the major aim of this study is to establish if a relationship exists between maintenance performance and resource productivity. To enable the relevant tests to be performed, changes in resource utilisation must be related to several sets of changes in maintenance activities. In part, the organisation is deemed to be fit for this study as it happened to adapt its maintenance policy several times over the period of study. Changes in the company's maintenance policy is described in section 5.2 of the next chapter. For now, it is sufficient to understand that three maintenance regimes were in force over non-overlapping time periods during the period of interest. These are referred to hereinafter as maintenance regime 1, maintenance regime 2 and maintenance regime 3.
3. From a statistical standpoint, sufficient observations are required to ensure that the results of the hypothesis tests are meaningful. To this end, 87 months worth of data are collected. Furthermore, over the period of interest, three plants which produce different types of output are studied, thus increasing data availability several fold. In total, there are 16 key resources which are examined from the production organisation over the period of 87 months giving rise to 1 392 observations.

Important aspects of the company can now be described in detail. Refer to table 4.1 for a summary of the resource related research variables along with their corresponding units of measurement.

For purposes of honouring the company's request to remain anonymous, the aforementioned plants are referred to as Metallurgical Plant 1, Metallurgical Plant 2 and Metallurgical Plant 3. Metallurgical Plant 1 uses four essential raw materials (including water). The raw materials excluding water are measured in terms of tonnes of usage while water consumption is measured in kilolitres. The plant also makes use of three types of energy which are converted to Giga Joules so that the total energy utilised can be aggregated. Time used during the production process is recorded in hours. Metallurgical Plant 2 makes use of four essential raw materials measured in tonnes, water which is measured in kilolitres and energy which is measured in Giga Joules. Metallurgical Plant 3 makes use of a single essential raw material which is measured in tonnes and energy which is measured in Giga Joules. In addition, Metallurgical Plant 1 makes use of a by-product from Metallurgical Plant 2 (also measured in tonnes) and Metallurgical Plant 2 makes use of a by-product from Metallurgical Plant 1 (which is also measured in tonnes). The by-products are recycled from production residue and so they are only available in limited quantities. As such, these by-products are only used as explanatory variables in models so that their effects do not confound the interpretation of results.

The following subsections detail the experimental procedures relevant in testing the hypotheses outlined in section 1.4.

Table 4.1: Units of Resource Variables Studied

Resource Input/Output Ratio	Unit
Metallurgical Plant 1:	
Raw Material 1	Tonne/Tonne
Raw Material 2	Tonne/Tonne
Raw Material 3	Tonne/Tonne
Metallurgical Plant 2 By-product	Tonne/Tonne
Water	Kilolitres/Tonne
Energy	Giga Joules/Tonne
Time	Production Hours/Tonne
Metallurgical Plant 2:	
Raw Material 1	Tonne/Tonne
Raw Material 2	Tonne/Tonne
Raw Material 3	Tonne/Tonne
Raw Material 4	Tonne/Tonne
Metallurgical Plant 1 By-product	Tonne/Tonne
Water	Kilolitres/Tonne
Energy	Giga Joules/Tonne
Time	Production Hours/Tonne
Metallurgical Plant 3:	
Raw Material 1	Tonne/Tonne
Energy	Giga Joules/Tonne
Time	Production Hours/Tonne

4.2.1 Hypothesis 1: Test Procedure

Hypothesis 1 Formulation

Hypothesis 1 is restated below for ease of reference:

Hypothesis 1 *Modifications in maintenance activities are related to changes in the average rates of resource consumption.*

The corresponding null and alternative hypotheses follow:

H_0 : Changes in the average rates of resource consumption are not related to modifications in maintenance activities.
H_1 : Changes in the average rates of resource consumption are related to modifications in maintenance activities.

Basic Test Logic

To test this hypothesis, it must be established if changes in resource utilisation ratios are significantly correlated with changes in maintenance activities. To this end, all 16 resource input/output ratios from all three plants are subjected to regression analysis in turn. Dummy variables for various production formulae utilised and the quantity of by-products utilised are inserted into the model so that these effects do not obscure the effect of the maintenance policies (if any exists). Dummy variables representing the second and third maintenance policies (referred to here as Regime 2 and Regime 3 respectively) are inserted as regression factors and the first maintenance policy (Regime 1) serves as the base variable.

To ensure that all important variables are captured in the regression analyses, for each resource input/output ratio modelled, each model is filled with all variables which may be relevant. These variables are then successively dropped from the models until only the significant variables remain.

The logic applied here is that if the null hypothesis is true, i.e. maintenance policies do not have an effect on average resource consumption, the effects of Regime 2 and Regime 3 should not differ significantly from Regime 1 in any of the resource input/output ratios studied (i.e. they should not show up as significant). However, it may be possible that the maintenance policy variables show up as significant as a result of random chance. If the alternative hypothesis is true, the maintenance policy variables will show up as significant in significant regression analyses in a great number of cases.

To conduct this hypothesis test, it must thus be established if the maintenance regime variables are significant in significantly more regression analyses than are likely to arise by random chance. Maintenance policy variables are tested for significance at a 10% alpha level. Seeing that there are two maintenance policy variables utilised in each set of regression analyses, the chance that at least one of them may show up as significant by random chance is less than 20%. This latter conclusion can be inferred from the work of Donaldson (1966). Donaldson (1966) conducted Monte-Carlo experiments of the F-Test and concluded that under circumstances of non-normality and heteroscedasticity of the underlying data, the chances of type 1 errors decrease.

To account for the aforesaid possibility of random coincidence in the overall hypothesis test, the following overall binomial test form is employed. Let X be the number of resource input/output ratios which, when subjected to regression analyses, lead to the conclusion that maintenance policy variables are significant. Under the null hypothesis stipulated above, X_1 should have a binomial distribution, i.e. $X_1 \sim bin(16, 20\%)$. $E[X_1] = 3.2$ with critical value $X_1 = 5$ at a 10% level of significance for the overall test.

Adjustment for Potentially Inconstant Model Error Variance

A crucial adjustment must be made as a result of one of the key assumptions of linear regression modelling. The model must be homoscedastic, i.e. model errors must be subject to constant variance. Within the framework of this study, hypothesis 2 states that changes in maintenance activities are related to changes in the variance of the rates of resource consumption. However, when executing the test for hypothesis 1, the validity of hypothesis 2 is unknown. As such, it is unknown if the distribution of resource input/output ratios may be affected by the maintenance policies implemented. Therefore, the error variances may differ with each maintenance regime.

To ensure that the foregoing complication does not render the regression models invalid, rigorous methodology is installed to make necessary provision for this possibility. Weighted least squares (WLS) regression is thus utilised for modelling purposes where a weight is estimated for each maintenance regime based on the variances of residuals resulting from preliminary regression analyses. When weighted least squares is performed where each data point is assigned a weight which corresponds with the reciprocal of its variance, the resulting model satisfies the assumption of homoscedasticity with a residual standard error of 1 (Gujarati, 2004). To utilise this technique, a weight corresponding with each maintenance regime must first be established.

To establish regression weights, a preliminary regression analysis can be performed so as to obtain a set of residuals. The variance of the residuals corresponding to each maintenance regime can then be estimated by summing the squares of the residuals and dividing by the corresponding estimated degrees of freedom over the maintenance regime.

To estimate the degrees of freedom corresponding to each maintenance regime, it is assumed that the degrees of freedom of the preliminary model is equally distributed across each data point. This stands to reason because in ordinary least squares, each data point is equally important as all data points are given the same weight. The residual degrees of freedom can thus be apportioned proportionately according to the number of observations in each maintenance regime.

Test Procedure

The relevant regression procedure in studying each of the 16 resource input/output ratios follows:

1. **Ensure that multicollinearity problems will not arise:** Before subjecting any of the resource input/output ratios to regression analysis, check that the model variables pertaining to resource consumption in each plant are not excessively correlated. If the condition number for multicollinearity exceeds 30, multicollinearity problems may exist in the models generated. If this is the case, the number of model variables must be reduced using Ridge Regression techniques before proceeding any further (see for instance Gujarati (2004)).

2. **Establish weights for WLS regression:** Perform a preliminary regression analysis using all variables which may affect the relevant input/output ratio. Calculate the model residuals and categorise them according to maintenance regime. Find the sum of squares of residuals belonging to each maintenance regime. Divide each sum of squares of residuals by the corresponding approximated degrees of freedom. The reciprocal of each of these results yields an approximate weight to be associated with the observations arising from each maintenance regime.

3. **Run WLS using established weights and ensure that model assumptions are met:** Run a WLS regression using the weights established. Check that the model standard error is approximately equal to 1 to ensure that the model is homoscedastic. Check that the model

residuals are normally distributed so that regression results may be endorsed. Razali *et al.* (2011) recommends the Shapiro-Wilk test for this purpose as it has superior statistical power to other available tests.

4. **Drop insignificant model variables:** Check which variables are significant in the regression using Student's T-tests. If any of the variables are significant at a 10% level, these variables should be retained to be used in further regression analysis. If any of the variables do not meet this criterion, another WLS regression using the weights determined from the preliminary model should be run with all other variables excepting the variables which do not show up as significant. Then a Generalised F-Test should be run to ensure that dropping such variables does not make a significant difference to the regression analysis. If it does, at least one of the dropped variables are significant in the model. This (these) variable(s) should be identified and retained. The retained variables constitute the variables of the following model.

5. Repeat step 2, 3 and 4 again using only the variables found to be significant in the initial regression analysis.

To complete the hypothesis test after the regression procedure is conducted for each of the 16 resource input/output ratios, the value of X_1 described above should be established and tested (X_1 = number of resource input/output ratios which, when subjected to regression analyses, are found to be related to maintenance policy variables). To establish the value of X_1, consider the final regression model for each resource input/output ratio. For each resource input/output ratio where at least one of the two maintenance policy dummy variables still remain in the final model, the value of X_1 should be incremented. If the overall test statistic, X_1, is found to be significantly high in value at a 10% alpha level, the null hypothesis can be rejected in favour of the alternative hypothesis. In particular, it can be concluded that average resource consumption is related to maintenance policy.

4.2.2 Hypothesis 2: Test Procedure

Hypothesis 2 Formulation

Hypothesis 2 is stated below for the sake of convenience.

Hypothesis 2 *Modifications in maintenance activities are related to changes in the variance of rates of resource consumption.*

The corresponding null and alternative hypotheses are as follows:

H_0 : Modifications in maintenance activities are not related to changes in the variance of rates of resource consumption.
H_1 : Modifications in maintenance activities are related to changes in the variance of rates of resource consumption.

Basic Test Logic

The relevant logic used to conduct this test is that if the null hypothesis is true, the variance of each of the 16 considered resource input/output ratios should not vary when maintenance policies vary. However, the variances of resource input/output ratios may possibly differ over maintenance regimes as a result of random chance. Thus, for the alternative hypothesis to be adopted, it must be demonstrated that the variances of a significantly large number of the considered input/output ratios differ over the considered maintenance regimes.

To account for the possibility of random changes in resource consumption variance, an overall binomial test is employed after the 16 tests for uniformity of variance have been conducted. To this end, the test statistic, X_2, is defined as the number of resource input/output ratios for which variances differ across maintenance regimes. Under the null hypothesis, the test statistic, X_2, should be binomially distributed. If each variance test is conducted at a 10% level of significance, $X_2 \sim bin(16, 10\%)$. $E[X_2] = 1.6$ with critical value $X_2 = 3$.

Selection of Test of Uniformity of Variances

There are several tests that can be performed to establish if variances of various populations are equal. Amongst them are Levene's test, Barlett's test and the Brown-Forsythe test. Barlett's test has great power when datasets are normally distributed but is very sensitive to departures from normality. Levene's test is far more robust to departures from normality but lacks power when compared with Barlett's test under conditions of normality. The Brown-Forsythe test is a minor variant of Levene's test, but has more power than Levene's test (Good, 2005). The Brown-Forsythe test is thus selected so as to ensure that results remain robust even if slight departures from normality occur.

Brown-Forsythe Test Form

For each resource input/output ratio, the relevant test form for variance uniformity follows (Brown and Forsythe, 1974):

$H_0 : \sigma^2_{1,i} = \sigma^2_{2,i} = \sigma^2_{3,i}$
H_1 : At least one of the three variances (i.e. $\sigma^2_{1,i}, \sigma^2_{2,i}, \sigma^2_{3,i}$) is not equal to the other two

where $\sigma^2_{1,i}, \sigma^2_{2,i}$ and $\sigma^2_{3,i}$ are the variances of resource i; $i = 1, 2, ..., 16$ over maintenance regimes 1, 2 and 3 respectively. The F-value $\sim F(2, 84)$ for a dataset consisting of 87 observations and 3 categories.

4.2.3 Hypothesis 3: Test Procedure

Hypothesis 3 Formulation

Hypothesis 3 is reprinted below:

Hypothesis 3 *Resource consumption rates have a negative monotonic correlation with production capacity.*

The corresponding null and alternative hypotheses follow:

H_0 : Resource consumption rates do not have a negative monotonic correlation with production capacity.
H_1 : Resource consumption rates have a negative monotonic correlation with production capacity.

Basic Test Logic

In order to test this hypothesis, estimates of production capacity are required for each month studied. The organisation aims to produce as much as possible, operating for 24 hours a day, 7 days a week for most of the year. Thus, production capacity can reasonably be estimated using total production as a proxy.

The test logic is simple. Each of the 16 resource input/output ratios are tested to establish if they bear negative monotonic correlations with total production. It is possible that negative monotonic correlations can exist between variables as a result of random chance. If the null hypothesis is true though, few of the resource input/output ratios should show negative monotonic correlations with total production in their corresponding plants. If the alternative hypothesis is true, a large number of the resource input/output ratios will have negative monotonic correlations with the quantity of output generated.

To account for the possibility that resource input/output ratios may have a significant negative monotonic correlation with production because of random coincidence, an overall binomial test is implemented. For this purpose, the test statistic, X_3, is defined as the number of resource input/output ratios which have significant negative monotonic correlations with total production. The test statistic is binomially distributed under the null hypothesis. If each test for correlation is conducted at a 10% level of significance, then under the null hypothesis, $X_3 \sim bin(16, 10\%)$. $E[X_3] = 1.6$ with a critical value, $X_3 = 3$, if the overall test is conducted at a 10% level of significance.

Confounding Factors

There are a few factors which may obscure the tests for negative monotonic correlations between resource input/output ratios and total production capacity. The most important of these follow:

1. Rates of resource consumption may be affected when production formulae are modified.

2. Rates of resource consumption may be affected when the quality of raw materials change.

Fortunately, these confounding factors tend to have the effect of making the results of this test more prudent. Monotonic correlations are less likely to show up as significant as a consequence of these factors.

Spearman's Ranked Correlation Test Form

The monotonic relationships between resource input/output ratios and total production need not be linear in form. Thus, Pearson's correlation test is inappropriate as it tests for linear correlations. However, Spearman's ranked correlation test tests for more general monotonic correlations (Conover, 1971). Each of the 16 resource input/output ratios can be tested for a negative monotonic correlation with production capacity using Spearman's ranked correlation test.

The null and alternative hypotheses of Spearman's ranked correlation test for each of the 16 tests are as follows (Conover, 1974):

$H_0 : \rho_i = 0$
$H_1 : \rho_i < 0$
where ρ_i is a measure of monotonic correlation between resource input/output ratio i and its corresponding level of production capacity; $i = 1, 2, ..., 16$.

4.2.4 Hypothesis 4: Test Procedure

Hypothesis 4 Formulation

Hypothesis 4 is reprinted below:

Hypothesis 4 *Increases in resource consumption rates are related to the manifestation of defects in machinery.*

The corresponding null and alternative hypotheses follow:

H_0 : Increases in resource consumption rates are not associated with the manifestation of defects in machinery.
H_1 : Increases in resource consumption rates are associated with the manifestation of defects in machinery.

Basic Test Logic

In order to test this hypothesis, per shift data must be procured which reflects increases in resource consumption rates and also reflects machinery defects that were reported. A contingency table is set up which records the number of instances where resource consumption ratios increased and machinery defects were reported. If the null hypothesis is true, these events will be shown to be statistically independent. If the alternative hypothesis is true, these events will show up as statistically dependent. The simple χ^2 test of independence is sufficient to test this hypothesis (see Hogg and Tanis (2006)). The relevant test statistic here, X_4, has the distribution $X_4 \sim \chi^2(1)$

Test Rigour

The test form as described above requires the construction of a 2×2 contingency table. Hogg and Tanis (2006) stipulate that the test is known to be rigorous provided that $\frac{\sum_i cell_{i,j} \times \sum_j cell_{i,j}}{\sum_i \sum_j cell_{i,j}} \geq 5$ for row $i = 1, 2$ and column $j = 1, 2$. If this condition is not met, Fisher's exact test should instead be utilised to guarantee correct inference.

Confounding Factors

Once again, there are a few factors which may obscure the results of this test. The following are chief amongst them:

1. Modification of production formulae
2. Changes in the quality of raw materials

Again, these confounding factors tend to have the effect of making the results of this test more conservative.

4.3 Conclusion

In this chapter, it has been demonstrated that it is possible to conduct tests to establish the truth of each of the stipulated hypotheses. In the following chapter, these hypothesis tests are implemented.

Chapter 5

Research Results and Robustness

5.1 Introduction

Thus far, the purpose and objectives of this study have been outlined and four research questions have been designed to achieve those objectives. Hypotheses have been proposed to assist in answering the research questions. The hypotheses of course must first be tested before they can be utilised to answer the research questions and so achieve the objectives of this study. The methodology pertaining to the hypothesis tests are outlined in chapter 4.

In this chapter, the hypothesis tests are implemented with the aid of the statistical package R to obtain the necessary information to answer the research questions. The first section of this chapter is devoted to a detailed description of the data collected for use in the hypothesis tests. In the following sections, the data is utilised to perform all required hypothesis tests.

5.2 Description of the Sample

The selected period of study ranges between March 2007 and May 2014 totalling a period of 87 months. Over this period, the data collected from the cost accounting system and breakdown record system of the metallurgical organisation under study have the following characteristics:

1. Over the period of study, the organisation in question managed three plants, each of which produce different products. Each of these plants operated for 24 hours a day, 7 days a week for the majority of each year with four production shifts per day. However, there are periods during which these plants were shut down to conduct maintenance procedures. For purposes of testing the first three hypotheses, monthly aggregated electronic cost accounting data is collected over the entire period of study. Graphs of the resource consumption data collected are shown in appendix A.

2. Per shift resource utilisation data is required for testing hypothesis 4. However, daily resource consumption data is aggregated over the four daily production shifts and thus, per shift data is inaccessible. Furthermore, under most cases, daily resource consumption data is averaged thus rendering it meaningless for testing hypothesis 4. Fortunately, disaggregated daily resource utilisation data has been retrieved for a period of a year for Metallurgical Plant 2 and can thus be used to test hypothesis 4 after a minor modification is made to the test form. See section 5.3.4 for details.

3. The first two hypotheses make postulations regarding changes in the rates of resource consumption over various sets of maintenance activities. Therefore, resource consumption data for various sets of maintenance activities is required to test these hypotheses. Over the period of interest, three maintenance policies were sequentially put in place. During the first maintenance regime, maintenance management was outsourced to an external company. Their tenure is studied for a period of 36 months. In 2010, the company took control of their maintenance activities for a period of 18 months. Thereafter, a maintenance planning improvement programme was facilitated by a third company. This thus gives rise to three maintenance policies over the period of interest which can be distinguished by the periods over which they were instituted.

4. It is essential to note that the organisation renders itself to continuous improvement. Such actions may have effects on the analysis of resource consumption ratios. During the 87 months subjected to study, the organisation experimented with 10 different production formulae in Metallurgical Plant 1, 8 different production formulae in Metallurgical Plant 2 and 7 different production formulae in Metallurgical Plant 3.

5. Changes in the source of raw material procurement may also affect the analysis of resource consumption. A salient point during the history of the company must be noted. During 2009, the organisation under study could not acquire the correct raw materials for production. The company therefore procured inappropriate substitutes which, when used, irreparably damaged the furnaces in Metallurgical Plant 2 and Metallurgical Plant 3. In assessing these plants, a factor must be inserted into the models to account for this so that its effects do not obscure the inference of information.

5.3 Analysis of Data

5.3.1 Hypothesis 1

Formulation of Hypothesis 1

Hypothesis 1 is reprinted below for ease of reference along with its corresponding null and alternative hypotheses:

Hypothesis 1 *Modifications in maintenance activities are related to changes in the average rates of resource consumption.*

H_0 : Changes in the average rates of resource consumption are not related to modifications in maintenance activities.
H_1 : Changes in the average rates of resource consumption are related to modifications in maintenance activities.

As explained in section 4.2.1, this hypothesis is tested by performing regression analysis on each of the 16 resource input/output ratios with maintenance policy dummy variables as regression variables. The null hypothesis above can be rejected if any of the maintenance policy variables are shown to have a significant effect in at least 5 significant regression analyses of the resource input/output ratios studied.

Case Study

As noted above, to test hypothesis 1, all 16 resource input/output ratios must be subjected to regression modelling. This entails an immense amount of analysis. Because the analysis is more or less similar for each resource input/output ratio, it would be unnecessarily cumbersome to record the details of each regression model here. However, to exemplify the process, the first raw material input/output ratio from Metallurgical Plant 1 is subjected to a detailed regression analysis. Analysis of all other production process resource input/output ratios is summarised in appendix B.

In the following case study, the regression routine stipulated in section 4.2.1 is adhered to.

Test for Multicollinearity

Multicollinearity arises when there are strong linear correlations between regression variables (Gujarati, 2004). Multicollinearity has the potential to impede inference from regression analysis as it has effects on the the standard deviations of the estimated regression coefficients (Gujarati, 2004). Therefore, the possibility of multicollinearity must be ruled out before further analysis can take place.

To test for the possibility of multicollinearity, condition numbers are computed. These condition numbers should preferably not exceed 30 or multicollinearity problems may manifest (Gujarati, 2004). Table 5.1 gives the condition numbers associated with the regressors (regression variables) to be used in analysing the resource input/output ratios from each plant. Although the condition number exceeds 30 for regression variables relevant to Plant 2 and Plant 3, removing a single variable from each regression analysis generally reduces the condition number to less than 10. In other words, any existent multicollinearity problem may be resolved by dropping a single variable from any of the regression analyses conducted. It is thus safe to assume that multicollinearity will not present a problem in this study.

Preliminary Regression Model

Dummy variables must be assigned to represent the effects of the maintenance regimes on the resource input/output ratios. Over the period considered, three

Table 5.1: Condition Numbers for the Variables Relevant to Each Plant

Plant	Condition Number
Metallurgical Plant 1	9.636634
Metallurgical Plant 2	84.80185
Metallurgical Plant 3	71.41873

maintenance regimes were put in place as was explained in section 5.2. However, because of the mechanics of regression analysis, only two of the three dummy variables related to maintenance policies can be explicitly inserted into the regression models. For this purpose, regime 2 and regime 3 are selected. The effect of the regime 1 thus forms part of the intercept term in regression. If regime 2 or regime 3 show up as significant, it implies that the average resource input/output ratio in question over regime 2 or regime 3 differs significantly from the average resource input/output ratio observed over regime 1.

As noted before, as a result of the firm's attempts at continuous improvement, 10 unique production formulae have been utilised in Metallurgical Plant 1 over the period studied. Dummy variables must be inserted to account for each of their effects lest their effects bias the regression analysis. The effect of the most basic production formula is included in the intercept term. Furthermore, to ensure that the use of the recycled by-product from Plant 2 does not confound the regression analyses, the by-product input/output ratio must also be included in regression analyses pertaining to Plant 1.

The following model is proposed for the first raw material input/output ratio of Metallurgical Plant 1:

Raw Material 1 I/O Ratio $= \beta_0 + \beta_1$.(Maintenance Regime 2) $+$
β_2.(Maintenance Regime 3) $+$ β_3.(Qty of Plant 2 By-product Used) $+$
β_4.(Formula 1 Used) $+$ β_5.(Formula 2 Used) $+$ β_6.(Formula 3 Used) $+$
β_7.(Formula 4 Used) $+$ β_8.(Formula 5 Used) $+$ β_9.(Formula 6 Used) $+$
β_{10}.(Formula 7 Used) $+$ β_{11}.(Formula 8 Used) $+$ β_{12}.(Formula 9 Used) $+ \varepsilon$;
where $\beta_i \in \mathbb{R}, i = 0, 1, ..., 12$; $\varepsilon \sim N(0, \sigma^2)$

Obtaining the Required Model Weights from a Preliminary Regression Analysis

To ensure that the regression models are homoscedastic (i.e. model residuals have constant variance), WLS regression must be employed (see section 4.2.1 for details). For this purpose, model weights are required.

To find appropriate weights for the observations corresponding to each maintenance regime, the reciprocal of the error variance is required. To this end, a preliminary regression analysis is run and the sum of squares of model errors associated with each maintenance regime is determined (this is referred to as RSS in table 5.2). The variance of the residuals corresponding with each maintenance regime can be approximated as follows: $Error\ Variance = \frac{RSS}{df}$

where *df* is the degrees of freedom corresponding with each maintenance regime.

To estimate the error degrees of freedom associated with each maintenance regime, it is borne in mind that degrees of freedom are related to information. Because the preliminary regression analysis is of the ordinary least squares (OLS) variety, information is extracted equally from all observations. Therefore, after estimation, the remaining degrees of freedom corresponding with each maintenance regime should be distributed equally in accordance with the number of observations in each regime.

There are 87 observations in the dataset. Therefore, after all 13 initial model coefficients are estimated in the preliminary model of raw material 1 from Plant 1, there are 74 remaining degrees of freedom. Now, there are in total 36 observations in the first maintenance regime, 18 in the second maintenance regime and 33 observations in the third maintenance regime. Therefore, it can be concluded that $\frac{36}{87} \times 74$ degrees of freedom belongs to the observations from the first maintenance regime, $\frac{18}{87} \times 74$ degrees of freedom belongs to the observations from the second maintenance regime and $\frac{33}{87} \times 74$ degrees of freedom belong to the observations from the third maintenance regime. A summary of the computation of the model error variance for all three maintenance regimes resulting from the preliminary regression analysis is given in table 5.2.

Table 5.2: RSS and Degrees of Freedom Corresponding to each Maintenance Regime Resulting from the Preliminary Regression Analysis of Raw Material 1 I/O Ratio

Maintenance Regime	RSS	Deg. of Freedom	Residual Error Variance
Maintenance Regime 1	0.7040	$\frac{36}{87} \times 74$	0,0230
Maintenance Regime 2	0.2997	$\frac{18}{87} \times 74$	0,0196
Maintenance Regime 3	0.4375	$\frac{33}{87} \times 74$	0,0156

Finally, the required model weights for each observation in each regime can be computed. These weights are taken as the reciprocal of the estimated residual error variance corresponding to each regime listed in table 5.2. The resulting model weights are listed in table 5.3.

Table 5.3: Weights of Initial Model of Raw Material 1 I/O Ratio

Maintenance Regime	Weight Ascribed
Regime 1	$0{,}0230^{-1} = 46.4310$
Regime 2	$0{,}0196^{-1} = 54.5344$
Regime 3	$0{,}0156^{-1} = 68.4879$

Initial WLS Regression Analysis

Finally, the initial WLS regression model can be formulated by assigning the weights in table 5.3 to the model form of the preliminary regression analysis. The regression results in table 5.4 are thus obtained.

Table 5.4: Metallurgical Plant 1 - Raw Material 1 I/O Ratio Regression Results

	Dependent variable:
	Raw Material 1 I/O Ratio
Maintenance Regime 2	0.060
	(0.049)
Maintenance Regime 3	0.081^{*}
	(0.045)
Qty of Plant 2 By-product Used	−1.783
	(1.152)
Formula 1 Used	0.058
	(0.117)
Formula 2 Used	-0.245^{***}
	(0.044)
Formula 3 Used	0.242^{*}
	(0.135)
Formula 4 Used	−0.053
	(0.133)
Formula 5 Used	-0.358^{***}
	(0.097)
Formula 6 Used	-0.404^{***}
	(0.080)
Formula 7 Used	-0.229^{***}
	(0.063)
Formula 8 Used	-0.475^{***}
	(0.116)
Formula 9 Used	−0.140
	(0.134)
Constant	0.693^{***}
	(0.050)
Observations	87
R^2	0.540
Adjusted R^2	0.466
Residual Std. Error	1.000 (df = 74)
F Statistic	7.252^{***} (df = 12; 74)
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Testing the Initial WLS Regression Model to Ascertain that Model Assumptions are Fulfilled

If the weighted least squares procedure is successful in ensuring homoscedasticity (equal error variance), then the residual standard error of the initial WLS regression model should be equal to 1. At the bottom of table 5.4, it can be observed that this is the case. Therefore, it can be concluded that there was either no heteroscedasticity (unequal error variance) problem to begin with or the WLS transformation employed corrected the problem.

Another key assumption in the modelling process which is very important for inference is that the model errors are normally distributed. To establish if the residual error terms have a normal distribution as is specified in the model design, the Shapiro Wilk normality test is employed on the residuals of the model. The test has the following form:

H_0 : The residuals are normally distributed.
H_1 : The residuals are not normally distributed.

Running the Shapiro Wilk normality test, a test value of $W = 0.9856$ is obtained with a p-value $= 0.4509$. There is clearly insufficient evidence to reject the null hypothesis at a 10% level of significance and therefore, it can be concluded that the residuals are likely to be normally distributed. The results of the regression analysis can thus be endorsed.

To ensure that the overall regression model is significant, the following hypothesis test can now be run:

H_0: None of the regressors describe the variation of the input/output ratio of Raw Material 1
H_1: At least one of the regressors describe the variation of the I/O ratio of Raw Material 1

The F-statistic for this test (as shown in table 5.4) has a value of 7.252 and a corresponding p-value < 0.01. The null hypothesis can thus be rejected at a 1% alpha level in favour of the alternative hypothesis. It is concluded that it is very likely that at least one of the variables in the regression model account for the variation of the I/O ratio of Raw Material 1.

Dropping Insignificant Regression Variables in the Initial WLS Regression Model

The following battery of tests can now be run to assess which variables are significant in the regression model:

H_0: $\beta_i = 0$
H_1: $\beta_i \neq 0$; $i = 1, 2, ..., 13$

According to the results listed in Table 5.4, H_0 can be rejected at a 10% level of significance for every regression variable except for the following regressors:

1. Maintenance Regime 2

2. Qty of Plant 2 By-product Used
3. Formula 1 Used
4. Formula 4 Used
5. Formula 9 Used

There is insufficient evidence to conclude that the listed regressors are significant in the initial model. In accordance with the procedure listed in section 4.2.1, these regressors can be considered for removal from the model. However, before removing these regressors from the model, it must first be ascertained that removal of any of these regressors will not affect the regression model adversely. Each of these regressors are thus subjected to the following F-test. The test compares the overall model standard error with the resulting model standard error if one of these variables are removed.

H_0: Removing the regressor from the model makes no difference to the model.
H_1: Removing the regressor from the model makes a difference to the model.

Table 5.5 lists the RSS of the models which result when each of the variables are dropped from the initial model as well as the p-value of the corresponding difference test. The null hypothesis cannot be rejected at a 10% level of significance for any of the model regressors considered. When all these variables are dropped simultaneously, the null hypothesis can still not be rejected. There is no evidence to conclude that these variables are necessary in the regression model. All of them will thus be removed.

Table 5.5: Tests of Effects of Removing Variables from Initial Model

Regressor to be Dropped	Model RSS when Removed	p-value
Maintenance Regime 2	75.506	0.2222
Qty of Plant 2 By-product Used	0 76.384	0.1261
Formula 1 Used	74.241	0.6179
Formula 4 Used	74.151	0.6896
Formula 9 Used	75.094	0.2969
All Listed Regressors	77.942	0.4194

Refined WLS Regression Model

To refine the initial model, a second WLS model is setup. The model consists of all regression variables which are retained from the initial WLS model. The next model is thus constructed as follows:

Raw Material 1 I/O Ratio = β_0 + β_1.(Maintenance Regime 3) + β_2.(Formula 2 Used) + β_3.(Formula 3 Used) + β_4.(Formula 5 Used) + β_5.(Formula 6 Used) + β_6.(Formula 7 Used) + β_7.(Formula 8 Used) + ε; where
$\beta_i \in \mathbb{R}, i = 0, 1, ..., 7$; $\varepsilon \sim N(0, \sigma^2)$

A preliminary OLS regression analysis is run using the foregoing model in order to obtain the model weights required for the second WLS regression model. These model weights are listed in table 5.6. The results of the second WLS regression appears in table 5.7.

Table 5.6: Weights of Second Model of Raw Material 1 I/O Ratio

Maintenance Regime	Weight Ascribed
Regime 1	42.2785
Regime 2	48.7899
Regime 3	64.3161

Table 5.7: Metallurgical Plant 1 - Raw Material 1 I/O Ratio Regression Results

	Dependent variable:
	Raw Material 1 I/O Ratio
Maintenance Regime 3	0.057^{*}
	(0.034)
Formula 2 Used	-0.223^{***}
	(0.038)
Formula 3 Used	0.236^{*}
	(0.130)
Formula 5 Used	-0.351^{***}
	(0.096)
Formula 6 Used	-0.400^{***}
	(0.077)
Formula 7 Used	-0.208^{***}
	(0.058)
Formula 8 Used	-0.516^{***}
	(0.114)
Constant	0.662^{***}
	(0.035)
Observations	87
R^2	0.500
Adjusted R^2	0.456
Residual Std. Error	1.000 (df = 79)
F Statistic	11.287^{***} (df = 7; 79)
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Testing the Refined WLS Model to Ascertain that Model Assumptions are Fulfilled

Once again, to establish that the model meets the assumption of constant error variance, it is noted the residual standard error has a value of 1 indicating that the model is homoscedastic. To check if the model conforms to the normality assumption, the Shapiro Wilk test is run on the refined model residuals:

H_0 : The residuals are normally distributed.
H_1 : The residuals are not normally distributed.

In running the Shapiro Wilk normality test, a test value of $W = 0.9793$ is obtained with a p-value $= 0.1768$. The null hypothesis cannot be rejected at a 10% level of significance and therefore, it can be concluded that the residuals are likely to be normally distributed. The results of the regression stipulated in table 5.7 can thus be endorsed.

To establish if the refined regression model is significant, the regression model is subjected to the following test:

H_0: None of the regressors describe the variation of the input/output ratio of Raw Material 1.
H_1: At least one of the regressors describe the variation of the I/O ratio of Raw Material 1.

H_0 is rejected at a 1% alpha level. It can therefore be concluded that at least one of the regression variables are significant in describing the consumption of Raw Material 1.

Dropping Insignificant Regression Variables in Refined Regression Model

The following battery of tests can now be run for each coefficient of each variable in the regression model so as to eliminate any unnecessary regression variables:

H_0: $\beta_i = 0$
H_1: $\beta_i \neq 0; i = 1, 2, ..., 7$

H_0 can be rejected at a 10% level of significance in the case of every coefficient in the model. Every model coefficient seems to be significant. This model is thus endorsed.

Conclusion of Case Study

It can be observed that the regression model is significant and at least one maintenance policy variable remains in the final model (see table 5.7). It can thus be concluded that the maintenance policies have an effect on the consumption rate of raw material 1 from Plant 1.

Conclusion of Hypothesis Test

A similar analysis is conducted for all the other 15 production resources considered (see appendix B for details). A summary of the most important results from this set of analyses are presented in table 5.8. The following conclusions can now be drawn:

Table 5.8: Pertinent Regression Results

Resource I/O Ratio	*Significant at 10% Level (True/False)* Overall Regression	Regime 2	Regime 3	Production Formulae
Metallurgical Plant 1:				
Raw Material 1	True	False	True	True
Raw Material 2	True	True	True	True
Raw Material 3	True	True	True	True
Water	True	True	False	True
Energy	True	False	False	True
Time	True	True	True	True
Metallurgical Plant 2:				
Raw Material 1	True	True	True	True
Raw Material 2	True	True	True	True
Raw Material 3	True	False	False	True
Raw Material 4	True	True	False	True
Water	True	False	True	True
Energy	True	True	False	True
Time	True	False	False	True
Metallurgical Plant 3				
Raw Material 1	True	True	False	True
Energy	True	False	True	True
Time	False	False	False	False

1. With the exception of the models constructed for the time input/output ratio of Metallurgical Plant 3, every other regression model is found to be statistically significant, i.e. at least one of the variables in each of the formulated models describes some of the variation of the resource input/output ratios.

2. In terms of the homoscedasticity assumption, the residual standard errors for the models are approximately equal to 1 in every case. Maintenance policy either does not affect the resource consumption variance or the WLS procedure employed resolves the problem.

3. As is to be expected, the production formulae generally have a significant effect on resource consumption. In fourteen out of the sixteen resources considered, at least one production formula is statistically significant.

4. The test can now be completed. In 12 out of 16 resource input/output ratios studied, at least one of the maintenance policy factors are significant at a 10% level indicating a difference between average resource consumption between regime 2, regime 3 and regime 1. The overall binomial test can now be run to account for the possibility of random coincidence in the regression analyses conducted. The test

statistic, X_1, referred to in section 4.2.1 has a value of $X_1 := 12$. The corresponding p-value of the test is $p < 0.00000025$. There is thus sufficient evidence to reject the null hypothesis at a 1% level of significance in favour of the alternative hypothesis. It can be concluded that maintenance activities are related to average resource consumption.

5.3.2 Hypothesis 2

Formulation of Hypothesis 2

Hypothesis 2 along with its corresponding null and alternative hypotheses are restated below.

Hypothesis 2 *Modifications in maintenance activities are related to changes in the variance of rates of resource consumption.*

H_0 : Modifications in maintenance activities are not related to changes in the variance of rates of resource consumption.
H_1 : Modifications in maintenance activities are related to changes in the variance of rates of resource consumption.

As noted in section 4.2.2, if the null hypothesis is true, the variance of resource consumption rates should not vary when maintenance policies vary in more than 3 of the resource input/output ratios considered. If the alternative hypothesis is true, at least 3 resource input/output ratios will be affected by changes in maintenance policy. Use is made of the Brown-Forsythe test to establish if the variances of resource input/output ratios remain consistent over various maintenance policies. The test form is reprinted below:

$H_0 : \sigma^2_{1,i} = \sigma^2_{2,i} = \sigma^2_{3,i}$
H_1 : At least one of the three variances (i.e. $\sigma^2_{1,i}, \sigma^2_{2,i}, \sigma^2_{3,i}$) is not equal to the others

where $\sigma^2_{1,i}, \sigma^2_{2,i}$ and $\sigma^2_{3,i}$ are the variances of the resource i; $i = 1, 2, ..., 16$ over maintenance regimes 1, 2 and 3 respectively.

The F-value $\sim F(2, 84)$ for a dataset consisting of 87 observations and 3 categories.

Conclusion of Hypothesis Test

Table 5.9 lists the results of the battery of uniformity of variance tests. The results indicate that the null hypothesis for equality of variances can be rejected at a 10% level of significance for 7 of the 16 resource input/output ratios studied. The overall test statistic, X_2, therefore has a value $X_2 := 7 > 3$ (see section 4.2.2 for details of the overall test). The p-value for the overall test is $p = 0.0000614$. Thus, there is sufficient evidence to reject the null hypothesis of hypothesis 2 and conclude that the variance of resource utilisation is related to the maintenance policy in place.

Table 5.9: Test of Equality of Variances of Resource Input/Output Ratios over 3 Maintenance Regimes

Resource Input/Output Ratio	F Statistic	p-value	Significant
Metallurgical Plant 1:			
Raw Material 1	4.3469	0.01598	True
Raw Material 2	3.6097	0.03134	True
Raw Material 3	4.0112	0.02169	True
Water	1.5842	0.2112	
Energy	7.1937	0.0013	True
Time	7.3685	0.0011	True
Metallurgical Plant 2:			
Raw Material 1	0.0098	0.9902	
Raw Material 2	0.1681	0.8455	
Raw Material 3	0.0348	0.9659	
Raw Material 4	0.0509	0.9504	
Water	2.7631	0.06884	True
Energy	0.2225	0.801	
Time	1.2253	0.2989	
Metallurgical Plant 3:			
Raw Material 1	10.347	0.0001	True
Energy	0.9712	0.3829	
Time	0.9704	0.3831	

5.3.3 Hypothesis 3

Formulation of Hypothesis 3

Hypothesis 3 is reprinted below along with its corresponding null and alternative hypotheses:

Hypothesis 3 *Resource consumption rates have a negative monotonic correlation with production capacity.*

H_0 : Resource consumption rates do not have a negative monotonic correlation with production capacity.
H_1 : Resource consumption rates have a negative monotonic correlation with production capacity.

The procedure established in section 4.2.4 requires use to be made of Spearman's ranked correlation test to establish if each of the 16 resource input/output ratios have a negative monotonic correlation with total production in their respective plants. The null and alternative hypotheses of this test are as follows (Conover, 1974):

$H_0 : \rho_i = 0$
$H_1 : \rho_i < 0$

where ρ_i is a measure of monotonic correlation between resource input/output ratio i and its corresponding level of production capacity; $i = 1, 2, ..., 16$.

Conclusion of Hypothesis Test

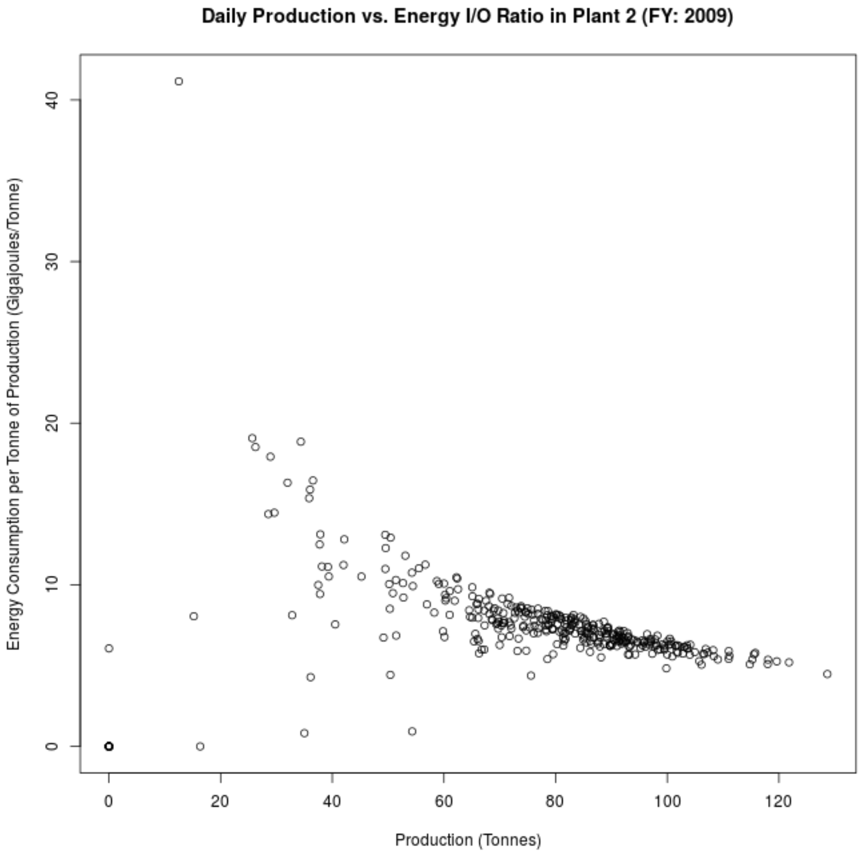

Figure 5.1: Graph of Production vs Energy Input/Output Ratio in Plant 2 during the 2009 Financial Year

Table 5.10 gives a summary of all 16 ranked correlation tests run. Of the 16 resource input/output ratios tested, 10 of them show a significant negative monotonic relationship with total production where the tests are conducted at a 10% level of significance. To account for the possibility of random coincidence in the ranked correlation tests, an overall binomial test is run. The binomial test statistic has a value of $X_3 := 10$ with a corresponding p-value of $p = 0.00000003$. The null hypothesis can be rejected at a 1% level of significance in favour of the alternative hypothesis. It can be concluded that resource consumption tends to have a negative monotonic correlation with production capacity. To make clear what this hypothesis suggests, figure 5.1 exemplifies what the relationship between resource consumption ratios and total production tends to look like when observed on a daily basis.

Table 5.10: Tests of Negative Monotonic Relations Between Resource I/O Ratios and Total Production Capacity

Resource Input/Output Ratio	Spearman's ρ	p-value	Significant
Metallurgical Plant 1:			
Raw Material 1	-0.0677	0.2666	
Raw Material 2	-0.1161	0.142	
Raw Material 3	0.1058	0.8352	
Water	-0.6731	< 0.00005	True
Energy	-0.0498	0.3234	
Time	-0.5013	< 0.00005	True
Metallurgical Plant 2:			
Raw Material 1	-0.3121	0.0016	True
Raw Material 2	-0.2283	0.0167	True
Raw Material 3	-0.2624	0.007	True
Raw Material 4	-0.394	0.0001	True
Water	-0.5326	< 0.00005	True
Energy	-0.5332	< 0.00005	True
Time	-0.6154	< 0.00005	True
Metallurgical Plant 3:			
Raw Material 1	-0.0202	0.4264	
Energy	-0.3924	0.0001	True
Time	-0.1288	0.1172	

5.3.4 Hypothesis 4

Formulation of Hypothesis 4

The relevant hypothesis and its corresponding null and alternative hypotheses are restated here for ease of reference.

Hypothesis 4 *Increases in resource consumption rates are related to the manifestation of defects in machinery.*

H_0 : Increases in resource consumption rates are not associated with the manifestation of defects in machinery.
H_1 : Increases in resource consumption rates are associated with the manifestation of defects in machinery.

Test Implementation

To test this hypothesis, a contingency table must be drawn up which relates increases in resource input/output ratios to reported machinery defects. A year's worth of data reflecting daily resource consumption in Plant 2 is used to assist in testing this hypothesis. As it turns out, resource utilisation is not recorded per shift but rather per day. Information from the organisation's Enterprise Resource Planning (ERP) system, JD Edwards, is used to match reported production process faults with daily resource consumption. Unfortunately, data obtained does not reflect the date on which the fault was logged but rather the scheduled point in time for repairs to be performed.

In order to make inferences from the dataset, it is assumed that repairs are scheduled on the day of the problem arising or on the following day. Furthermore, in some instances, Plant 2 was shut down for repairs. Whenever any resource input/output ratios increase on the day of Plant 2 shutting down for repairs or the day prior to Plant 2 being shut down for repairs, the increase in resource consumption rates are associated with any faults logged during the period when the plant is shut down.

Conclusion of Hypothesis Test

Table 5.11 summarises the incidents during the selected year regarding increases in resource consumption rates and reported defects in equipment. In total, defects were reported on 51 days during the year and each of those days are associated with increases in resource consumption ratios. The contingency table conforms to the requirement that $\frac{\sum_i cell_{i,j} \times \sum_j cell_{i,j}}{\sum_i \sum_j cell_{i,j}} \geq 5$ for row $i = 1, 2$ and column $j = 1, 2$ and so the χ^2 test results can be endorsed (Hogg and Tanis, 2006). The relevant test statistic, $X_4 := 6.5096$ with a corresponding $p - value = 0.0107$. Therefore, the null hypothesis can be rejected at a 5% level of significance. It can be concluded that increases in rates of resource consumption are associated with defects in equipment.

Table 5.11: Contingency Table for Increases in Resource I/O Ratios and Reported Equipment Defects

	I/O Ratios Increased	No I/O Ratios Increased	Total
Defect Reported	51	0	51
Defect Not Reported	277	36	313
Total	328	36	364

5.4 Conclusion

As a result of the hypothesis tests run in this section, the following conclusions are manifest:

1. Modifications in sets of maintenance activities are related to changes in the average and the variance of rates of resource consumption.
2. Resource consumption rates have a negative monotonic correlation with production capacity.
3. Increases in resource consumption rates are associated with machine defects.

Chapter 6

Conclusions and Implications

6.1 Introduction

The objectives of this research are repeated below once again for ease of reference.

The purpose of this theoretical and empirical study is to explore the relationship between maintenance activities and resource productivity. The purpose of this exploratory research is threefold:

1. Firstly, this research aims to establish with statistical rigour if a relationship exists between maintenance activities and resource productivity. If a relationship does exist, it aims to establish the nature of the relationship.
2. Secondly, it aims to identify if opportunities for productivity enhancement exist as a result of such a relationship.
3. Thirdly, it aims to establish if resource productivity may be used as a measure of maintenance performance.

To achieve these objectives, four research questions have been designed (see figure 1.1 for a schematic flow chart which indicates how the research questions are used to achieve the research objectives). In order to answer the research questions and so achieve the objectives of this study, two propositions are proven and four hypotheses are postulated. The tests designed in chapter 4 and implemented in chapter 5 confirm that these hypotheses can be endorsed.

In this chapter, the research questions are answered using the aforesaid propositions and hypotheses. The answers to the research questions are then combined to achieve the objectives of the study.

Given the fact that this research is born out of a research gap, the knowledge that is gained through achieving the research objectives are related to the existing body of literature in order to demonstrate that the purpose of the study has been fulfilled. Finally, the implications of this study are discussed and recommendations are made for further research.

6.2 Conclusions of Hypothesis Tests

Tests of the postulated hypotheses have been detailed in chapter 4 and implemented in chapter 5. Evidence suggests that each of the following hypotheses are valid at a 5% alpha level. These hypotheses can now be used for answering the research questions:

Hypothesis 1 *Modifications in maintenance activities are related to changes in the average rates of resource consumption.*

Hypothesis 2 *Modifications in maintenance activities are related to changes in the variance of rates of resource consumption.*

Hypothesis 3 *Resource consumption rates have a negative monotonic correlation with production capacity.*

Hypothesis 4 *Increases in resource consumption rates are related to the manifestation of defects in machinery.*

6.3 Conclusions of the Research Problem

In this section, the research questions are each considered in turn. Thereafter, their conclusions are combined to achieve the objectives of this study.

6.3.1 Research Question 1

Research question 1 is restated below for ease of reference:

> Do maintenance activities have an effect on the probability distribution of resource productivity and if so, what effects is it likely to have?

The motivation behind this research question is to achieve the key objective of this research, i.e. to explore the relationship between maintenance activities and resource productivity. To this end, it makes use of statistical results to test if a relationship exists. If a relationship is found to exist, it uses theoretical results to postulate a description of the potential nature of the relationship. Otherwise, it is concluded that there is insufficient evidence to prove that a relationship exists and the matter is not pursued any further.

The Existence of a Relationship between Maintenance Activities and the Probability Distribution of Resource Productivity

The following conclusions can be drawn with respect to the existence of a relationship between maintenance activities and resource consumption. From the results of the first two hypothesis tests, there is sufficient evidence to conclude that modifications in sets of maintenance activities have a relationship with changes in the average and variance of rates of resource consumption. The rate of resource utilisation is the selected measure for resource productivity. Therefore, maintenance activities have a relationship with the probability distribution of resource productivity. The existence of this relationship may be a consequence of one or both of the said entities affecting each other directly. It is also possible however that both entities are instead driven by a common influencing factor.

Postulation of an Explanatory Relationship

Given that a relationship between maintenance activities and resource productivity has been detected, the answer to the first research question can be pursued further. The two propositions proven in section 3.2.2 are now used to postulate a description of the potential nature of the relationship between maintenance activities and the probability distribution of resource productivity.

Proposition 1 implies that if maintenance activities serve to reduce (increase) the degree of failure and/or inefficiency, then they serve to reduce (increase) wastage and thus serve to reduce (increase) resource consumption. This in turn implies that the probability distribution of resource productivity may be controlled to some extent by controlling maintenance performance. Moreover, proposition 2 suggests that if other factors remain unchanged, the incidence of failure and inefficiency affects the probability distribution of future failure. This implies that current maintenance performance may have effects on the current and future distribution of resource productivity.

It is the purpose of the following two research questions to empirically test the veracity of these postulations.

6.3.2 Research Question 2

Research question 2 is reprinted below:

> Is the postulated relationship between maintenance activities and resource productivity consistent with the relationship between production capacity and resource productivity as reflected by the sample data?

The motivation behind this research question is to serve as verification of the relationship proposed in research question 1. The postulation made in research question 1 is that if maintenance activities serve to reduce (increase) the degree of failure and/or inefficiency, then they serve to increase (reduce) resource productivity. To verify this postulation in this research question, the purpose of maintenance activities is construed from the perspective of Coetzee (2006; 2013).

From Coetzee's perspective, the purpose of the maintenance function is to ensure adequate equipment capability (i.e. to limit the rate of equipment failure) in order to generate production capacity. Maintenance performance, the extent to which the maintenance function serves its purpose, can thus be measured by the production capacity generated by maintenance activities. Therefore, if the relationship postulated in research question 1 holds, maintenance performance should have a positive relationship with resource productivity. Equivalently, production capacity should bear a negative relationship with the rate of resource consumption.

The test of hypothesis 3 indicates that for the company in question, resource consumption rates have a negative monotonic relationship with production capacity.

The proposed description of the relationship between maintenance activities and resource productivity constructed in research question 1 is thus consistent with the sample data.

6.3.3 Research Question 3

Research question 3 is reprinted below:

> Does the sample data reflect that resource productivity decreases before defects in machinery are reported?

This research question serves as a secondary means to test the relationship postulated in research question 1.

Once again, it is noted that the relationship proposed in answering research question 1 suggests that if maintenance activities serve to reduce (increase) the degree of failure and/or inefficiency, then they serve to increase (reduce) resource productivity. In order to verify the relationship postulated in the answer to research question 1, the purpose of maintenance activities is considered from the perspective of Muchiri and Pintelon (2011) and Pintelon and van Puyveld (2006).

From the perspective of the aforesaid scholars, the purpose of maintenance activities is to ensure adequate equipment capability (i.e. to limit the rate of failure of machinery). Maintenance performance, the extent to which maintenance activities serve their purpose, can thus be measured in terms of the presiding equipment capability at a particular point in time. If the relationship postulated in research question 1 holds, maintenance performance should have a positive relationship with resource productivity. In other words, increases in resource consumption rates should be associated with the manifestation of defects in machinery.

The test of hypothesis 4 indicates that increases in resource consumption rates are associated with reports of equipment defects. This serves to demonstrate that the relationship constructed in research question 1 is consistent with the sample data.

6.3.4 Research Question 4

Research question 4 is reprinted below:

> Does resource productivity have the potential to serve as a measure of maintenance performance?

To answer this research question, the following information is utilised:

1. In order for resource productivity to feasibly serve as a measure of maintenance performance, it is necessary to establish that resource productivity has a sufficiently strong relationship with maintenance performance. To this end, an assessment is made of the relationship between maintenance performance and resource productivity set out in research question 1 and tested in research question 2 and research question 3.
2. To test if resource productivity has the potential to serve as a measure of maintenance performance, use is made of the characteristics for good maintenance performance metrics stipulated in section 2.3.3.

Feasibility of Utilizing Resource Productivity as a Measure of Maintenance Performance

Resource productivity presents itself as a feasible measure of maintenance performance. The theoretical propositions utilised in answering research question 1 and tested for its applicability in practice in research question 2 and research question 3 indicates that maintenance performance has an inextricable positive relationship with resource productivity. Equipment capability (which the maintenance function fundamentally serves to effect) can thus be interpreted as the ability of equipment to utilise resources productively. With this new perspective of equipment capability borne in mind, resource productivity presents itself as one of the most obvious measures of maintenance performance.

Adequacy of Utilizing Resource Productivity as a Measure of Maintenance Performance

To test if resource productivity satisfies the characteristics to serve as a measure of maintenance performance, resource productivity as a maintenance performance metric is assessed against the standards outlined in section 2.3.3:

1. The first standard specifies that the metric should be aligned with company objectives. This standard is automatically satisfied for every profit seeking company when considering the proposed performance metric. It is in the interest of every production organisation to ensure that its maintenance policies are efficient. It is also in their interest to minimise wastage. Because of the potential inextricable positive relationship between resource productivity and maintenance performance, both interests are satisfied simultaneously when maintenance performance improves.
2. As is required, resource input/output ratios are easy and inexpensive to calculate. Their computation depends on simple ratios of basic and essential cost accounting measurements. Obtaining such information is cheap as such data should routinely be collected in every production organisation for cost accounting purposes.
3. As is required to satisfy the third standard, resource input/output ratios have an obvious interpretation. They indicate the quantity of resources utilised per unit quantity of quality production (i.e. they indicate

resource productivity). Furthermore, when production formulae remain consistent, resource input/output ratios can also be construed to be a measure of the degree of failure and/or inefficiency.

4. The fourth standard specifies that the metric should indicate if corrective action is warranted and where necessary, it should indicate what corrective action should be taken. With the exception of changes in production formulae, increases in resource consumption rates represent a warning that production operations are not proceeding according to plan as more resources are required for production purposes than the amount intended to be used. In other words, whenever wastage increases, it is a sure signal that the degree of failure and/or inefficiency has increased. While such signals may pertain in part to problems with machine operation, they also offer valuable signals indicating the necessity for course correction with respect to the rest of the production process.

5. The final standard requires that the metric should reflect the consequences of the actions taken by management. According to the relationship postulated in research question 1 and verified in research question 2 and research question 3, if management undertake any actions which affect machine capability, resource productivity levels are likely to be affected.

The evidence that has been amassed indicates that resource productivity has the potential to serve as a measure of maintenance performance.

6.3.5 Key Research Objective

The key objective of this research is to determine with statistical rigour if a relationship exists between maintenance activities and resource productivity. If such a relationship is found to exist, it aims to establish the nature of the relationship. If on the other hand it is determined that a relationship is likely not to exist, then this research effort serves to demonstrate that there may not be any merit in undertaking further studies regarding the relationship between maintenance activities and resource productivity. The first research question is posed to achieve this objective. The second and third research questions are meant to verify the proposed explanatory relationship.

The key objective of this research is achieved. It is determined in answering research question 1 that if maintenance activities serve to reduce (increase) the degree of failure and/or inefficiency, then they serve to increase (reduce) resource productivity. The postulated relationship is successfully verified in answering the second and third research questions.

6.3.6 Second Research Objective

The second research objective is to determine if opportunities for productivity enhancement exist as a result of the relationship postulated between maintenance activities and resource productivity.

This objective is achieved by inferring from the proposed and verified relationship between maintenance activities and resource productivity. In particular, maintenance performance and resource productivity potentially have a positive relationship. As such, resource productivity can potentially be improved by improving maintenance performance. This serves to imply that for companies to minimise wastage, machines should be kept in the best operating condition possible at all times. When defects are identified, equipment should be repaired as quickly as possible to minimise wastage.

6.3.7 Third Research Objective

The third research objective is to determine if resource productivity has the potential to serve as a measure of maintenance performance. Resource productivity can only serve as a measure of maintenance performance if resource productivity has a strong relationship with maintenance performance. To achieve this objective, the first research question is used to explore the relationship between maintenance performance and resource productivity. The fourth research question then makes an overall assessment of resource productivity as a measure of maintenance performance.

The third research objective is achieved. It is determined that resource productivity has the potential to serve as a measure of maintenance performance.

6.4 Relation to Theory

As is discussed in chapter 1 and demonstrated in chapter 2, the subject matter of this study represents a research gap. Filling this research gap is the ultimate purpose of this study. Now that the objectives of this study have been accomplished, it is possible to identify the resulting benefits of this research in terms of the pre-existing body of knowledge.

The purpose of this research pertains to the verification and potential theoretical induction of postulations which have been made in literature without rigorous proof. In section 2.4. it is discussed that Wells (2004), Abdul Raouf (2004) and Khan and Darrab (2010) suggest without sufficient statistical evidence that maintenance performance is related to raw material productivity. Burgoon *et al.* (2012) hypothesise that inadequately maintained equipment results in the wastage of energy. In response, this research presents a rigorous exploration of the relationship between maintenance performance and resource productivity (resource productivity here includes productivity related to raw materials, energy and the rate of production of quality output). This research provides theoretical and empirical evidence that if maintenance performance improves, the probability distribution of resource productivity is likely to improve as well.

6.5 Implications and Recommendations

The following are immediate consequences of the conclusions of this research:

1. **Measuring resource productivity gives rise to a potentially powerful and apt measure of maintenance performance:** This

conclusion arises because equipment capability, the fundamental entity involved in maintenance performance measurement, can be construed in general as the ability of machines to utilise resources productively in the generation of quality output.

2. **Measuring resource productivity can potentially be used to indicate when corrective action is required in production plants:** With the exception of deviations caused by changes in production formulae, decreases in resource productivity signifies that one or more facets of the production process may require corrective action. Such corrective action could pertain to the quality of raw materials utilised, machinery defects or it may pertain to problems with labour.
3. **Savings can be made by keeping equipment in the best condition possible and by restoring equipment to maximum capability in a timely fashion:** This conclusion follows from the theoretical results of this study which indicate that when machines malfunction, wastage is likely to result.
4. **The value of the maintenance function is now clearer:** The maintenance function enables production to take place and potentially reduces the wastage of valuable production resources.

6.6 Limitations

This study is limited in that its postulations are tested on sample data which arises from a single company only. More experimentation is thus required to give credence to the conclusions of this research.

6.7 Recommendations for Future Research

Measuring resource productivity may possibly be applied to monitor the condition of equipment. This possibility is of interest for the following reasons:

1. The results of the test of hypothesis 4 indicates that decreases in resource productivity tends to precede reports of machinery malfunction.
2. Swanson (2001) reports on a survey conducted on companies from the metallurgical industry. The results indicate that there is a correlation between proactive maintenance policies (which involve condition monitoring of equipment), decreases in overall production costs and increases in product quality.
3. Burgoon *et al.* (2012) hypothesise that condition monitoring of equipment assists in lengthening the life of machinery and reducing energy consumption.

Given that resource productivity can be inexpensively measured by easily accessible accounting data and may lead to a cost effective means of condition monitoring which may ultimately be used to improve production plant efficiency, this prospect appears to be a promising research area. A review of the literature reveals that little effort has been made in this direction. As a consequence, it seems that this important research area represents a research gap.

6.8 Conclusions

This study emerges from a research gap which concerns the global need for companies to use resources more efficiently. Previously conducted but inconclusive research indicates that maintenance activities may possess a relationship with resource productivity. At outset, this relationship appeared to have the potential to be exploited for purposes of productivity enhancement and for purposes of making improved measurements of the value of maintenance. At this juncture, it seems that exploration of this potential has proven to be profitable.

Regarding the scope of this research, this study is designed so that its conclusions are potentially universally applicable. The statistical data is sampled from a company which has been selected on the basis that it is complex enough to be representative of production operations world wide. The theoretical results available are encompassing, promising and can be rigorously proven. The study is however limited in that its postulations are tested on sample data which arises from a single company only. Even though its findings are intuitively sound, more experimentation is required to give credence to the conclusions of this research.

The key objective of this research involves the exploration of the relationship between maintenance activities and resource productivity. This study achieves its fundamental aim. A series of statistical tests indicate that if maintenance activities serve to reduce (increase) the degree of failure and/or inefficiency, then they serve to increase (reduce) resource productivity. Thus, the extent to which the maintenance function serves its purpose (i.e. maintenance performance) is likely to have a positive relationship with resource productivity.

Two other objectives are also pursued. The first involves making use of the relationship between maintenance activities and resource productivity to identify opportunities for productivity enhancement for use in industry. The second involves the use of the said relationship to establish if resource productivity may serve as a measure of maintenance performance. Both of these objectives are attained. As a consequence of the potentially positive effect maintenance performance has on resource productivity, the following conclusions can be drawn:

1. Resource productivity has great propensity to serve as a measure of maintenance performance. Evidence suggests that equipment capability, the fundamental entity involved in maintenance performance measurement, can be construed in general as the ability of machines to utilise resources productively in the generation of quality output.

2. In terms of possibilities for productivity enhancement, evidence suggests that machinery should always be kept in the best operating condition

possible. Moreover, when machinery malfunctions are discovered, it should be repaired in a timely fashion to prevent unnecessary wastage from occurring.

In terms of possibilities for further research, the results of one of the hypothesis tests of this study indicates that it may be worthwhile investigating if measuring resource productivity could be used to monitor the condition of machinery. Such research may result in an inexpensive means of enhancing the operating life of equipment and improving the safety, reliability and cost efficiency of production plants.

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Appendices

Appendix A

Graphs of Monthly Data Collected

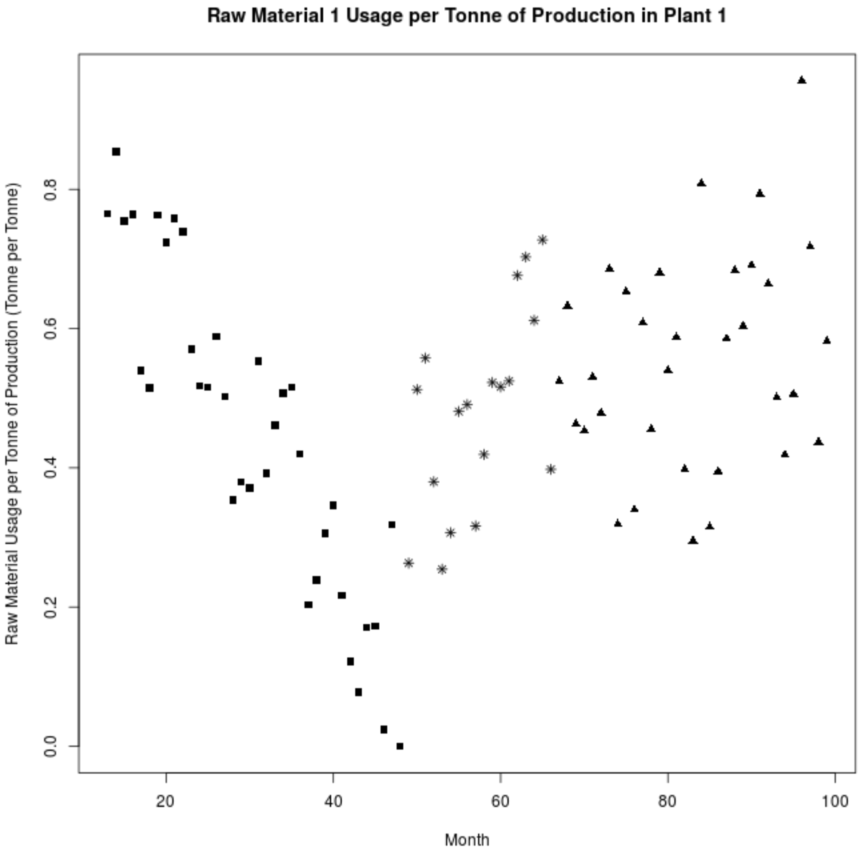

Figure A.1: Plant 1 Raw Material 1 Input/Output Ratio over Time

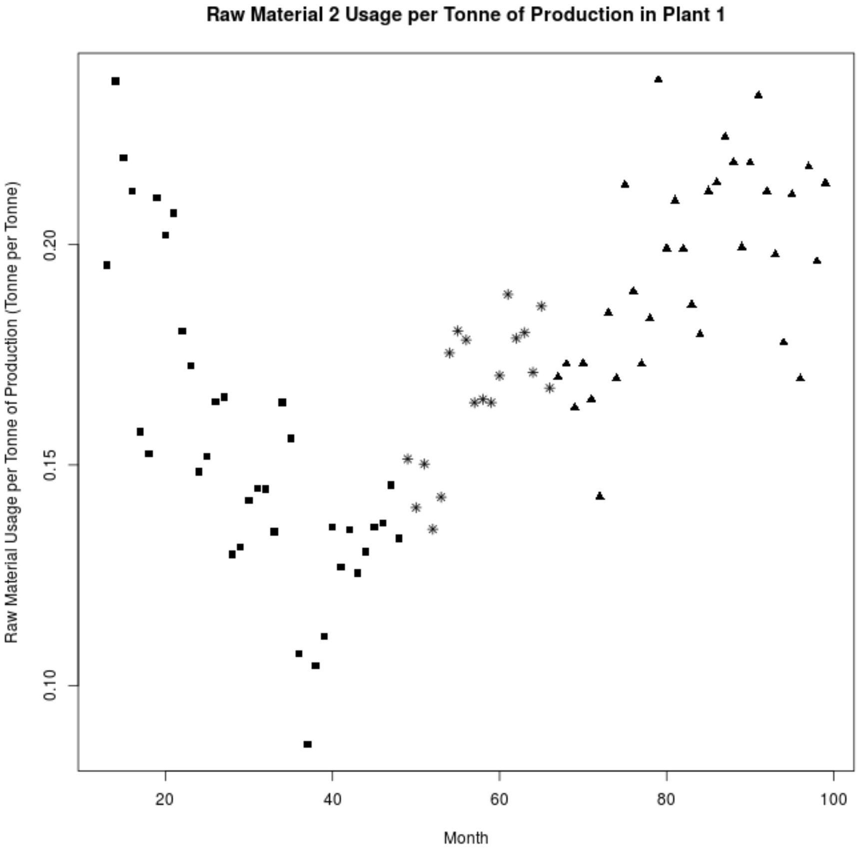

Figure A.2: Plant 1 Raw Material 2 Input/Output Ratio over Time

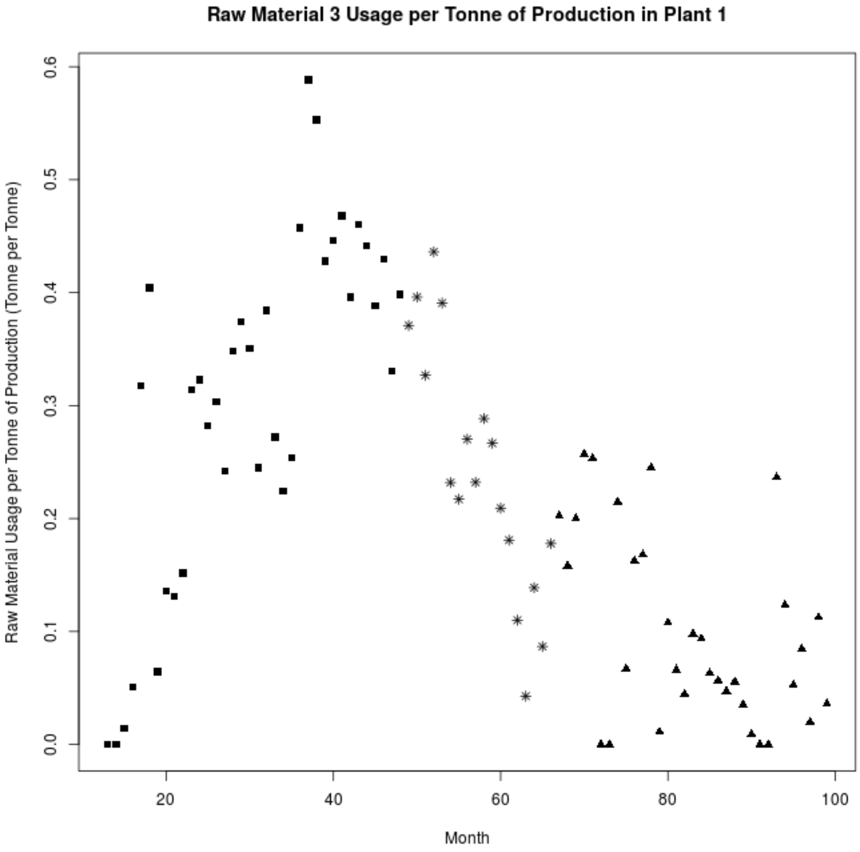

Figure A.3: Plant 1 Raw Material 3 Input/Output Ratio over Time

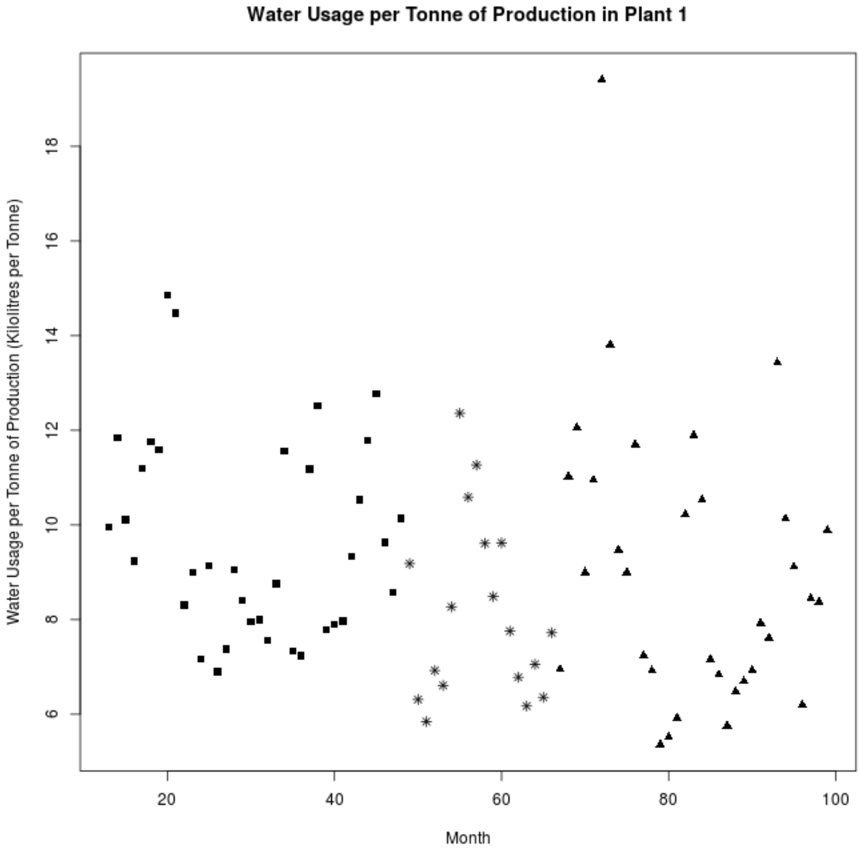

Figure A.4: Plant 1 Water Input/Output Ratio over Time

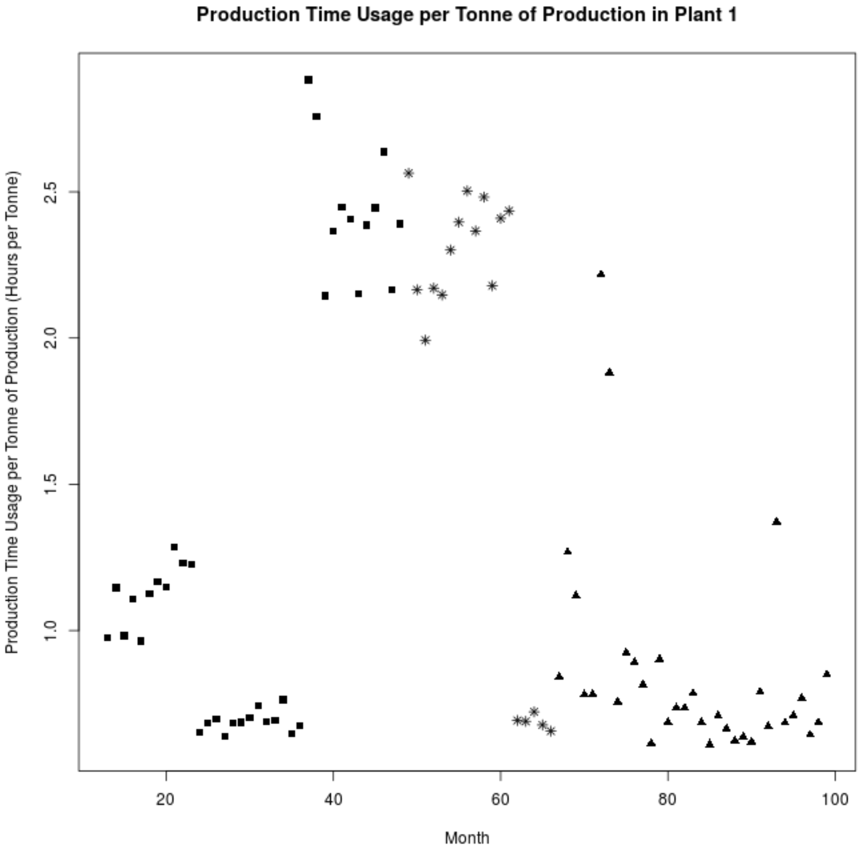

Figure A.5: Plant 1 Production Time Input/Output Ratio over Time

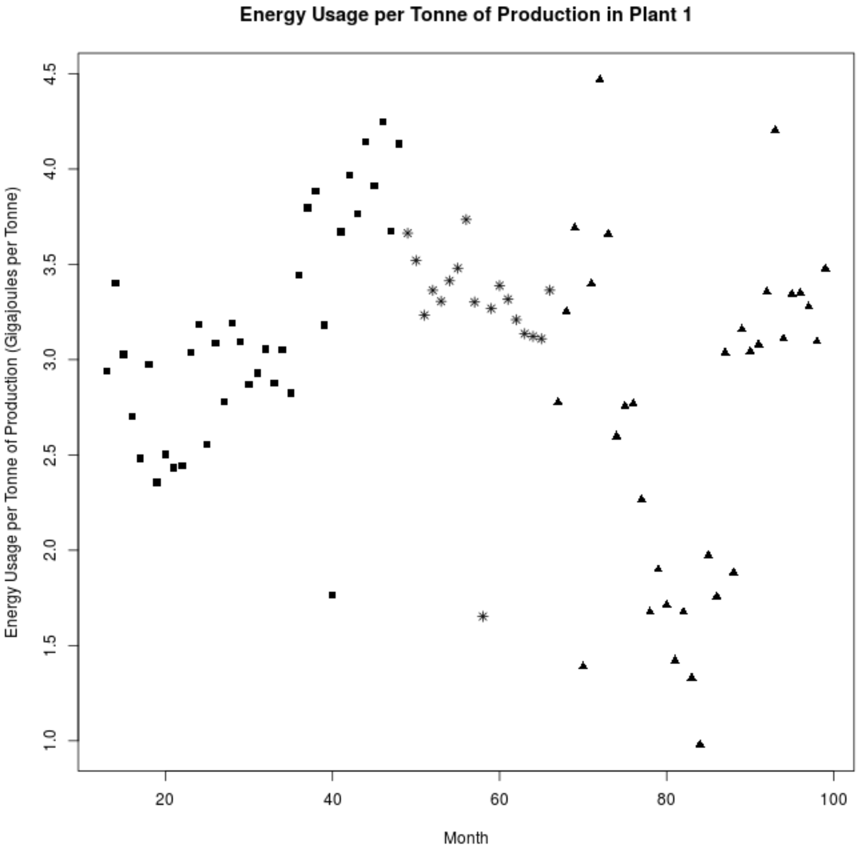

Figure A.6: Plant 1 Energy Input/Output Ratio over Time

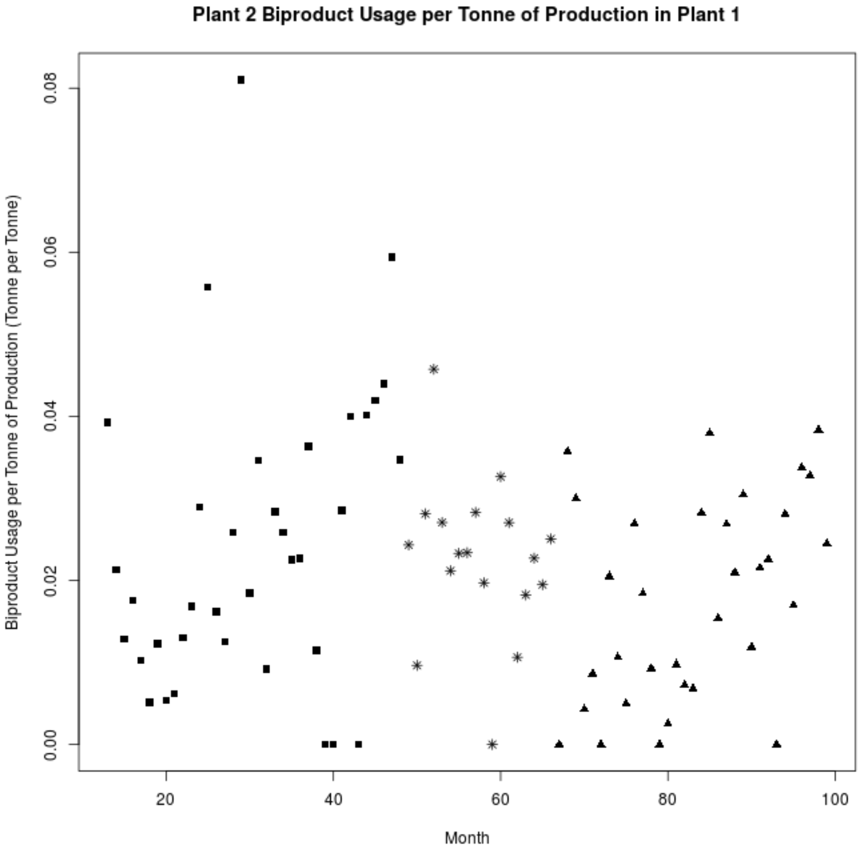

Figure A.7: By-product Input/Output Ratio over Time (in Plant 1)

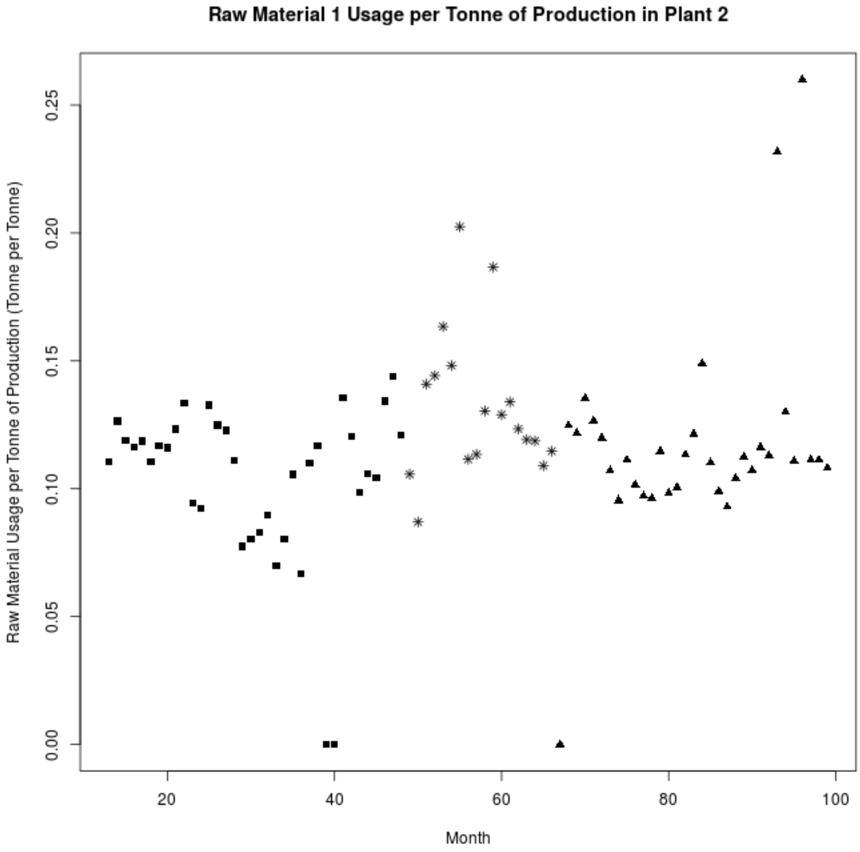

Figure A.8: Plant 2 Raw Material 1 Input/Output Ratio over Time

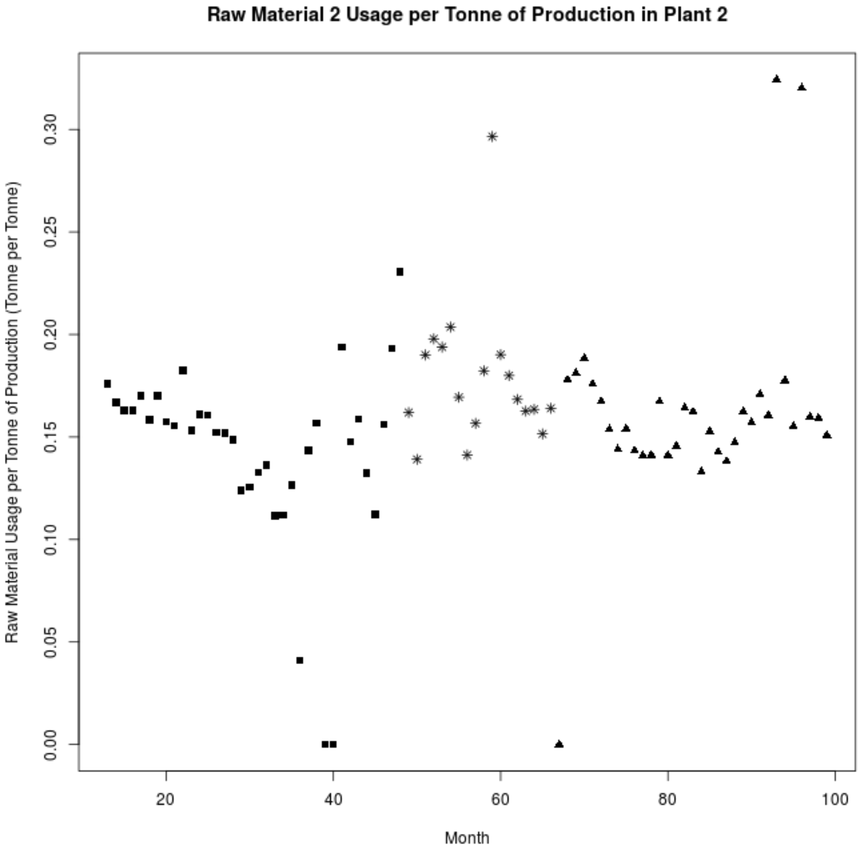

Figure A.9: Plant 2 Raw Material 2 Input/Output Ratio over Time

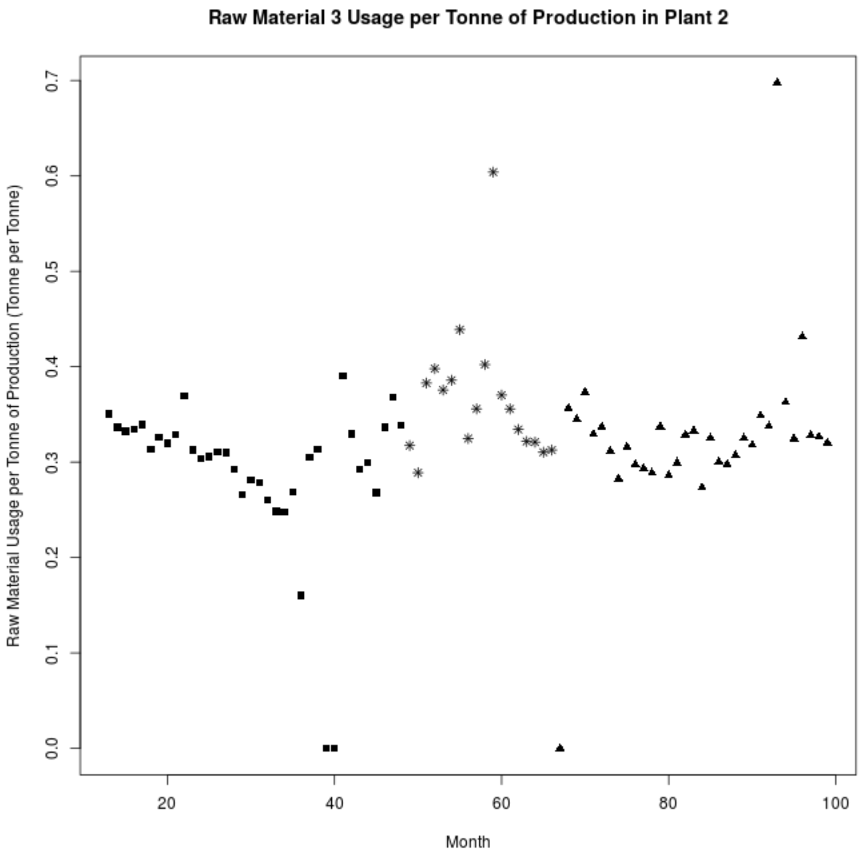

Figure A.10: Plant 2 Raw Material 3 Input/Output Ratio over Time

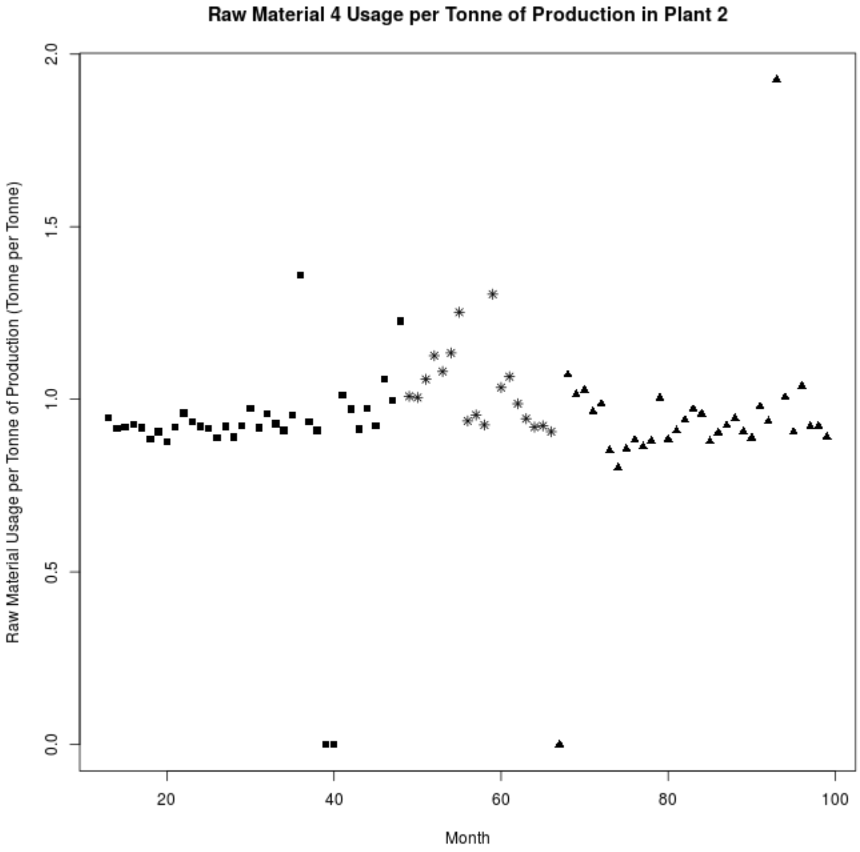

Figure A.11: Plant 2 Raw Material 4 Input/Output Ratio over Time

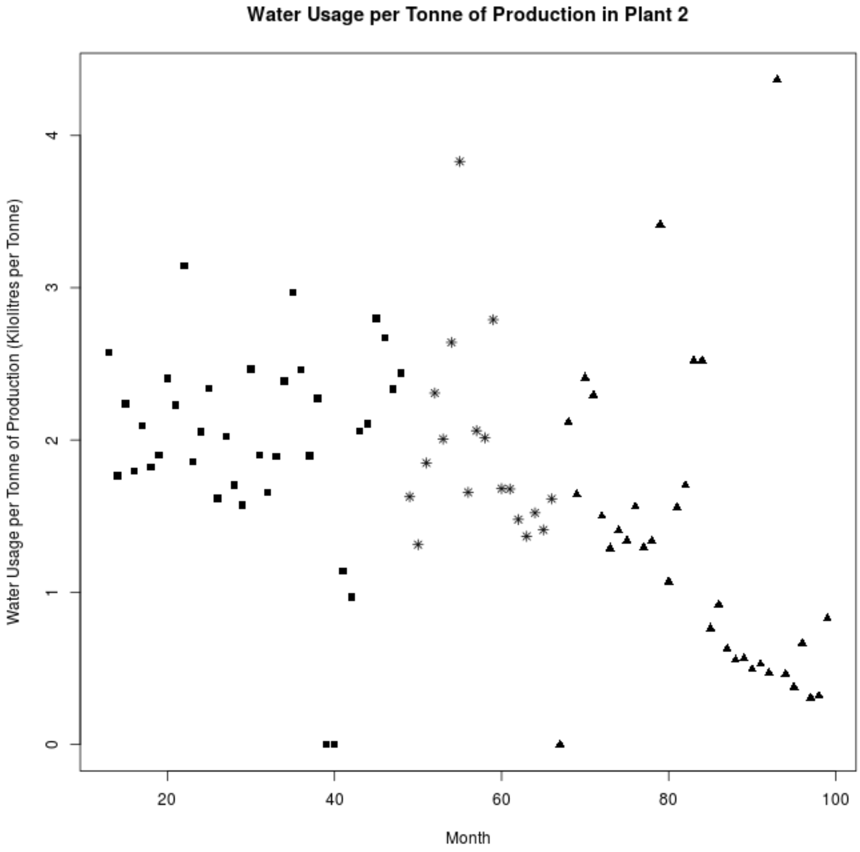

Figure A.12: Plant 2 Water Input/Output Ratio over Time

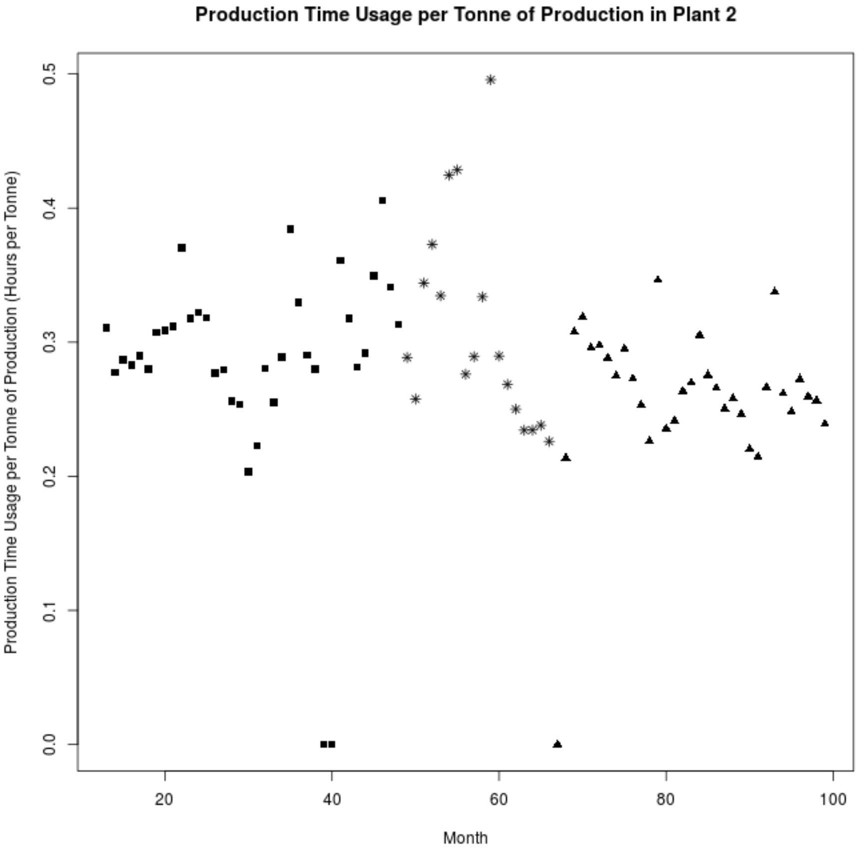

Figure A.13: Plant 2 Production Time Input/Output Ratio over Time

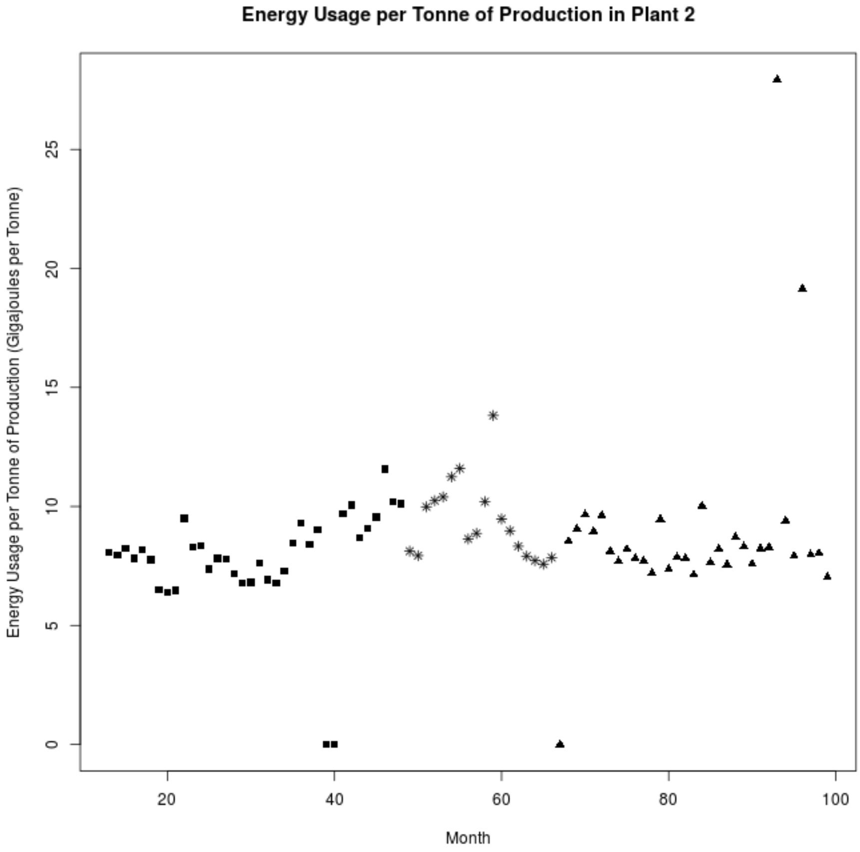

Figure A.14: Plant 2 Energy Input/Output Ratio over Time

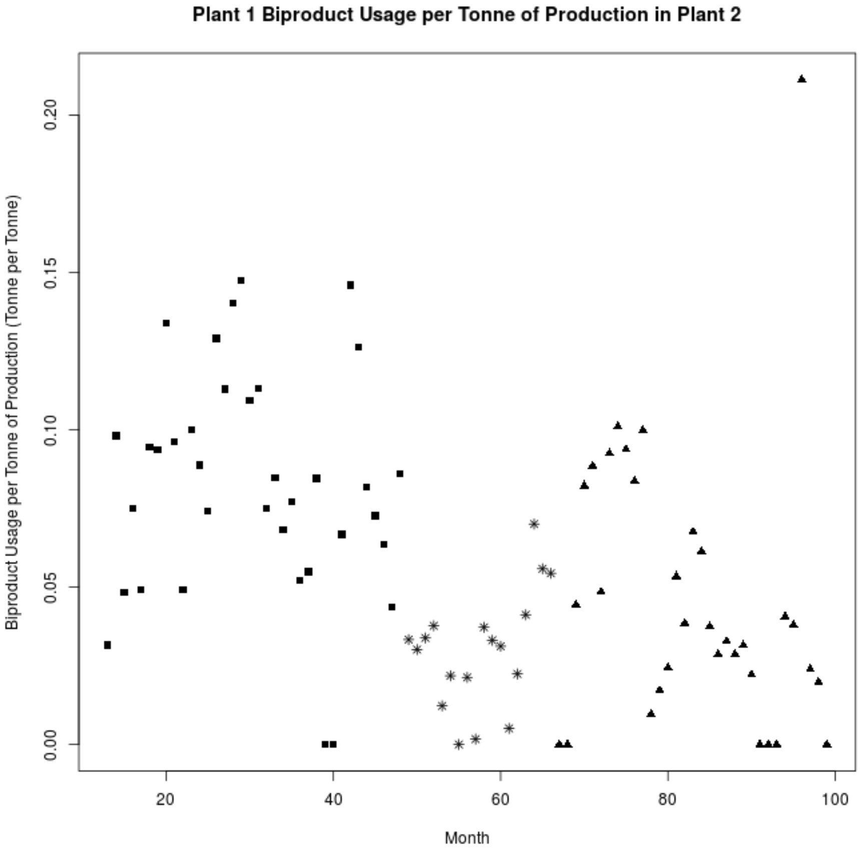

Figure A.15: By-product Input/Output Ratio over Time (in Plant 2)

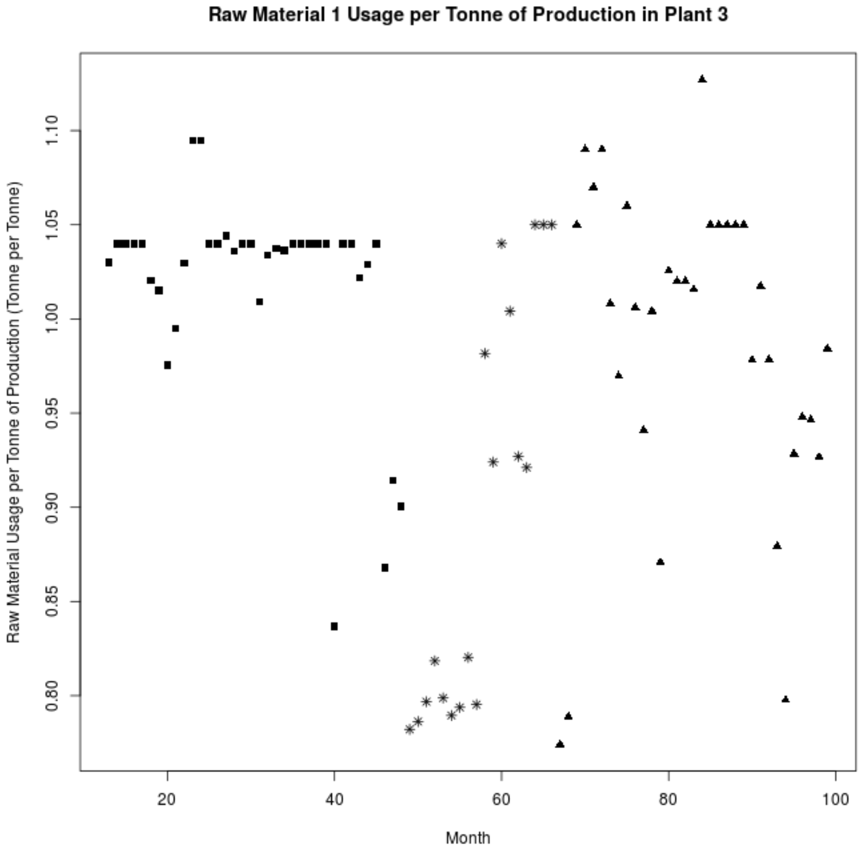

Figure A.16: Plant 3 Raw Material 1 Input/Output Ratio over Time

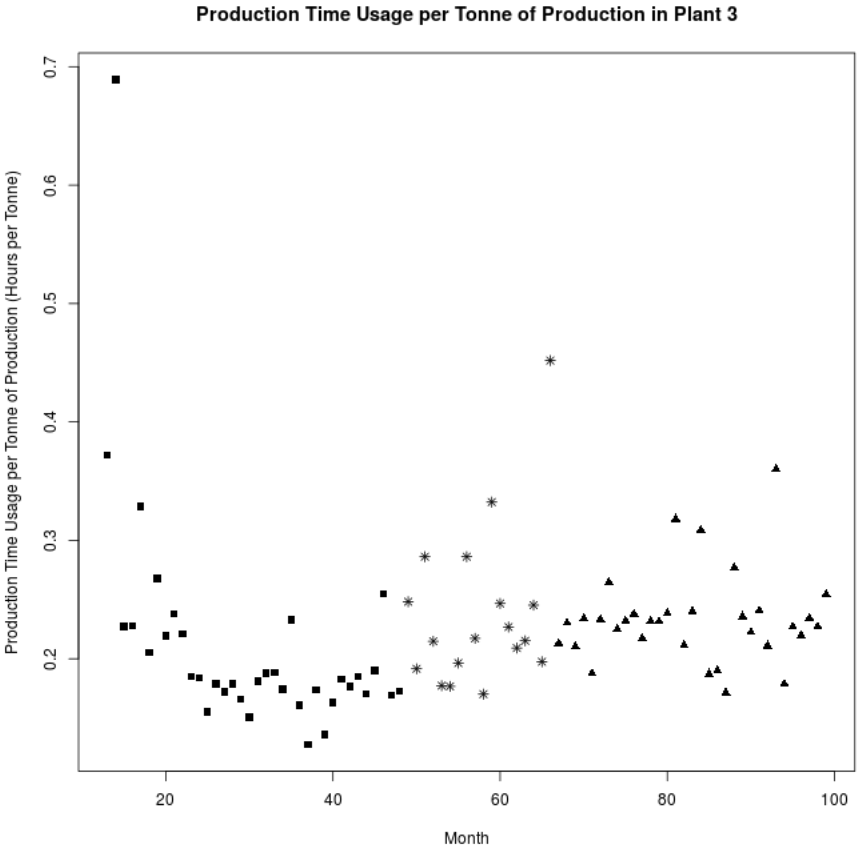

Figure A.17: Plant 3 Production Time Input/Output Ratio over Time

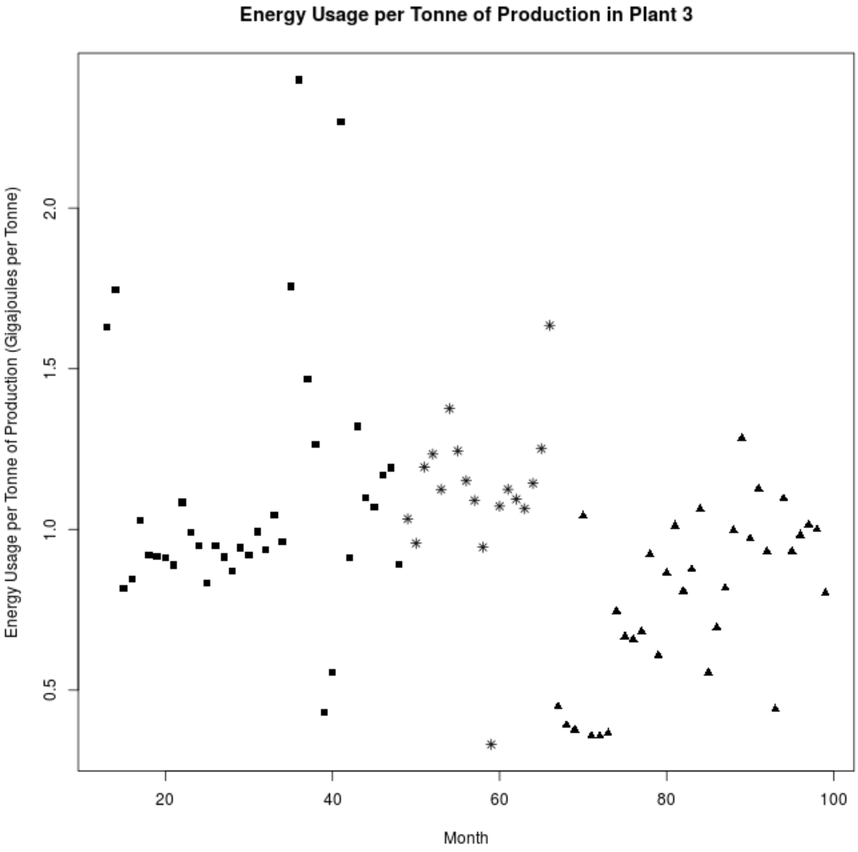

Figure A.18: Plant 3 Energy Input/Output Ratio over Time

Appendix B

Regression Analyses of Resource I/O Ratios

Table B.1: Metallurgical Plant 1 - Raw Material 1 I/O Ratio Regression Results

	Dependent variable:	
	Raw Material 1 I/O Ratio	Raw Material 1 I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	0.060	
	(0.049)	
Maintenance Regime 3	0.081^{*}	0.057^{*}
	(0.045)	(0.034)
Qty of Plant 2 By-product Used	-1.783	
	(1.152)	
Formula 1 Used	0.058	
	(0.117)	
Formula 2 Used	-0.245^{***}	-0.223^{***}
	(0.044)	(0.038)
Formula 3 Used	0.242^{*}	0.236^{*}
	(0.135)	(0.130)
Formula 4 Used	-0.053	
	(0.133)	
Formula 5 Used	-0.358^{***}	-0.351^{***}
	(0.097)	(0.096)
Formula 6 Used	-0.404^{***}	-0.400^{***}
	(0.080)	(0.077)
Formula 7 Used	-0.229^{***}	-0.208^{***}
	(0.063)	(0.058)
Formula 8 Used	-0.475^{***}	-0.516^{***}
	(0.116)	(0.114)
Formula 9 Used	-0.140	
	(0.134)	
Constant	0.693^{***}	0.662^{***}
	(0.050)	(0.035)
Observations	87	87
R^2	0.540	0.500
Adjusted R^2	0.466	0.456
Residual Std. Error	1.000 (df = 74)	1.000 (df = 79)
F Statistic	7.252^{***} (df = 12; 74)	11.287^{***} (df = 7; 79)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.1516	0.1538
Maintenance Regime 2	0.1399	0.1432
Maintenance Regime 3	0.1249	0.1247

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table B.2: Metallurgical Plant 1 - Raw Material 2 I/O Ratio Regression Results

	Dependent variable:	
	Raw Material 2 I/O Ratio	Raw Material 2 I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	0.014^{**}	0.013^{**}
	(0.007)	(0.006)
Maintenance Regime 3	0.033^{***}	0.030^{***}
	(0.007)	(0.006)
Qty of Plant 2 By-product Used	-0.245	
	(0.176)	
Formula 1 Used	0.020	
	(0.017)	
Formula 2 Used	-0.030^{***}	-0.028^{***}
	(0.007)	(0.006)
Formula 3 Used	-0.041^{*}	
	(0.024)	
Formula 4 Used	0.005	
	(0.024)	
Formula 5 Used	-0.043^{***}	-0.040^{***}
	(0.014)	(0.014)
Formula 6 Used	-0.069^{***}	-0.067^{***}
	(0.012)	(0.011)
Formula 7 Used	-0.012	
	(0.011)	
Formula 8 Used	-0.043^{**}	-0.047^{***}
	(0.017)	(0.017)
Formula 9 Used	0.012	
	(0.024)	
Constant	0.186^{***}	0.180^{***}
	(0.007)	(0.005)
Observations	87	87
R^2	0.629	0.570
Adjusted R^2	0.569	0.538
Residual Std. Error	1.000 (df = 74)	1.000 (df = 80)
F Statistic	10.443^{***} (df = 12; 74)	17.685^{***} (df = 6; 80)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.0218	0.0226
Maintenance Regime 2	0.017	0.0164
Maintenance Regime 3	0.0225	0.0236
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.3: Metallurgical Plant 1 - Raw Material 3 I/O Ratio Regression Results

	Dependent variable:	
	Raw Material 3 I/O Ratio	Raw Material 3 I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	−0.066*	−0.056*
	(0.036)	(0.033)
Maintenance Regime 3	−0.170***	−0.155***
	(0.030)	(0.025)
Qty of Plant 2 By-product Used	0.437	
	(0.781)	
Formula 1 Used	−0.045	
	(0.082)	
Formula 2 Used	0.130***	0.111***
	(0.030)	(0.022)
Formula 3 Used	0.064	
	(0.085)	
Formula 4 Used	0.041	
	(0.084)	
Formula 5 Used	0.169**	0.156**
	(0.068)	(0.065)
Formula 6 Used	0.314***	0.303***
	(0.056)	(0.052)
Formula 7 Used	0.045	
	(0.041)	
Formula 8 Used	0.226***	0.225***
	(0.081)	(0.077)
Formula 9 Used	0.030	
	(0.084)	
Constant	0.176***	0.194***
	(0.035)	(0.024)
Observations	87	87
R^2	0.656	0.643
Adjusted R^2	0.600	0.616
Residual Std. Error	0.999 (df = 74)	0.998 (df = 80)
F Statistic	11.769*** (df = 12; 74)	23.999*** (df = 6; 80)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.1067	0.1045
Maintenance Regime 2	0.1117	0.1083
Maintenance Regime 3	0.0785	0.0777

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.4: Metallurgical Plant 1 - Water I/O Ratio Regression Results

	Dependent variable:	
	Water I/O Ratio	Water I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	-0.802	-1.148^{**}
	(0.657)	(0.512)
Maintenance Regime 3	0.651	
	(0.769)	
Qty of Plant 2 By-product Used	5.918	
	(16.582)	
Formula 1 Used	4.904^{***}	5.355^{***}
	(1.326)	(1.227)
Formula 2 Used	-0.951	
	(0.652)	
Formula 3 Used	-4.386	
	(3.074)	
Formula 4 Used	-4.022	
	(3.050)	
Formula 5 Used	-0.818	
	(1.110)	
Formula 6 Used	-0.349	
	(0.915)	
Formula 7 Used	-2.216^{*}	
	(1.328)	
Formula 8 Used	0.596	
	(1.342)	
Formula 9 Used	-4.777	
	(3.059)	
Constant	9.727^{***}	9.310^{***}
	(0.606)	(0.254)
Observations	87	87
R^2	0.313	0.239
Adjusted R^2	0.201	0.221
Residual Std. Error	0.999 (df = 74)	0.999 (df = 84)
F Statistic	2.807^{***} (df = 12; 74)	13.188^{***} (df = 2; 84)
Est. Original Residual Std. Error		
Maintenance Regime 1	1.702	1.6986
Maintenance Regime 2	2.055	1.8885
Maintenance Regime 3	2.9337	2.9855
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.5: Metallurgical Plant 1 - Energy I/O Ratio Regression Results

	Dependent variable:	
	Energy I/O Ratio Initial Model	Energy I/O Ratio Final Model
Maintenance Regime 2	0.182	
	(0.169)	
Maintenance Regime 3	−0.026	
	(0.210)	
Qty of Plant 2 By-product Used	10.741**	11.192***
	(4.660)	(4.116)
Formula 1 Used	−0.333	
	(0.394)	
Formula 2 Used	0.097	
	(0.183)	
Formula 3 Used	0.273	
	(0.812)	
Formula 4 Used	−1.055	
	(0.805)	
Formula 5 Used	0.369	
	(0.329)	
Formula 6 Used	0.358	
	(0.271)	
Formula 7 Used	−0.993***	−1.163***
	(0.354)	(0.276)
Formula 8 Used	0.886**	0.734*
	(0.397)	(0.373)
Formula 9 Used	0.036	
	(0.808)	
Constant	2.739***	2.873***
	(0.176)	(0.111)
Observations	87	87
R^2	0.361	0.290
Adjusted R^2	0.258	0.264
Residual Std. Error	0.999 (df = 74)	0.998 (df = 83)
F Statistic	3.489*** (df = 12; 74)	11.280*** (df = 3; 83)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.5082	0.5107
Maintenance Regime 2	0.4615	0.464
Maintenance Regime 3	0.7732	0.7617
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.6: Metallurgical Plant 1 - Time I/O Ratio Regression Results

	Dependent variable:	
	Time I/O Ratio Initial Model	Time I/O Ratio Final Model
Maintenance Regime 2	0.749***	0.722***
	(0.227)	(0.208)
Maintenance Regime 3	−0.164	−0.279**
	(0.154)	(0.122)
Qty of Plant 2 By-product Used	0.980	
	(4.012)	
Formula 1 Used	0.085	
	(0.443)	
Formula 2 Used	−0.036	
	(0.153)	
Formula 3 Used	−0.227	
	(0.405)	
Formula 4 Used	−0.360	
	(0.400)	
Formula 5 Used	0.019	
	(0.369)	
Formula 6 Used	1.378***	1.378***
	(0.301)	(0.272)
Formula 7 Used	−0.291	
	(0.198)	
Formula 8 Used	1.231***	1.255***
	(0.436)	(0.411)
Formula 9 Used	−0.325	
	(0.402)	
Constant	1.127***	1.142***
	(0.186)	(0.104)
Observations	87	87
R^2	0.504	0.477
Adjusted R^2	0.423	0.452
Residual Std. Error	0.992 (df = 74)	1.000 (df = 82)
F Statistic	6.262*** (df = 12; 74)	18.730*** (df = 4; 82)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.5811	0.5624
Maintenance Regime 2	0.7897	0.7653
Maintenance Regime 3	0.374	0.3604
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.7: Metallurgical Plant 2 - Raw Material 1 I/O Ratio Regression Results

	Dependent variable:	
	Energy I/O Ratio Initial Model	Energy I/O Ratio Final Model
Maintenance Regime 2	0.026	0.035^{***}
	(0.021)	(0.010)
Maintenance Regime 3	0.020	0.030^{***}
	(0.023)	(0.009)
Qty of Plant 1 By-product Used	0.376^{***}	0.379^{***}
	(0.104)	(0.096)
Formula 1 Used	-0.039^{*}	-0.040^{*}
	(0.023)	(0.021)
Formula 2 Used	0.001	
	(0.013)	
Formula 3 Used	-0.017^{*}	-0.020^{***}
	(0.009)	(0.007)
Formula 4 Used	0.017	
	(0.022)	
Formula 5 Used	-0.002	
	(0.016)	
Formula 6 Used	0.035^{**}	0.036^{***}
	(0.014)	(0.013)
Formula 7 Used	0.009	
	(0.015)	
Plant in Damaged Condition	0.012	
	(0.021)	
Constant	0.075^{***}	0.078^{***}
	(0.010)	(0.009)
Observations	87	87
R^2	0.377	0.366
Adjusted R^2	0.286	0.318
Residual Std. Error	0.998 (df = 75)	0.999 (df = 80)
F Statistic	4.128^{***} (df = 11; 75)	7.681^{***} (df = 6; 80)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.029	0.0284
Maintenance Regime 2	0.0259	0.0254
Maintenance Regime 3	0.0352	0.0341
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.8: Metallurgical Plant 2 - Raw Material 2 I/O Ratio Regression Results

	Dependent variable:	
	Raw Material 2 I/O Ratio	Raw Material 2 I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	0.042	0.040^{***}
	(0.026)	(0.013)
Maintenance Regime 3	0.038	0.035^{***}
	(0.029)	(0.012)
Qty of Plant 1 By-product Used	0.471^{***}	0.416^{***}
	(0.146)	(0.133)
Formula 1 Used	−0.043	
	(0.031)	
Formula 2 Used	0.002	
	(0.017)	
Formula 3 Used	−0.015	
	(0.012)	
Formula 4 Used	0.004	
	(0.033)	
Formula 5 Used	0.007	
	(0.025)	
Formula 6 Used	0.039^{**}	0.045^{***}
	(0.018)	(0.014)
Formula 7 Used	−0.007	
	(0.022)	
Plant in Damaged Condition	0.003	
	(0.026)	
Constant	0.108^{***}	0.108^{***}
	(0.015)	(0.013)
Observations	87	87
R^2	0.308	0.283
Adjusted R^2	0.207	0.248
Residual Std. Error	0.998 (df = 75)	1.000 (df = 82)
F Statistic	3.041^{***} (df = 11; 75)	8.078^{***} (df = 4; 82)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.0445	0.0439
Maintenance Regime 2	0.0314	0.0282
Maintenance Regime 3	0.0478	0.0487

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table B.9: Metallurgical Plant 2 - Raw Material 3 I/O Ratio Regression Results

	Dependent variable:	
	Raw Material 3 I/O Ratio	Raw Material 3 I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	0.049	
	(0.050)	
Maintenance Regime 3	0.035	
	(0.056)	
Qty of Plant 1 By-product Used	0.566^{**}	
	(0.279)	
Formula 1 Used	-0.059	
	(0.062)	
Formula 2 Used	-0.003	
	(0.032)	
Formula 3 Used	-0.010	
	(0.023)	
Formula 4 Used	0.009	
	(0.060)	
Formula 5 Used	0.002	
	(0.045)	
Formula 6 Used	0.087^{**}	0.110^{***}
	(0.034)	(0.023)
Formula 7 Used	-0.002	
	(0.041)	
Plant in Damaged Condition	0.027	
	(0.049)	
Constant	0.246^{***}	0.313^{***}
	(0.029)	(0.009)
Observations	87	87
R^2	0.291	0.213
Adjusted R^2	0.187	0.204
Residual Std. Error	0.998 (df = 75)	1.000 (df = 85)
F Statistic	2.794^{***} (df = 11; 75)	23.051^{***} (df = 1; 85)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.0804	0.0849
Maintenance Regime 2	0.0602	0.0559
Maintenance Regime 3	0.0967	0.0934
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.10: Metallurgical Plant 2 - Raw Material 4 I/O Ratio Regression Results

	Dependent variable:	
	Raw Material 4 I/O Ratio Initial Model	Raw Material 4 I/O Ratio Final Model
Maintenance Regime 2	0.175*	0.062*
	(0.100)	(0.037)
Maintenance Regime 3	0.142	
	(0.114)	
Qty of Plant 1 By-product Used	1.011	
	(0.698)	
Formula 1 Used	−0.141	
	(0.169)	
Formula 2 Used	0.018	
	(0.070)	
Formula 3 Used	0.060	
	(0.054)	
Formula 4 Used	0.083	
	(0.160)	
Formula 5 Used	0.176	
	(0.118)	
Formula 6 Used	0.175***	0.133***
	(0.064)	(0.045)
Formula 7 Used	0.262**	
	(0.109)	
Plant in Damaged Condition	−0.002	
	(0.091)	
Constant	0.741***	0.917***
	(0.074)	(0.030)
Observations	87	87
R^2	0.258	0.181
Adjusted R^2	0.149	0.161
Residual Std. Error	0.997 (df = 75)	1.000 (df = 84)
F Statistic	2.367** (df = 11; 75)	9.267*** (df = 2; 84)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.2157	0.2417
Maintenance Regime 2	0.1073	0.0924
Maintenance Regime 3	0.2669	0.2494
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.11: Metallurgical Plant 2 - Water I/O Ratio Regression Results

	Dependent variable:	
	Water I/O Ratio	Water I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	-0.372	
	(0.443)	
Maintenance Regime 3	-0.775	-0.509^{**}
	(0.501)	(0.194)
Qty of Plant 1 By-product Used	1.259	
	(2.482)	
Formula 1 Used	-0.056	
	(0.634)	
Formula 2 Used	-0.296	
	(0.307)	
Formula 3 Used	0.143	
	(0.203)	
Formula 4 Used	0.404	
	(0.483)	
Formula 5 Used	0.577	
	(0.360)	
Formula 6 Used	0.686^{**}	0.582^{***}
	(0.301)	(0.220)
Formula 7 Used	0.680^{**}	0.599^{*}
	(0.329)	(0.307)
Plant in Damaged Condition	0.397	
	(0.441)	
Constant	1.659^{***}	1.819^{***}
	(0.244)	(0.094)
Observations	87	87
R^2	0.274	0.207
Adjusted R^2	0.168	0.179
Residual Std. Error	0.997 (df = 75)	1.000 (df = 83)
F Statistic	2.578^{***} (df = 11; 75)	7.230^{***} (df = 3; 83)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.6456	0.6532
Maintenance Regime 2	0.5361	0.5257
Maintenance Regime 3	0.9981	0.9761

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table B.12: Metallurgical Plant 2 - Energy I/O Ratio Regression Results

	Dependent variable:	
	Energy I/O Ratio	Energy I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	1.228	0.355^{*}
	(1.185)	(0.205)
Maintenance Regime 3	1.695	
	(1.449)	
Qty of Plant 1 By-product Used	15.770^{**}	
	(7.906)	
Formula 1 Used	−1.659	
	(2.613)	
Formula 2 Used	−0.009	
	(0.910)	
Formula 3 Used	0.684	
	(0.619)	
Formula 4 Used	0.498	
	(1.486)	
Formula 5 Used	2.298^{**}	
	(1.106)	
Formula 6 Used	2.888^{***}	2.580^{***}
	(0.790)	(0.499)
Formula 7 Used	2.702^{***}	
	(1.014)	
Plant in Damaged Condition	0.847	
	(1.128)	
Constant	5.615^{***}	8.025^{***}
	(0.775)	(0.344)
Observations	87	87
R^2	0.360	0.306
Adjusted R^2	0.267	0.290
Residual Std. Error	0.975 (df = 75)	0.995 (df = 84)
F Statistic	3.843^{***} (df = 11; 75)	18.554^{***} (df = 2; 84)
Est. Original Residual Std. Error		
Maintenance Regime 1	2.0311	2.3406
Maintenance Regime 2	1.3744	1.0368
Maintenance Regime 3	4.303	4.3016
Note:		$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table B.13: Metallurgical Plant 2 - Time I/O Ratio Regression Results

	Dependent variable:	
	Time I/O Ratio Initial Model	Time I/O Ratio Final Model
Maintenance Regime 2	0.021 (0.046)	
Maintenance Regime 3	0.010 (0.050)	
Qty of Plant 1 By-product Used	0.433^{**} (0.209)	0.414^{**} (0.161)
Formula 1 Used	0.008 (0.039)	
Formula 2 Used	−0.005 (0.023)	
Formula 3 Used	0.014 (0.018)	
Formula 4 Used	0.034 (0.056)	
Formula 5 Used	0.045 (0.041)	
Formula 6 Used	0.120^{***} (0.031)	0.126^{***} (0.023)
Formula 7 Used	0.097^{**} (0.038)	0.080^{**} (0.033)
Plant in Damaged Condition	0.002 (0.046)	
Constant	0.224^{***} (0.023)	0.242^{***} (0.011)
Observations	87	87
R^2	0.333	0.305
Adjusted R^2	0.235	0.280
Residual Std. Error	0.999 (df = 75)	0.999 (df = 83)
F Statistic	3.408^{***} (df = 11; 75)	12.153^{***} (df = 3; 83)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.0752	0.0729
Maintenance Regime 2	0.0572	0.0569
Maintenance Regime 3	0.0577	0.0546
Note:		$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table B.14: Metallurgical Plant 3 - Raw Material 1 I/O Ratio Regression Results

	Dependent variable:	
	Raw Material 1 I/O Ratio	Raw Material 1 I/O Ratio
	Initial Model	Final Model
Maintenance Regime 2	−0.111**	−0.050**
	(0.046)	(0.020)
Maintenance Regime 3	−0.072	
	(0.050)	
Formula 1 Used	0.001	
	(0.016)	
Formula 2 Used	−0.135***	−0.139***
	(0.016)	(0.016)
Formula 3 Used	−0.004	
	(0.030)	
Formula 4 Used	−0.075*	−0.082**
	(0.039)	(0.039)
Formula 5 Used	−0.225***	−0.220***
	(0.041)	(0.042)
Formula 6 Used	−0.151***	−0.157***
	(0.028)	(0.027)
Plant in Damaged Condition	0.109**	0.044***
	(0.047)	(0.015)
Constant	1.030***	1.029***
	(0.009)	(0.007)
Observations	87	87
R^2	0.673	0.658
Adjusted R^2	0.635	0.633
Residual Std. Error	1.000 (df = 77)	1.000 (df = 80)
F Statistic	17.590*** (df = 9; 77)	25.704*** (df = 6; 80)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.0411	0.0405
Maintenance Regime 2	0.0611	0.0627
Maintenance Regime 3	0.0633	0.0625
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.15: Metallurgical Plant 3 - Energy I/O Ratio Regression Results

	Dependent variable:	
	Energy I/O Ratio Initial Model	Energy I/O Ratio Final Model
Maintenance Regime 2	−0.032	
	(0.200)	
Maintenance Regime 3	-0.459^{**}	-0.344^{***}
	(0.211)	(0.061)
Formula 1 Used	−0.215	
	(0.157)	
Formula 2 Used	-0.152^{*}	-0.157^{**}
	(0.080)	(0.064)
Formula 3 Used	0.031	
	(0.307)	
Formula 4 Used	0.222	
	(0.156)	
Formula 5 Used	0.003	
	(0.161)	
Formula 6 Used	0.108	
	(0.112)	
Plant in Damaged Condition	0.068	
	(0.181)	
Constant	1.179^{***}	1.176^{***}
	(0.086)	(0.050)
Observations	87	87
R^2	0.345	0.294
Adjusted R^2	0.269	0.278
Residual Std. Error	1.000 (df = 77)	0.998 (df = 84)
F Statistic	4.509^{***} (df = 9; 77)	17.516^{***} (df = 2; 84)
Est. Original Residual Std. Error		
Maintenance Regime 1	0.4173	0.4121
Maintenance Regime 2	0.2358	0.2335
Maintenance Regime 3	0.247	0.2485

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.16: Metallurgical Plant 3 - Time I/O Ratio Regression Results

	Dependent variable:	
	Time I/O Ratio Initial Model	Time I/O Ratio Final Model
Maintenance Regime 2	0.011	
	(0.053)	
Maintenance Regime 3	−0.006	
	(0.056)	
Formula 1 Used	−0.008	
	(0.037)	
Formula 2 Used	−0.007	
	(0.015)	
Formula 3 Used	−0.038	
	(0.073)	
Formula 4 Used	−0.010	
	(0.026)	
Formula 5 Used	−0.039	
	(0.044)	
Formula 6 Used	0.008	
	(0.019)	
Plant in Damaged Condition	0.025	
	(0.051)	
Constant	0.216^{***}	0.231^{***}
	(0.020)	(0.006)
Observations	87	87
R^2	0.045	0.000
Adjusted R^2	−0.066	0.000
Residual Std. Error	0.997 (df = 77)	0.994 (df = 86)
F Statistic	0.405 (df = 9; 77)	
Est. Original Residual Std. Error		
Maintenance Regime 1	0.0996	0.4073
Maintenance Regime 2	0.067	0.2308
Maintenance Regime 3	0.041	0.2456
Note:		$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$