Investigating the effect of non-assembled product kits on the resource efficiency of process chains

by

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

……………………………… ……December 2017……

Signature Date

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Abstract

In order for manufacturing suppliers to stay competitive in the global market, innovative and resource-efficient process chains need to be a part of the manufacturing strategy. Global megatrends are macroeconomic and geostrategic forces that shape our world. Thus, the manufacturing industry must adapt to benefit from these opportunities or risk being left behind.

These rapid advancements are changing the way in which we approach the manufacturing of products. The nature of products, the change in consumer demand, the economics of production and the economics of the supply chain have led to a fundamental shift in the way that companies do business. There is an increased demand for customisation and personalisation from customers. IKEA is one example of a company successfully benefitting from the use of non-assembled product kits and do-it-yourself (DIY) products. The 'IKEA effect' shows that people tend to place more value on products that they created themselves, even if these products are mundane and not unique; customers are satisfied if the products are fun to build, or customised.

A firm's competitive advantage is sustained only by transforming its resources into customer-valued products, services and DIY experiences through various operational capabilities. Therefore, the aim of this research was to investigate the effect of non-assembled product kits on the resource efficiency of process chains. The research objectives included the design of a framework to determine this effect on the process chain as well as determining the advantages and disadvantages of using non-assembled product kits.

Case studies of IKEA furniture, Dell computers and bamboo bicycle kits were used to understand the market for non-assembled product kits. This information was used to develop a framework to be used by companies to determine the impact of incorporating non-assembled product kits on the resource efficiency of their process chains. A bamboo bicycle was manufactured to aid in the development of equations to be used by the framework. A titanium satellite was manufactured and used as a validation study to determine the accuracy of the framework. The results were compared to traditional products and illustrated by using graphs that showed the comparison in terms of cost, time, waste, quality and energy consumption.

The results illustrate that the use of non-assembled product kits has more advantages than selling fully assembled products. The value chain for non-assembled product kits has an impact on every stage of the traditional value chain. The newly developed framework illustrates the effect of converting an existing product to a non-assembled product kit. The results are not a specific value but give the investigating company an indication of the effect of using non-assembled product kits on the resource efficiency of the given process chain for its product. A bamboo bicycle was validated and showed a decrease of 24% for the total manufacturing time. The only setback being the 30% decrease in quality control due to the assembly step being outsourced to the customer.

Opsomming

Vir vervaardigingsleweransiers om mededingend in die globale mark te bly, moet innoverende en hulpbrondoeltreffende proseskettings deel van die vervaardigingstrategie wees. Globale megatendense is die makro-ekonomiese en geostrategiese kragte wat vorm aan ons wêreld gee. Daarom moet die vervaardigingsbedryf aanpas om voordeel uit hierdie geleenthede te trek of die risiko loop om agter te bly.

Hierdie snelle vorderings verander die manier waarop ons die vervaardiging van produkte benader. Die aard van produkte, veranderings in verbruikersvraag, die ekonomie van produksie en die ekonomie van die aanbodketting het gelei tot 'n fundamentele skuif in die manier waarop maatskappye sake doen. Daar is 'n verhoogde vraag na doelgemaaktheid en verpersoonliking by kliënte. IKEA is een voorbeeld van 'n maatskappy wat met sukses voordeel trek uit die gebruik van niegemonteerde produkboustelle en selfgemaakte produkte. Die "IKEA-effek" toon dat mense geneig is om meer waarde te heg aan produkte wat hulle self geskep het, selfs al is hierdie produkte alledaags, nie uniek nie, pret om te bou of doelgemaak.

'n Firma se mededingende voordeel word volgehou alleen deur die omskepping van sy hulpbronne in kliënt gewaardeerde produkte, dienste en doen-dit-self-ervarings deur verskeie bedryfsvermoëns. Daarom is die fokus van hierdie studie om die effek van niegemonteerde produkboustelle op die hulpbrondoeltreffendheid van proseskettings te ondersoek. Die navorsingsdoelwitte sluit in die ontwerp van 'n raamwerk om hierdie effek op die prosesketting te bepaal, asook om die voordele en nadele van die gebruik van niegemonteerde produkboustelle vas te stel.

Gevallestudies van IKEA-meubels, Dell Computers en bamboesfietsboustelvervaardigers word gebruik om die mark vir niegemonteerde produkboustelle te verstaan. Dit word gebruik om 'n raamwerk te ontwikkel waarmee maatskappye kan bepaal watter impak die inkorporering van niegemonteerde produkboustelle op hulle proseskettings se hulpbrondoeltreffendheid het. 'n Bamboesfiets is vervaardig om te help met die ontwikkeling van vergelykings wat in die raamwerk gebruik word. 'n Titaniumsatelliet is vervaardig en gebruik as 'n stawingstudie om die akkuraatheid van die raamwerk te bepaal. Die resultate word met tradisionele produkte vergelyk en geïllustreer deur grafieke te gebruik wat die vergelyking ten opsigte van koste, tyd, vermorsing, gehalte en energieverbruik aandui.

Die resultate illustreer dat die gebruik van niegemonteerde produkboustelle meer voordele inhou as die verkoop van volledig gemonteerde produkte. Die waardeketting vir niegemonteerde produkboustelle het 'n impak op elke stadium van die tradisionele waardeketting. Die nuut ontwikkelde raamwerk illustreer die effek van die omskepping van 'n bestaande produk in 'n niegemonteerde produkboustel. Alhoewel die resultate nie 'n spesifieke waarde bied nie, gee dit die ondersoekmaatskappy 'n aanduiding van die effek wat die gebruik van niegemonteerde produkboustelle op die hulpbrondoeltreffendheid van sy produk se bepaalde prosesketting het.

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Glossary

6R	recycle, reuse, reduce, remanufacture, redesign and recover
BTO	build to order
CTO	configure to order
DFA	design for assembly
IKEA	Ingvar Kamprad Elmtaryd Agunnaryd (Swedish home furnishing retailer)
SKU	stock-keeping unit
VBA	Visual Basic for Applications
VOC	voice of the customer

Nomenclature

$C_{manufacturing}$	total manufacturing process cost	[R]
C_p	machine purchase price per part	[R]
C_o	operating costs	[R]
C_l	labour costs	[R]
C_m	material costs	[R]
T_b	building time in hours	[hours]
X	percentage up-time of the machine	[%]
Y	machine life	[hours]
C_{m-rate}	cost rate of the machine being used	[R]
C_{l-rate}	labour rate for the skill required	[R]
C_u	cost per unit of material	[R]
U_m	units of material used	[units]
T_c	cycle time	[min]
T_o	operation time	[min]
T_p	processing time	[min]
T_s	setup time	[min]
T_r	run time	[min]

1 INTRODUCTION

Designing and manufacturing a new or improved product in modern times have become more and more complicated as technology improves (1). Together with the improvement of technology (2), manufacturing has changed its emphasis with regard to product volume and variety, and these paradigm changes can be seen in Figure 1.1. As more processes become available, choosing the best ones is vitally important. Social manufacturing includes the shared creation, distribution trade, production and consumption of goods, resources and services by different people and organisations (3). This new manufacturing paradigm has already been implemented successfully by various businesses.

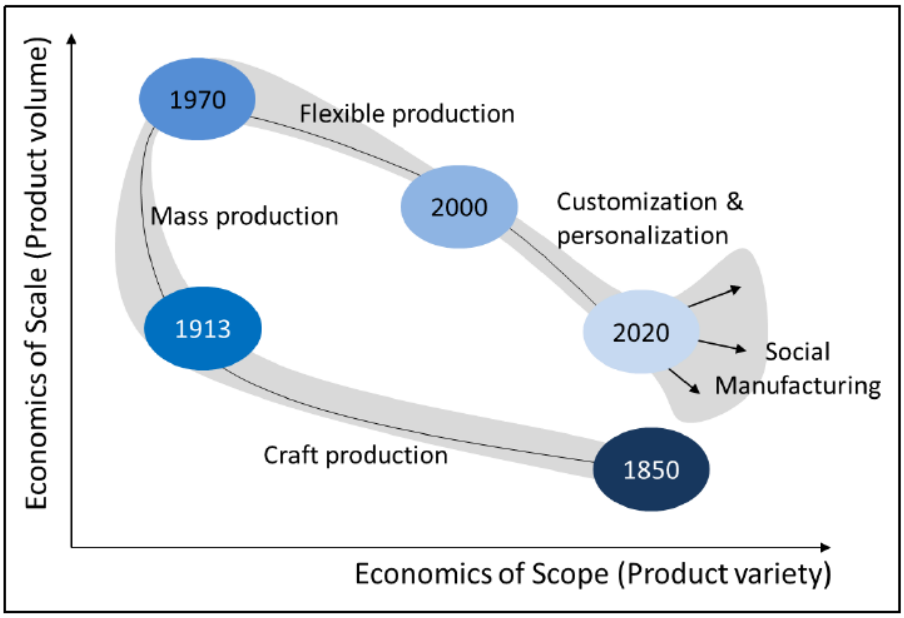


Figure 1.1: Changes in manufacturing paradigms illustrating the movement towards social manufacturing (4)

Manufacturing is defined as an activity that is used to convert the form of raw materials in order to create products (5) and is continuously changing due to the improvement of available technologies. While some industries use new and advanced methods, others maintain a highly skilled traditional craftsmanship (6). Each manufacturing process is generally characterised by some advantages and limitations compared with other processes.

Primary manufacturing processes involve the initial conversion of the raw materials into the semifinal product stage. The output of primary manufacturing processes is then subjected to secondary manufacturing processes to obtain the final or finished product geometry. Secondary manufacturing processes involve assembly, surface treatment and finishing.

Manufacturing is always going to be an important part of any product's life cycle. Manufacturing not only provides the goods needed by consumers and industries worldwide; it also accounts for a significant portion of employment, community presence and economic strength (7). Therefore, it is vital to choose the right manufacturing processes to develop a product to keep cost, time and waste to a minimum. The purpose of this research project was to expand my knowledge regarding the capabilities of incorporating non-assembled product kits into the process chain of existing companies. The aim was to promote human development and to encourage economic growth.

In this study, resource efficiency was regarded as the amount of resources required to produce a given level of output; in this case, it was understood to be desirable to minimise the amount of resources in order to achieve the required level of output (8).

According to SAP (Systems, Applications & Products), a German multinational software corporation that produces enterprise software to manage business operations and customer relations, "a process chain is a sequence of processes that are scheduled to wait in the background for an event" (9). Some of these processes trigger a separate event that can, in turn, start other processes. Process chains are usually displayed in a linear sequence, but according to Thompson et al. (10), all manufacturing processes can be defined as the interaction of various items. The main item, which is the final product, determines the production requirements as this is the designed part of the manufacturing process.

An increasing number of manufacturing companies are realising that to compete effectively, they must be able to reduce the cost of their products while at the same time improving or at least maintaining their quality (11). A wide variety of companies have started to allow customers to design and create their own products, such as coffee mugs, ties and t-shirts (12). An experiment by Mochon et al. (12) showed that participants were willing to pay significantly more for an IKEA storage box that they had to assemble themselves than for an identical box assembled by someone else. This effect is labelled as the 'IKEA effect', and it shows that people tend to place more value on products that they created themselves, even if these products are mundane and not unique; customers are satisfied if the products are fun to build, or customised (12).

For companies to stay competitive, they need to invest in more efficient strategies and change their approach to manufacturing to fulfil the customers' needs. Customers request more variety and options while still seeking for the lowest prices. To keep costs at a minimum, several different aspects and strategies can be analysed and maybe implemented. Non-assembled product kits could reduce costs for an existing product while at the same time value is added to that specific product.

Different strategies have a different impact on the entire value chain of a company, as illustrated by the case studies in Chapter 2. Flat-packed furniture from IKEA is an excellent example of the benefits of using non-assembled product kits, whereby customers form part of the value chain by completing the assembly of the product after it is purchased. Non-assembled product kits have limitations, however, as not every product can be transformed into a kit to be sold to customers. The focus of this study was only on the advantages and limitations of products that were eligible to be sold as non-assembled product kits.

Complexity may be a direct result of a strategy for competitiveness. One example is Dell, which rose to prominence by facilitating customers' configuring their computers to their own requirements. Dell managed its operations, specifically regarding suppliers and inventories, to handle the complexity challenge as it knew that this would give the company a competitive advantage over its peers who built to stock. At the time, Compaq, Dell's biggest competitor, maintained a massive inventory with complex variations of its computers while Dell simply assembled as late as possible using a build-to-order (BTO) business model. Instead of maintaining warehouses full of finished products, Dell assembled final configurations after customers had placed their orders and thereby it could ensure that the customers received exactly what they wanted and did not pay for features that they did not need. This flexibility proved invaluable to Dell's success. The ability to build and sell any configuration was its competitive advantage, and this is also the case with some automotive manufacturing plants. Where the same model is built in multiple global locations, a manufacturing plant that cannot produce a certain variant or configuration is at a disadvantage as it cannot compete with other plants to produce those orders.

The term 'value creation' has been receiving more attention over the past years as companies are seeking for ways to add value to their product or service while keeping costs at a minimum. The main focus should always be on the customer and determining what the customer perceives as value being added to a certain product. Value could be interpreted by different customers in different ways, and this should be taken into account when designing a product according to the modern manufacturing paradigm. The strategy to deliver more for less is no longer sustainable, making future-focused manufacturers look for alternative ways to create and capture value. Value creation was investigated in the study to determine the impact that it had when added to the traditional product versus non-assembled product kits.

The research was aimed at investigating the effect of non-assembled product kits on the resource efficiency of process chains. Therefore, the research focused on understanding value creation and the market for non-assembled product kits. IKEA, Dell and bamboo bicycle manufacturers were used as case studies to determine customer needs and to gain the necessary understanding to develop a framework to be used to answer the main research question.

1.1 Problem statement

Increased changes in customer demand, competition and technology force companies to alter the way in which they operate. Companies who are still relying on the conventional company-centric practices find themselves to be troubled by declining profits and a decrease in customer satisfaction. The traditional value creation strategy is isolated and is losing its utility in the emerging economy. A firm's competitive advantage is sustained only by transforming its resources into customer-valued products, services and do-it-yourself experiences through various operational capabilities. Therefore, the aim of this research was to investigate the effect of non-assembled product kits on the resource efficiency of process chains, as illustrated in Figure 1.2.

Figure 1.2: Illustration of the problem statement, namely whether a company should sell its product as a non-assembled product kit or as a fully assembled product

The problem statement was used to determine the scope of this project in more detail.

1.2 Project scope

This study included the investigation of value creation in the manufacturing industry. This included the hard and soft values associated with the individual value chain as well as the process chain of companies manufacturing products, as illustrated in Figure 1.3. The hard metrics include the need for companies to be competitive and resource efficient, which is measured by using data and statistics. Soft metrics focus on strategies that are against automation, focusing more on skills development and job creation, which is measured by the level of attachment from the customer.

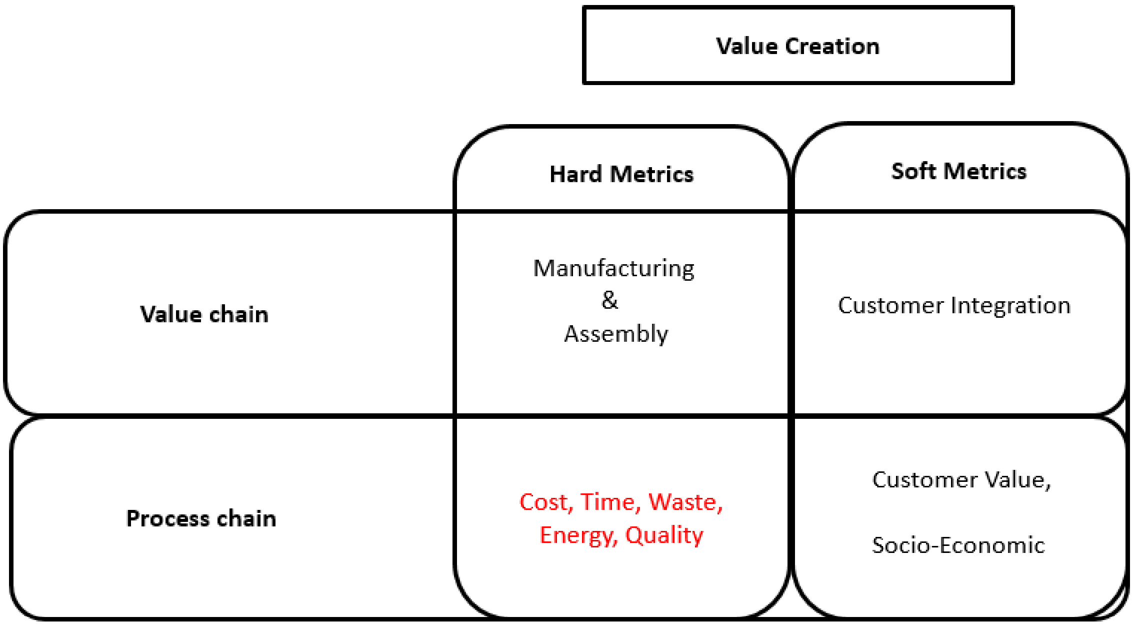


Figure 1.3: Diagram illustrating the scope and the main focus of the research (for illustrative purposes only)

The IKEA effect supported the main focus of this research, illustrating the advantages of using non-assembled product kits and the effect thereof on the resource efficiency of process chains. The project scope provided the necessary focus to formulate the research questions.

1.3 Research questions

From the problem statement and project scope, the following research questions arose:

- How does the use of non-assembled product kits impact the manufacturing process chain?
- Are there examples of companies benefitting from using non-assembled product kits?
- How does the use of non-assembled product kits impact the process chain of a product?
- How does one decide whether to make use of non-assembled product kits or not?
- Can a developed framework be used to validate the findings?

1.4 Research objectives

From the research questions, the following four research objectives were identified to determine the effect of using non-assembled product kits on the resource efficiency of process chains:

1. Identify the advantages and disadvantages of selling fully assembled products versus non-assembled product kits.
2. Develop a framework to evaluate the impact of using non-assembled product kits compared to using fully assembled products on the resource efficiency of process chains.
3. Validate the framework with manufacturing research experiments.
4. Make recommendations for future studies leading from this research.

1.5 Report layout

A summary of the different chapters included in this report follows below with a short description of each chapter:

- Chapter 1: Introduction – the chapter gives the background and motivation for the research study.
- Chapter 2: Literature review – the chapter is used to investigate the value chain, manufacturing process chain, non-assembled product kits, existing frameworks for resource efficiency and case studies to complete the required research objectives.
- Chapter 3: Research methodology – the chapter illustrates and describes the methods used during this research study to achieve the required results.
- Chapter 4: Experimental setup and design – the chapter is used to develop the framework to be validated by the experiments in the next chapter.
- Chapter 5: Results and discussion – the chapter describes and discusses the results obtained from the experimental projects.
- Chapter 6: Conclusion – the chapter concludes the research study and describes possible future research leading from this research.

2 LITERATURE REVIEW

This chapter reviews the current literature in order to illustrate the requirements for achieving the research objectives; this literature was used in designing the research methodology. The chapter is divided into value creation systems, the manufacturing process chain, non-assembled product kits, resource-efficient frameworks and case studies of IKEA furniture, bamboo bicycle kits and Dell computers.

2.1 Value creation systems

Value is a measure of environmental, economic and social benefits created within the transformation of raw materials or applied services (13). For engineers to design sustainable production systems, they must be educated to understand the environmental, economic and social effects of value creation within local and global limitations (13). This serves as the background for designing and analysing value creation at every stage of the sustainable development process. The process of adding value is interpreted as a transfer function that describes the inputs and outputs. The required factors for creating the added value in products are process, organisation, equipment and human related.

It is obvious that companies are likely to be more profitable when creating more value. This also increases competitive advantage by providing more value to customers. For companies to develop a personalised competitive strategy, they need to understand how they are creating value and to identify ways to create more value. Porter's value chain will be investigated to understand the importance of the value chain and serves as a means of identifying possible areas for value creation in a company.

2.1.1 Porter's value chain

The term 'value chain' was coined by Harvard Business School Professor Michael Porter in 1985 to describe the set of activities performed to design, produce, market, deliver and support products (14). Porter proposed a general-purpose value chain for companies to use to examine their activities to see how they were connected. The way in which the activities of the value chain are performed determines costs and therefore affects profits. This tool can help companies to understand the sources of value and to determine where they are able to increase the most value with the least effort (15).

Porter's value chain puts the focus on systems and how a company's inputs are changed into outputs that are purchased by customers (16). Porter illustrated a chain of activities common to all businesses, which are divided into primary and support activities, as shown in Figure 2.1.

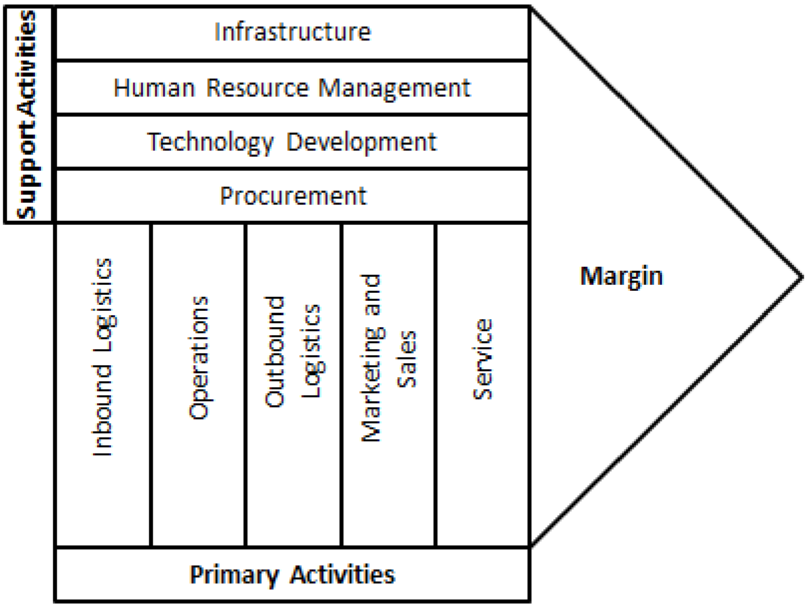


Figure 2.1: Porter's value chain illustrating the interaction between primary and support activities (adapted from (16))

The primary activities of a company relate directly to the physical creation, maintenance, sale and support of a product or service. They consist of the following elements, as illustrated in the figure:

Inbound logistics: All the processes related to receiving, storing and distributing inputs internally. The key factor for creating value with this activity is supplier relationships.

Operations: All the activities to change inputs into outputs to be sold to customers. For this activity, operational systems are used to create value.

Outbound logistics: All the activities performed to deliver a product or service to the customer. Examples include storage, collection and distribution systems; these could be either internal or external to the company.

Marketing and sales: All the processes used to persuade clients to buy the company's products instead of buying from its competitors. Sources of value are the benefits that the company offers and how well it communicates them.

Service: All the activities carried out to maintain the value of the product or service delivered to the customers from when they purchased it.

As seen in Figure 2.1 above, the support activities offer support to the primary functions. They consist of the following:

Procurement: All the activities to acquire all the necessary resources needed to operate, including finding vendors and negotiating for the best prices.

Human resource management: Determined by how well a company hires, recruits, trains, rewards, retains and motivates its workers. Employees are a significant source of value, so businesses can create a great deal of value by using excellent human resource practices.

Technology development: All the activities relating to managing and processing information as well as protecting a company's knowledge base. Some sources of value creation include staying up to date with technological advances, maintaining technical excellence and minimising the costs of information technology.

Infrastructure: The support systems of a company and all the functions allowing it to maintain its daily operations. Examples of necessary infrastructure include legal, general management, accounting and administrative systems, all of which can be used to the company's advantage.

Companies make use of these primary and support activities as 'building blocks' to develop a valuable service or product. Porter's value chain illustrates the importance of all the activities in a firm and how they can incrementally add customer value, resulting in the best product for its customers (17).

Value chain analysis describes the activities within and around an organisation and relates them to an analysis of the competitive strength of the organisation (18). Therefore, value chain analysis evaluates which value each activity adds to the organisation's products or services. This idea was built upon the insight that an organisation is more than a random compilation of machinery, equipment, people and money. Only if these elements are arranged into systems and activities will it be possible to produce something for which customers are willing to pay a price (15). Porter argues that the ability to perform activities and to manage the linkages among these activities is a source of competitive advantage (19).

In most industries, it is rather unusual that a single company performs all activities including product design, production of components, final assembly and delivery to the end user by itself. Generally, organisations are elements of a value system or supply chain, as illustrated in Figure 2.2. Hence, value chain analysis should cover the whole value system in which the organisation operates.

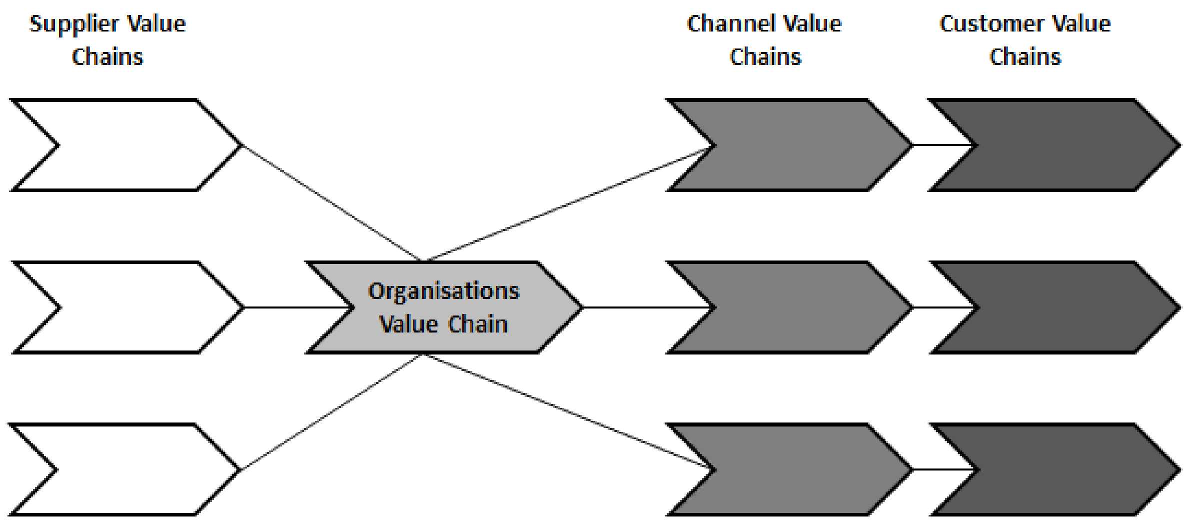


Figure 2.2: Illustration of how an organisation fits into the value system (adapted from (18))

Within the whole value system, there is only a certain value of profit margin available. This is the difference between the final price that the customer pays and the sum of all costs incurred during the production and delivery of the product or service (18). It depends on the structure of the value system how this margin spreads across the suppliers, producers, distributors, customers and other elements of the value system. Each member of the system will use its market position and negotiating power to obtain a higher proportion of this margin. Nevertheless, members of a value system can cooperate to improve their efficiency and to reduce their costs to achieve a higher total margin to the benefit of all of them. The focus of this research was mainly on manufacturing companies and how they fitted into this value system, and therefore the manufacturing value chain will be investigated in the next section.

2.1.2 Manufacturing value chains

A value chain is oriented around the generation of value for the customer, as defined by the customer, while a supply chain is oriented around the flow of inputs and outputs from raw materials to finished goods (20). A typical manufacturing value chain consisting of all the required elements is illustrated in Figure 2.3.

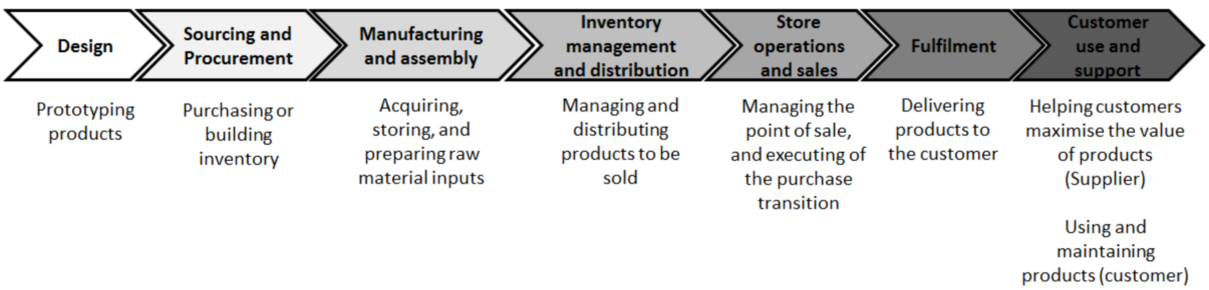


Figure 2.3: Illustration of a typical manufacturing value chain

Supply chain efforts will tend toward improving efficiency and integrating processes in ways that incrementally reduce risks or costs for the company (20). However, value chain restructuring in the context of the same pattern focuses on how new approaches might be used at each stage to meet evolving customer needs in significantly different ways to deliver greater value to the customer (21). This new arrangement of participants and stages can create added value for the customer and the producer beyond the increased cost savings already derived from having fewer steps or shifting work to other participants (22). Through a variety of different strategies, IKEA's value chain greatly differs from the typical manufacturing value chain illustrated above, and this impact is discussed in the next section.

2.1.3 IKEA's value chain

IKEA was founded in 1943 by Ingvar Kamprad and sold cigarette lighters, fountain pens and other items (23). In 1956 IKEA invented flat-packed furniture by accident when a designer took the legs off a Lovet table to fit it into his car boot to take it to a photo shoot (24). This accident resulted in IKEA's global dominance as it became the furniture world leader in 2002 and the United States of America leader by 2010 (25). This simple discovery was the inspiration for a larger cascade of changes in which responsibility for multiple stages of the value chain, including in-store service and assembly, was shifted to the customer. The impact on the traditional value chain of this new approach from IKEA is illustrated in Figure 2.4.

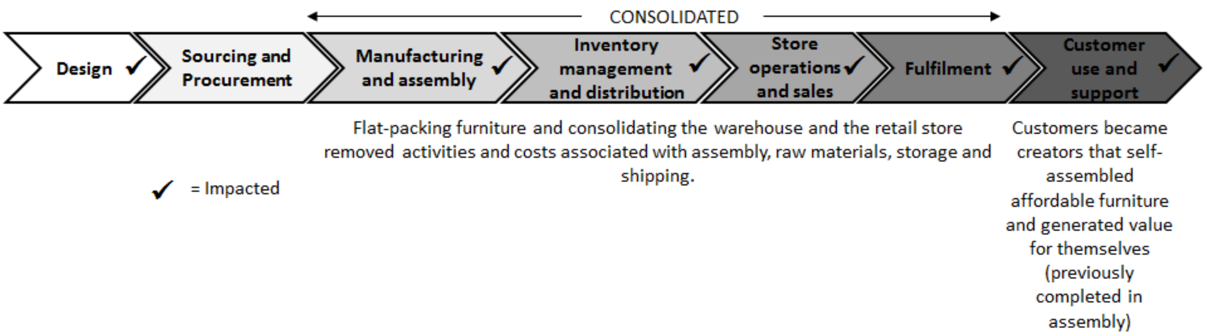


Figure 2.4: Illustration of the impact that IKEA's flat-packing has on the traditional value chain (adapted from (20))

Selling furniture as condensed, unassembled pieces has allowed IKEA to remove some raw material, storage costs and shipping as well as eliminating the order-taking and fulfilment stages and their associated costs from the typical furniture value chain. This also creates an experience for the customer by participating in the value chain and eliminates the lag that usually occurs between a customer's picking out and ordering furniture and receiving it. IKEA customers can pick out desired furniture in one of the company's hybrid retail warehouses, take it home and assemble it on the same day. Consequently, IKEA offers its customers more than just low prices; it changes how businesses interact with their customers by cultivating a shift in customers' mind-set from passive buyers to active participants and mobilising customers to create product value.

2.2 The manufacturing process chain and its elements

Process chains are usually displayed in a linear sequence, but according to Thompson, Alessandro & Mischkot (10), all manufacturing processes can be defined as the interaction of various items. The main item, which is the final product, determines the production requirements as this is the designed part of the manufacturing process. Figure 2.5 illustrates a generic manufacturing process chain used to manufacture a product.

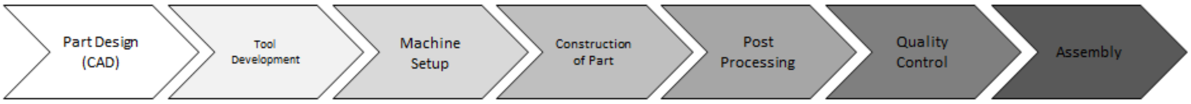


Figure 2.5: A generic manufacturing process chain illustrating all the possible steps to manufacture a product

The key factors influencing the manufacturing process chain include manufacturing cost, manufacturing time, material waste, energy consumption and quality control.

2.2.1 Manufacturing cost

Manufacturing costs are defined as the material, labour and overhead costs of manufacturing a complete product and are one of the most significant qualities and factors to be monitored in the manufacturing process. Figure 2.6 shows the flow of manufacturing costs from an accounting management perspective.

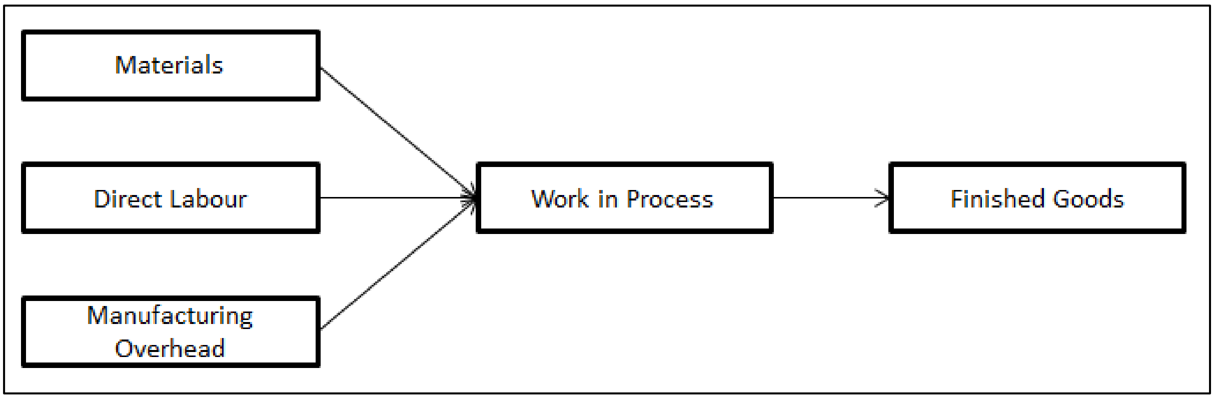


Figure 2.6: Illustration of the flow of manufacturing costs (adapted from (26))

All these costs need to be considered when designing a new product or making improvements to an existing one, and all fall under the manufacturing cost for the product. A cost model approach was developed by Gibson et al. (27) to estimate the costs associated with manufacturing processes. Four main cost areas were identified, namely the operating costs (C_0), the material costs (C_m), the machine purchase price per part (C_p) and the labour costs (C_l) (27). The sum of these costs will be calculated to determine the cost of a part, as seen in equation (1).

$$C_{manufacturing} = C_p + C_o + C_l + C_m \tag{1}$$

To calculate the machine purchase price per part, the purchase price of the machine together with the machine life (Y) and the building time in hours (T_b) of the part needs to be known. The calculation for this cost is illustrated in equation (2).

$$C_p = \frac{Purchase\ price \times T_b}{X \times 24 \times 365 \times Y} \tag{2}$$

X is the percentage up-time of the machine (percentage of the time that the machine is used during the year). Understandably, 24×365 accounts for the number of hours in a year.

To calculate the operating cost, the building time (T_b) of the part is multiplied by the cost rate (C_{m-rate}) of the machine being used. The calculation for the operating cost can be seen in equation (3).

$$C_0 = T_b \times C_{m-rate} \tag{3}$$

To calculate the direct labour cost, the number of labour hours (T_l) must be multiplied by the labour rate (C_{l-rate}) for the skill required. The calculation for the direct labour cost can be seen in equation (4).

$$C_l = T_l \times C_{l-rate} \tag{4}$$

The final cost to be calculated with this model is the material cost. This requires a simple calculation whereby the cost is determined by multiplying the cost per unit of material (C_u) by the number of units of material used during the manufacturing process (U_m) (28). The final calculation for the material cost can be seen in equation (5).

$$C_m = C_u \times U_m \tag{5}$$

These formulas are the most basic to calculate the total manufacturing cost, but more detailed cost models exist for different manufacturing processes. Different manufacturing techniques make use of different machines and limitations, resulting in different ways to determine the cost of a given process.

2.2.2 Manufacturing time

The cycle time is the most important element of each process and is the manufacturing time as this determines the capacity of the production process known to the manufacturers. Standard timing procedures are used in practice to calculate the processing/manufacturing time of a given part. When a production process involves several different parts, the operation times need to be recorded separately for each individual part as its own processing time.

The process quantity also needs to be shown by recording the batch size of the production in addition to the previously mentioned processing time. To calculate the cycle time (T_c) for single or for batch production, two equations are considered, as illustrated in equations (6) and (7).

$$T_c = \frac{T_o \times \#P}{\#Res} \tag{6}$$

$$T_c = \frac{T_p \times \#P}{PQ \times \#Res} \tag{7}$$

The processing time (T_p) is the average time between the completion of units and *PQ* is the batch production for process quantity. The operating time (T_o) is determined by adding the setup time (T_s) and the run time (T_r), as seen in equation (8) (29).

$$T_o = T_s + T_r \tag{8}$$

Equation (9) illustrates how to determine the throughput rate of a product being manufactured.

$$Throughput\ rate = \frac{1}{T_c} \tag{9}$$

When manufacturing time is evaluated from an industry and business perspective, this factor makes up a very large portion of the production lead time. Lead time refers to the time from the moment that an order for the component is placed until the completed product is placed in the hands of the customer (30).

2.2.3 Material waste

Since manufacturing is the core operation in a product's supply chain, when investigating a physical product, designing the system and promoting sustainability in its operations must centre on a sustainable manufacturing approach by focusing on a broader recycle, reuse, reduce, remanufacture, redesign and recover (6R) methodology, as illustrated in Figure 2.7, to not only recycle, reuse and reduce but also to remanufacture, redesign and recover the products over multiple life cycles (31) (32).

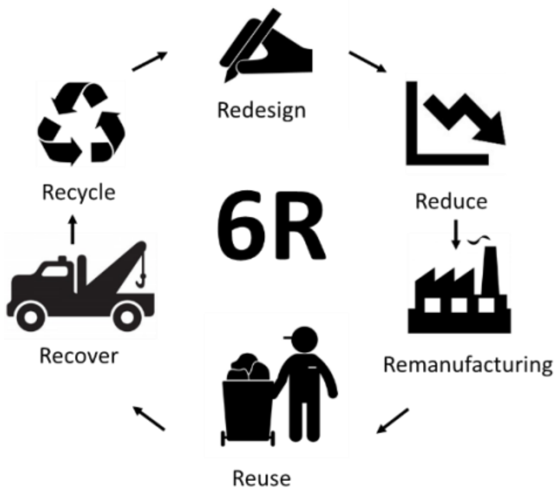


Figure 2.7: Illustration of the 6R concept to minimise the total manufacturing waste

According to the 6R methodology, the main focus of recycle involves the process of converting material that would otherwise be considered waste into new products or materials (33). Reuse refers to the reuse of the product or its components after the product's first life cycle for future life cycles to reduce the use of new raw materials to produce the same products or components (33). The main focus of reduce is on the first three stages of the product life cycle and refers to the reduced use of resources in premanufacturing, the reduced use of energy and materials during manufacturing and the reduction of waste during the use stage (33). Remanufacture refers to the new manufacturing methods and processes performed on the used product (34). Redesign cooperates with the reduce stage by involving the simplification of the component to facilitate postuse processes (34). Recover involves the activities of collecting components that have reached their 'end of life' so that they can be used in subsequent postuse activities (34).

The drive to be more sustainable is a driver for innovation. Innovation in turn encourages fast-tracked growth in manufacturing. Manufacturing is the engine room for wealth generation and social well-being. Jawahir (35) is of the opinion that the 6R approach is core to sustainable manufacturing.

Seven basic types of waste are identified by lean manufacturing, including transportation waste, process waste, inventory waste, waste of motion, waste from product defects, waiting time and overproduction (36). The common causes of waste include poor layout, long setup times, inefficient processes, poor maintenance, poor work methods, lack of training, inconsistent performance measures, ineffective production planning, lack of workplace organisation and poor supply quality (37). Waste can be eliminated by using focused factory networks (38), group technology (39) (40), quality at the source, just-in-time production (41), uniform plant loading, kanban production control systems and/or minimised setup times.

2.2.4 Energy consumption

The manufacturing industry is the leader in energy consumption by consuming as much as 33% of the total available energy in the world (42). This increases the demand for energy and drives up the price for energy as well. Research has found that the energy usage of different manufacturing technologies varies and depends on the volume of the production. The most basic way to determine energy consumption (E_c) is to convert the watts (W) used by the machine to kilowatt hours (kWh), as shown in equation (10).

$$E_c = \frac{W}{1\,000} \times T_c \qquad (10)$$

It is necessary to divide the energy efficiency into different levels. In Figure 2.8, the most important factors affecting energy efficiency are outlined. The lowest level is the process level, which refers to the loss of energy regarding the physical mechanisms of the process (34). The next level is the machine level. Although the machine does use energy during the process itself, it also spends energy on the peripherals of the process. It is important to separate the process and machine levels as energy losses are caused by different technologies and mechanisms. Finally, one should consider the system line level and the factory level of the process.

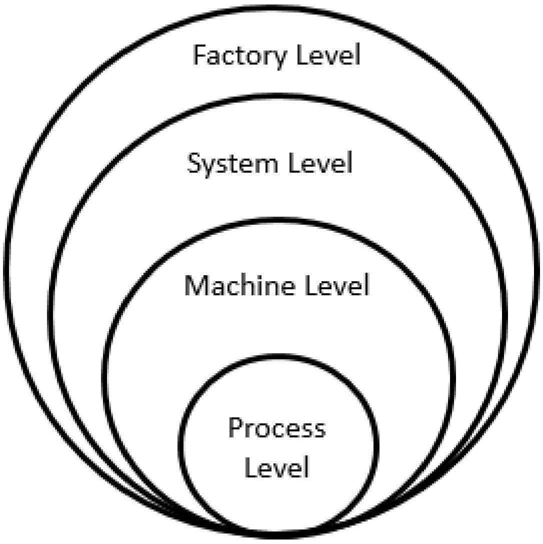


Figure 2.8: Illustration of the different levels of energy consumption in a typical manufacturing process chain (adapted from (43))

It is advantageous that the machine and process levels be separated since the relevant energy losses are due to completely different mechanisms. The International Energy Agency has highlighted the need for energy efficiency measures to achieve a reduction by two-thirds in the energy intensity of the global economy by 2050 (44).

2.2.5 Quality control

Quality control is a process through which a company seeks to ensure that its product quality is maintained or improved and that manufacturing errors are reduced or eliminated (45). Since the common aim in manufacturing is maximising profit and minimising cost, the quality of the product being produced is often an issue when trying to fully adhere to the requirements of the customer (34). Often products are developed in a time frame that is not, in standard cases, possible, resulting in defects and, in turn, material waste (34).

A major aspect of quality control is the establishment of well-defined controls that help to standardise both production and reactions to quality issues (45). Quality control involves the testing of units to determine whether they are within the specifications for the required final product (45). The main purpose of testing the products is to determine whether there is a need to take corrective actions in the manufacturing process (45).

The voice of the customer (VOC) is a term used in business to describe the process of capturing customers' requirements (46). The VOC is a product development technique that produces a detailed set of customer wants and needs that are organised into a hierarchical structure and are then prioritised in terms of relative importance and satisfaction with current alternatives (46).

The VOC provides product developers with the following information:

- A detailed understanding of the customer's requirements.
- A common language for the team going forward.
- Key input for the setting of appropriate design specifications for the new product or service.
- A highly useful springboard for product innovation.

The VOC is a tool used by many organisations to understand the needs of their customers to fulfil those needs to the best of their ability. The main idea is to ensure that the quality of the product is appropriate for customer acceptance to eliminate the possibility of producing defects.

2.3 Non-assembled product kits

Non-assembled product kits are about taking multiple separate stock-keeping units (SKUs) and bundling them into one unit for sale to be shipped as a single order. Two scenarios present the perfect opportunity to kit, namely related products and the components of a single product.

2.3.1 The IKEA effect

A wide variety of companies started to allow customers to design and create their own products, such as coffee mugs, ties and t-shirts (12). An experiment by Mochon et al. (12) showed that participants were willing to pay significantly more for an IKEA storage box that they had to assemble themselves than for an identical box assembled by someone else. This effect is labelled as the 'IKEA effect, and it shows that people tend to place more value on products that they created themselves, even if these products are mundane and not unique; customers are satisfied if the products are fun to build, or customised.

Norton et al. (47) demonstrated the existence and the magnitude of the IKEA effect by performing four experiments. They showed that successful completion was an essential component of the link between labour and liking to emerge; participants who built and then unbuilt their creations or were not permitted to finish those creations did not show an increase in willingness to pay (47). These experiments also addressed other possible explanations for the increased valuation by people of their own creations. They showed that successful assembly of products led to value over and above the value that arose from merely being endowed with a product or merely handling that product; in addition, by using simple IKEA boxes and Lego sets that did not permit customisation, the experiments demonstrated that the IKEA effect did not arise solely because of participants' idiosyncratic tailoring of their creations to their preferences (47). The enjoyment of the assembly process itself could be a contributor to the IKEA effect, but this valuation could vary by product type (47).

2.3.2 Customer engagement

Research and development resulted in improved and even new materials to be used alongside the evolution of manufactured goods. Changing technology, chemicals and plastics have played a role in transforming the way in which items are produced, including the way that they feel and look. The increasing demand to move to virtual technologies leads to new ways of manufacturing products in a different environment, but the need to see the tangible is just as important. This is seen in the perceived higher value of items manufactured using natural materials as reflected in their higher prices and also the high quality of the item itself. The level of attachment to a certain object is the amount of value ascribed to that object. This value can be derived from the object itself, but it can also be generated by the level of engagement by the customer. The level of attachment to products comes from the level of ownership and responsibility assumed by the customer (48). In this context, owning means to hold a personal claim on an object and along with that the responsibility to care for it.

Effort and engagement stimulate the pleasure pathways of the brain, which then reward the behaviour. These pathways have evolved from thousands of years of gathering, hunting, chopping, grinding, cooking foods, farming, building shelters, cleaning those shelters, creating objects to furnish the shelters and to deliver the foods, and creating fabrics and other necessities of life. As stated earlier, modern work has become more virtual, but the brain has not yet evolved to associate hours spent in front of a computer or the swipe of a credit card with sensations of contentment. Therefore, if it is possible to trigger these pleasure pathways by developing products that encourage a level of physical effort from the customer, this may lead to an increased level of attachment.

2.3.3 Design for assembly

Design for assembly (DFA) is the method of design of the product for ease of assembly. DFA is a tool used to assist design teams in the design of products that will transition to productions at a minimum cost, focusing on the number of parts, handling and ease of assembly (49). While design for manufacturing focuses on the reduction of overall part production cost, DFA is concerned only with the reduction of product assembly cost.

The principles included in DFA are to minimise part count, design parts with self-locating features, design parts with self-fastening features, minimise reorientation of parts during assembly, design parts for retrieval, handling and insertion, emphasise 'top-down' assemblies, standardise parts to minimise the use of fasteners, encourage modular design, design for a base part to locate other components and design for component symmetry for insertion (49). The DFA process includes the following seven steps (49):

1. Gather product information: establish functional requirements, carry out functional analysis, identify parts that can be standardised and determine part count efficiencies.
2. Determine the practical part count.
3. Identify quality (mistake proofing) opportunities.
4. Identify handling (grasp and orientation) opportunities.
5. Identify insertion (locate and secure) opportunities.
6. Identify opportunities to reduce secondary operations.
7. Analyse data for new design.

This process proves to be an asset when optimising a design for the assembly step of the product's process chain. This process could lead to a reduced manufacturing time and a decrease in manufacturing cost by making the assembly step as easy as possible for all employees involved in this step. This step may increase the design cost and time, but the benefits obtained from it outweigh the extra expenses.

2.4 Frameworks as theoretical foundation

This section illustrates existing frameworks used to determine the resource efficiency of manufacturing process chains. This determined the starting point for designing the new framework required for this study. The existing frameworks include a resource-efficient framework for titanium process chains, a process chain simulation framework for energy efficiency and a sustainable manufacturing performance measurement framework.

2.4.1 Resource-efficient framework for titanium process chains

Richard Girdwood (34) developed a framework to investigate the resource efficiency of process chains, as illustrated in Figure 2.9. According to his research, there was no benchmark framework and template for the manufacturing of resource-efficient titanium process chains. This developed framework allows manufacturers to determine the optimal procedure to incorporate resource efficiency and sustainability into their manufacturing process chains. The outcomes of both the framework and the excel-based tool can assist manufacturers in

- assessing titanium manufacturing process chains;
- benchmarking a newly developed process chain to an old one;
- identifying the key factors affecting resource efficiency; and
- using the framework to potentially effect a large resource saving together with sustaining the environment through the 6R concept of the framework.

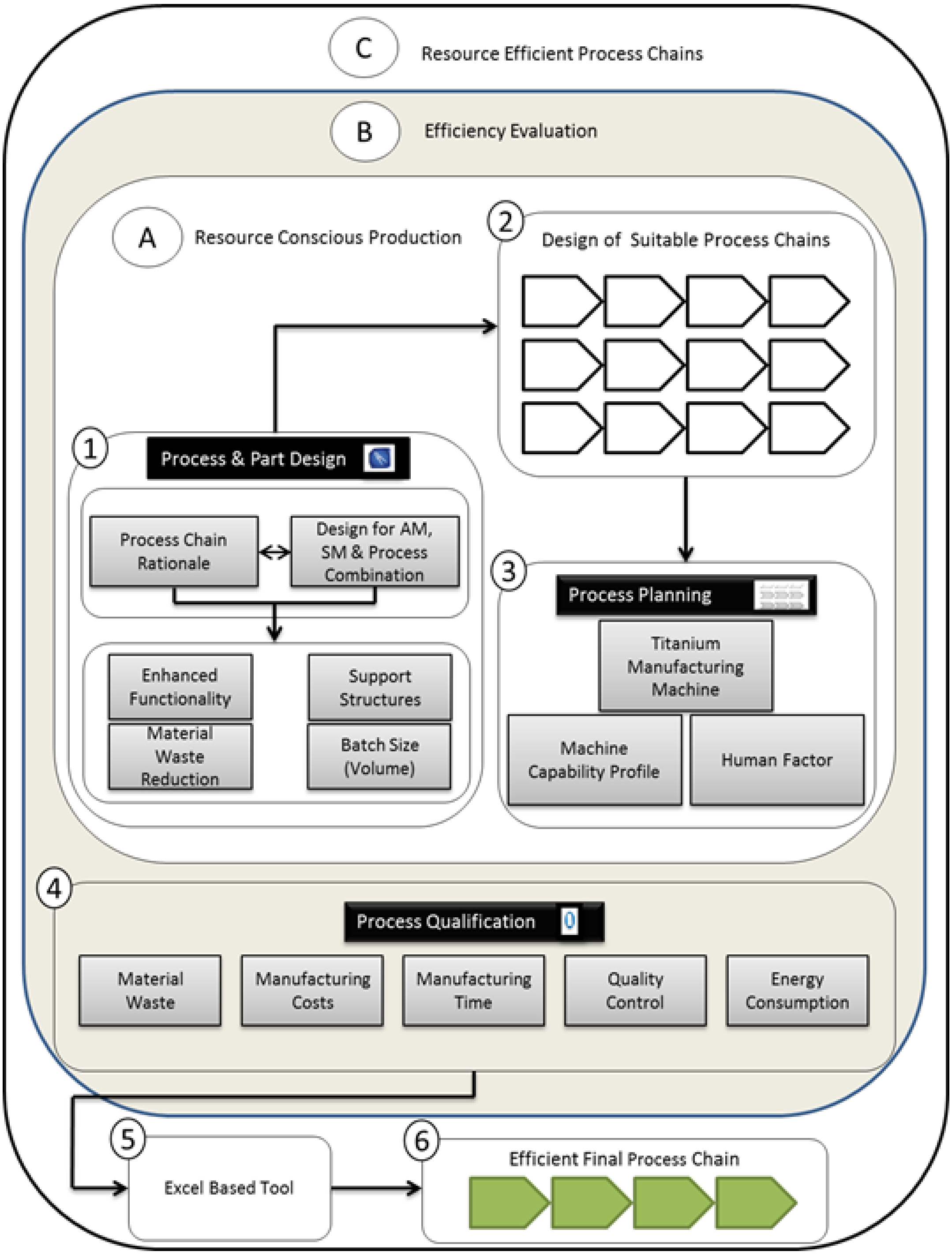


Figure 2.9: A framework used to determine the resource efficiency of process chains (34)

The Excel-based tool from Step 5 of the framework is illustrated in Appendix A. The main focus of this resource-efficient framework is on titanium process chains, but with a few minor changes, this framework can be applied to different materials and process chains in the manufacturing industry.

2.4.2 Process chain simulation framework for energy efficiency

Herrmann and Thiede (50) developed an approach that could determine and evaluate the technical as well as the organisational measures to increase energy efficiency with respect to both economic and ecological objectives. A specific set of data is required as the informational basis when analysing production systems regarding ecological and economic objectives. Therefore, the authors propose an integrated process model, as illustrated in Figure 2.10 below.

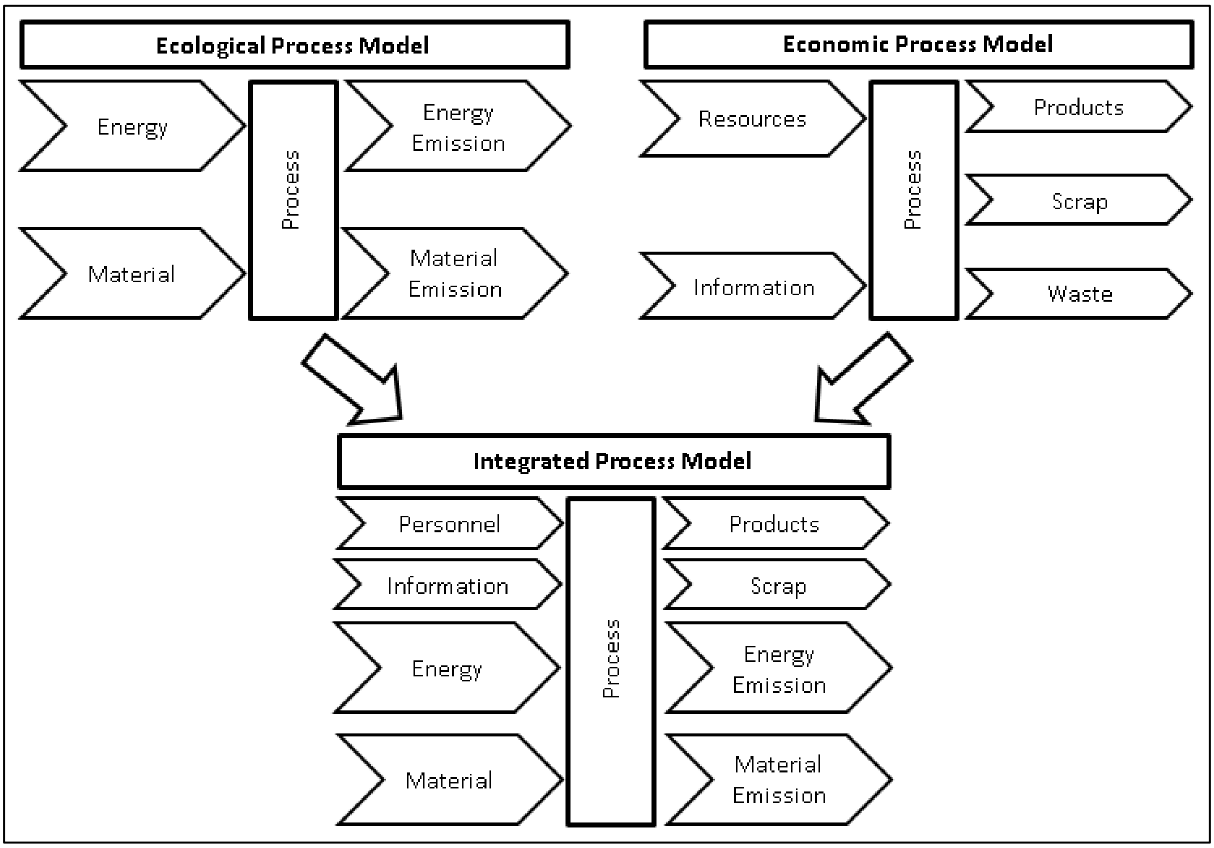


Figure 2.10: Integrated process model illustrating the combination of the ecological and economic process models (adapted from (50))

The integrated process model illustrates a description model of production system flows that allows the capturing of all the relevant input and output flows and their quantitative values. A systematic approach is required to ensure that full coverage of all energy-related aspects is achieved and to enable the derivation and prioritisation of strategies. Therefore, a five-step improvement plan was developed, as illustrated in Figure 2.11.

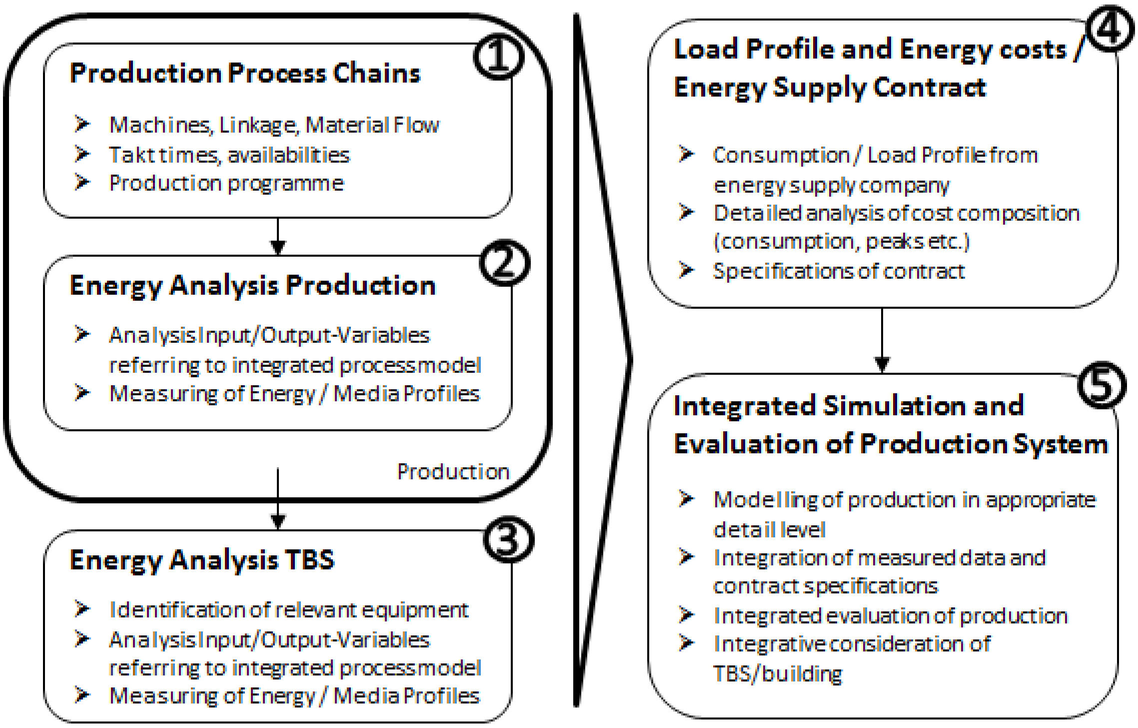


Figure 2.11: Systematic approach to increasing energy efficiency in manufacturing companies (adapted from (51))

Each of these steps will be explained in more detail below:

Step 1: Production process chains

The first step is to gain an understanding of the system, and therefore important data for further steps that are relevant in characterising technical as well as organisational specifications of the processes within the production system need to be analysed. This involves information about the production machines itself, including the cycle times and availability, the material flow and production management.

Step 2: Energy analysis of production (equipment)

The next step involves analysis of the production machines regarding all the input and output flows. Therefore, it is important to move beyond conventional economic process models towards integrated process models that include all the relevant energy and media coming in or out of the machine. Technical documentation will serve as a good starting point to gain an overview and to prioritise processes, but own measurements of energy must be made for at least the major processes.

Step 3: Energy analysis of technical building services

Like in Step 2, all relevant input and output variables in the sense of integrated process models must also be analysed for the technical building services. Typical systems that should be considered here are air compressors, cooling water supply equipment or the air conditioning system.

Step 4: Load profile and energy costs/energy supply contract analysis

An analysis of load profiles is an appropriate way to identify possible drivers and specific characteristics of consumption (e.g. consumption during weekends and peak times). As mentioned before, in case of electricity the costs directly depend on the power load profile (for a month) with significant influence of not only the amount but also the specific pattern of consumption (e.g. surcharges for peaks and cheaper electricity at night). Against this background, the actual composition of the electricity costs and the detailed specifications of the contract have to be analysed. Besides electricity, costs for oil and gas supply naturally also have to be considered in this step to have the full picture of the monetary impact of all energy inputs.

Step 5: Integrated simulation and evaluation of production system

Only the perspective of the whole production system with its process chains allows the consideration of technical interdependencies among different machines (production and technical building services) and the consequences of technical and organisational measures. Simulation as presented above is necessary to cope with the dynamics of the problem when all data are combined, resulting in a cumulative load curve for the whole system. Whereas energy costs and also requirements for technical building services relate to cumulative consumption patterns, the evaluation of actual impacts is also only possible on this layer. While measures to improve energy efficiency may conflict with other target criteria such as throughput times or utilisation, an integrated evaluation is necessary to derive decision support.

2.4.3 Sustainable manufacturing performance measurement framework

It is important to incorporate process and product sustainability metrics when sustainable manufacturing metrics are identified for the enterprise level. Most previous research only focused on premanufacturing, manufacturing and the use stages of a product life cycle, but at a product level, there must be a move from ‘cradle to grave’ to ‘cradle to cradle’. A total life cycle approach that incorporates upstream suppliers and downstream customers requires the implementation of the 6R concept (52). When focusing on the process level, sustainable manufacturing is used to ensure more efficient resource utilisation, reduction of emissions as well as improvement to health and safety. According to Huang and Badurdeen (53), researchers overlooked the integration of process and product sustainability for system sustainability. Design and improvements must be coordinated across products, processes and the system to achieve sustainability in manufacturing.

A comprehensive framework was proposed for developing sustainable manufacturing metrics at the systems level that integrated product and process sustainability metrics, as illustrated in Figure 2.12 as a sustainable manufacturing performance measurement house. Sustainable manufacturing forms the foundation of the framework while 6R, triple bottom line and total life cycle create the pillars to support the house. The performance measurement framework is in the middle of the house to provide an acceptable and consistent approach to systematically collect, analyse, utilise and report the sustainability performance.

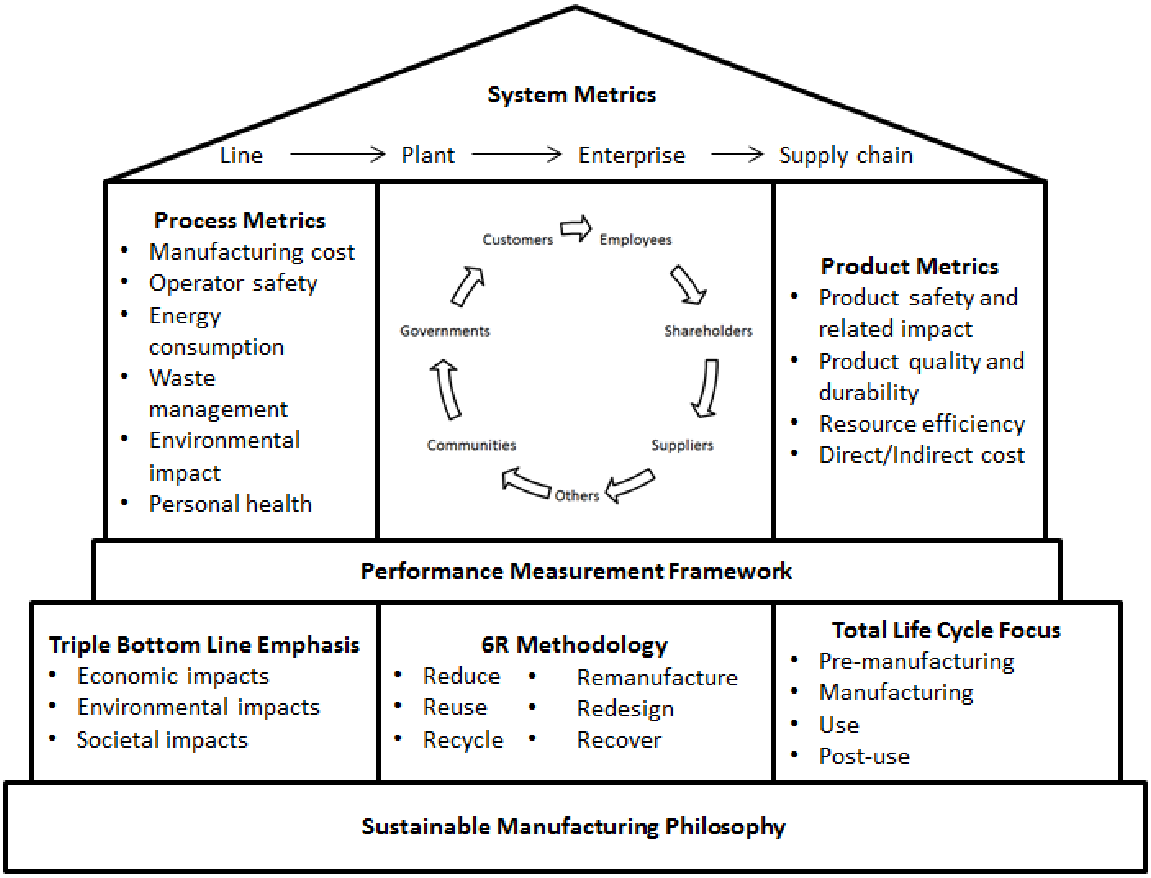


Figure 2.12: Sustainable manufacturing performance measurement framework (adapted from (53))

The stakeholders are illustrated in the middle of the house and should also be considered for sustainability metrics development. The roof of the house is formed by system metrics, which are formulated at four different levels: line level, plant level, enterprise level and supply chain level.

2.5 Evaluating case studies

The final section of the literature review entails case studies of different companies that incorporate resource-efficient techniques to give them the competitive advantage that they require in their respective industries. The lessons learned from these case studies were used to develop the framework for the purpose of this study.

2.5.1 Case study: IKEA furniture

The IKEA group is one of the best known companies in Sweden, with a revenue of over 29 billion euros in 2014, 315 stores in 27 countries, 9 500 product types and 147 000 employees (54). IKEA's business idea is to offer a wide range of furniture with good design and function while keeping prices low enough to allow as many people as possible to be able to afford it (55). Most furniture suppliers focus on expensive and good-looking furniture, which is only affordable by wealthy customers. IKEA turned its focus to low-cost, durable furniture. IKEA creates a relevant offer at a low price by shortening the distance between the need of its customers and the possibilities at its suppliers, as seen in Figure 2.13.

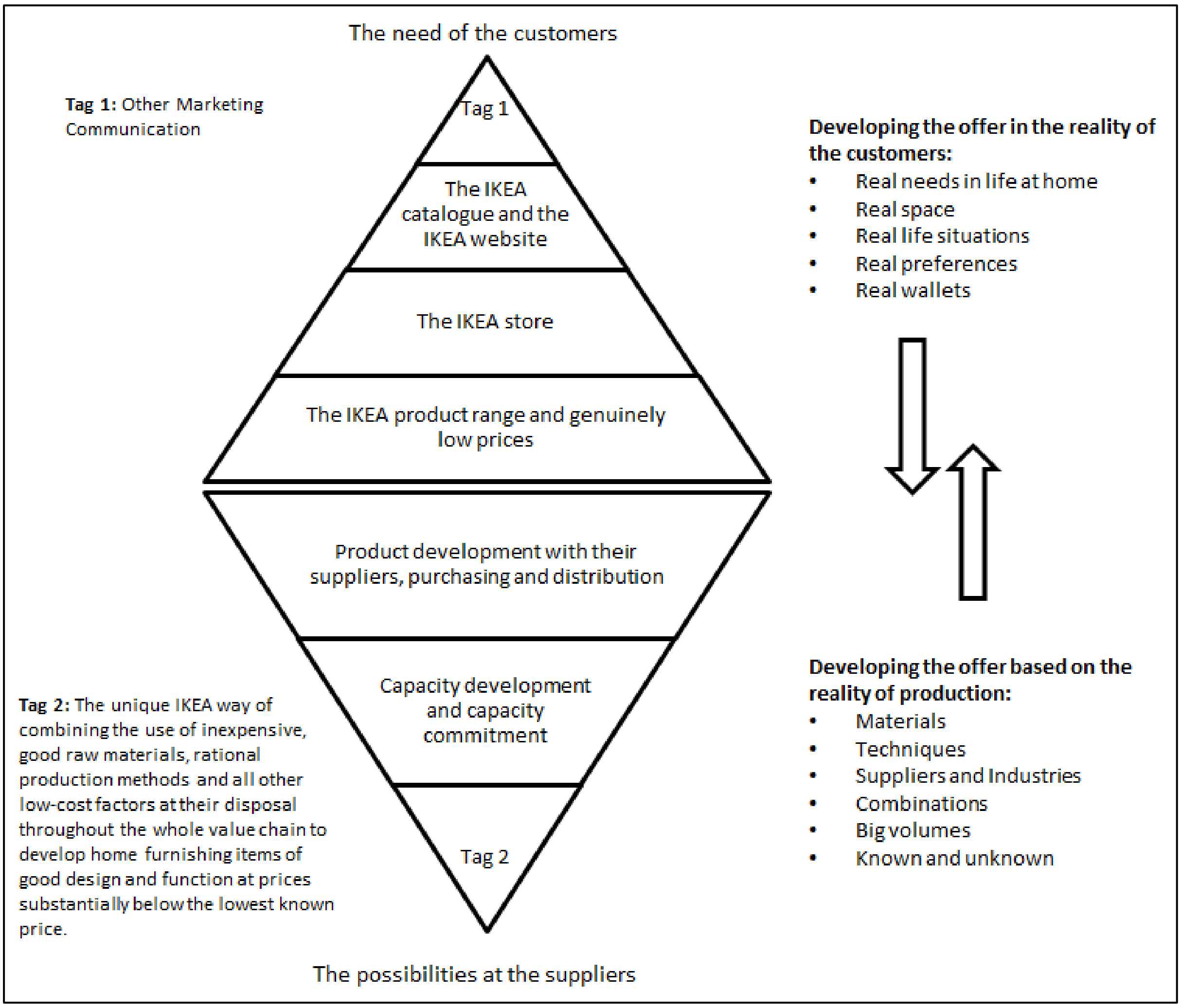


Figure 2.13: Illustration of how IKEA closes the gap between the needs of its customers and the possibilities at its suppliers (adapted from (55))

The business model of IKEA illustrates the value that it creates and the connections that it requires to make a success of its business idea. IKEA is an excellent example of a company that successfully aligns its business model and operating model. In order to deliver on its customer promise of providing quality furniture at affordable prices, IKEA relies on its value chain as a tool to optimise production and to decrease overhead costs (54).

IKEA identified four criteria that each product must meet before it reaches the retail floor, namely sustainability, functionality, good design and affordability. Therefore, it starts the design-planning process of any product by first finalising the price that the product is to be sold at. This forces designers to select raw materials, design elements and manufacturing techniques that reduce production costs. The design team also works on the factory floor for most of the time where it can interact directly with the manufacturing team, helping it to understand the constraints and capabilities of the manufacturing department. This streamlines the process of designing and minimises the cost incurred by the prototyping phase of each new product. IKEA standardises its production processes by using a limited selection of raw materials across the product ranges, and it uses the same basic design for different products. This results in less cost and waste due to lower rates of scrap and defects (54). A few products sold as non-assembled product kits from IKEA are illustrated in Appendix B.

2.5.2 Case study: Bamboo bicycle kits

The popularity of bamboo bicycles has increased over the past few years. In order to expand the market even more in developing countries, it has become important to find the best way of mass producing bamboo bicycles while keeping costs to a minimum (56). Existing methods for building bamboo bicycle frames have a long manufacturing time and are expensive. The case study focused on benchmarking existing approaches on manufacturing bamboo bicycle frames. A typical bamboo bicycle frame is illustrated in Figure 2.14(a) and a fully assembled bamboo bicycle in Figure 2.14(b).

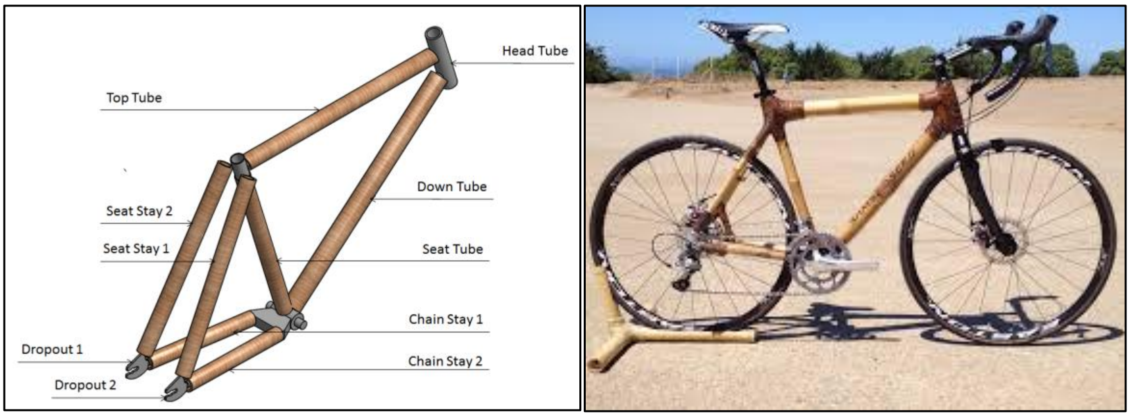


Figure 2.14: a) A typical bamboo bicycle frame showing the parts and what they are referred to; b) A fully assembled bamboo bicycle

Following are benchmark processes from the Bamboo Bicycle Club and HERObike.

2.5.2.1 Bamboo Bicycle Club

The Bamboo Bicycle Club in London strives to help people who have a passion for cycling to be able to build and ride bamboo bicycles by using their workshops (57). The club provides people with all the necessary parts and tools, as seen in Figure 2.15(a), to be creative and to build their own bamboo bicycle from scratch.

Figure 2.15: Bamboo bicycle kit provided by the Bamboo Bicycle Club

All the bamboo is sourced from an importer in the United Kingdom. The club generally uses Mos or Tonkin, which are two of the most common bamboo species for building bamboo bicycles. Both species have good environmental performance and excellent strength properties. The bamboo is hand selected and treated at the source. The club recommends that the bamboo be coated with a protective layer to prevent movement of moisture and to seal the frame against the elements.

The Bamboo Bicycle Club uses a biofibre for the binding material. This material provides a high level of performance and is easier to process than materials that are glass reinforced. These materials make use of twistless technology in order to provide a combination of performance, processability and sustainability. Biofibre offers improved environmental impact, reduced weight, vibration damping and safer handling compared to human-made fibres. Application is easy enough for beginners while still very effective. The properties of biofibre are displayed in Table 2.1.

Table 2.1: Properties of biofibre used for the assembly of bamboo bicycles by the Bamboo Bicycle Club

Property	Biofibre
Fibre volume fraction	60%
Density	1.38 g/cm^3
Tensile strength	78 MPa
Tensile modulus	9.3 GPa
Flexural strength	195 MPa
Flexural modulus	7 GPa

The club also uses a glue to hold the frame together. This is a plant-based bioresin with a 50% reduction in carbon emissions when compared to regular products. The resin shows excellent performance in both compression and tension. The club makes use of a fast-curing resin that allows for roughly 30 minutes of handling time at room temperature. It has good ultraviolet stability and is excellent for all environments. The manufacturing process chain for the Bamboo Bicycle Club's bamboo bicycle is illustrated in Appendix C.

2.5.2.2 HERObike

HERO works as a catalyst for community development in the Alabama Black Belt to end rural poverty. HERObike began in 2009 in partnership with HERO, led by a young designer named John Bielenberg. HERObike has grown over the past years with the help of the Bamboo Bike Studio into a widely known manufacturer of bamboo bicycle kits (58).

Figure 2.16: Bamboo bicycle kit delivered by HeroBike

HERObike sells a bicycle kit, as seen in Figure 2.16, which anyone can use to build her/his own bamboo bicycle by using a simple set of tools. This process involves 11 steps that can be followed in order to complete the frame of the bamboo bicycle. The steps involving secondary manufacturing processes are as follows (58):

I. Fibreglass the lugs and carbon-wrap the dropouts

This step involves eight substeps and takes about one hour to complete. The goal is to strengthen the lugs and to wrap the dropouts. Materials required include fibreglass packets, a mini pump, epoxy resin, epoxy hardener, plastic cups, gloves, safety sleeves, carbon spools, compression tape, a push razor and scissors.

Fibreglass is used to make a basecoat for the lugs. This material is selected because fibreglass can be moulded around the joints in any shape required, which is necessary for the angles and places that are difficult to reach. Fibreglass has a 30-minute handling time after the hardener is added to the epoxy.

The fibre pieces are crossed at the head tube for increasing support. The crossover helps to counteract the stresses applied to the head tube. Fibre is looped where the material and the bamboo meet for extra support. It is important to mix the epoxy in the correct ratio to ensure strength. It is also important to wet the surface before applying the fabric. The fibreglass should be as flat as possible, with all the bubbles worked out and layered on each other. The fibreglass must set for about 15 minutes before compressing it.

Vinyl compression is used to compress the fibre and resin to remove all bubbles. All the resin should be covered but not too tightly to prevent it from making lines. With the adhesive side upwards, the tape is pulled as tightly as possible. Any excess resin is wiped off with a rag, and the tape is kept on for 2.5 hours.

For the seat lug side support, pieces of fibreglass are used to prevent the bike from moving too much. The fabric is cut to length and applied to each side of the seat tube after wetting the entire surface. Loops are added where the material meets the bamboo at the front and stay. The same process is followed as with the head tube. Apply epoxy, apply fabric, set for 15 minutes and apply the compression tape.

The bottom lug follows the same process as the seat tube and also makes use of the side support pieces. Small loops for the chain stays and a main loop for the down tube and seat tube are used.

The last parts of this step are to carbon-wrap and compress the dropouts. It is important to always remember the four laws of wrapping:

i) Always completely wet the carbon fibre in epoxy.
ii) Always lay the carbon wide and flat; avoid its twisting.
iii) Always wrap the carbon fibre tightly; wrapping it loosely will make the bicycle weak.
iv) Cross the carbon over itself; do not simply spiral it around the bamboo.

The dropouts are compressed using the same method as previously described.

II. Prepare lugs for wrapping

This step involves three substeps and takes about one hour to complete. The goal is to remove the compression tape and rough the lugs in final preparation for wrapping. Materials used during this step include a rounded file, razor, sandpaper, dust mask, safety goggles and gloves.

After waiting 2.5 hours for the fibreglass to set, the compression tape needs to be removed. The four-sided file is then used to remove stress concentrators on a macro level and rough up the surface of the cured epoxy on a micro level. The aim is to remove all smooth fibreglass surfaces so that the carbon fibre adheres to the fibreglass. The process is repeated for all the lugs.

III. Carbon-wrap lugs

This step involves eight substeps and takes about one hour to complete. The goal is to carbon-wrap and compress the main lugs. Materials used during this step include gloves, scissors, a mini pump, carbon fibre spools, epoxy resin, epoxy hardener, carbon fibre patches, safety sleeves, plastic container, sandpaper, mixing stick and compression tape.

Once you start wrapping a lug, it is important to make sure that you finish wrapping the lug and compress it before taking a break. The dried resin should be as smooth as possible. There should be no sharp pieces of resin that will act as stress concentrators in the lug. Sandpaper is used to smooth the entire surface with a circular motion. The bottom lug is the most difficult bracket to wrap. Carbon-wrap all the lugs with the same technique as described in Step 1. It is important to remember to slightly offset the pattern to maximise coverage and to vary the positioning of the lock-off points.

The fingers are used to smooth out any lumps in the lug. Carbon patches are used to cover the remaining balsa wood, generally three places where it is difficult to reach. It is advisable to use more carbon spools for heavier people. Use your hands to compress the lug and to squeeze out any extra resin. Any excess resin is wiped off with a rag and left to set for 15 minutes. Compression tape is applied and kept on for 2.5 hours.

IV. Install brake bridge

This step involves four substeps and takes about one hour to complete. The goal is to install the brake bridge. Materials used during this step include gloves, safety sleeves, epoxy resin, epoxy hardener, a mini pump, plastic cup, mixing stick, compression tape, scissors, brake bridge mount, brake bridge, bolts and files.

All the compression tape is removed from the lugs. The file is used to rough the carbon on the seat stays where the brake bridge will be wrapped. Use the four laws of wrapping to wrap the brake bridge in place. The brake bridge and the seat lug are compressed with the compression tape. Any excess resin is wiped off with a rag, and the tape is kept on for 2.5 hours.

V. Finish lugs

This step involves two substeps and takes more than four hours to complete. The goal is to smooth the lugs and to clean up the transitions from carbon to bamboo. This step also completes the building of the bike frame. Materials used during this step include safety goggles, mask, safety sleeves, file, sandpaper, gloves, epoxy resin, epoxy hardener, a mini pump, plastic container, mixing stick, razor, scissors, damp paper towel, two adjustable wrenches and Tung oil.

For this step, the bike is removed from the jig. The lugs are smoothed by using the coarse edge of the file. The aim is to remove all bumps, bulges and divots in order to remove all stress concentrators. One must be careful not to remove too much carbon. The smooth lugs are wiped with a damp paper towel, and the finishing coat of epoxy is applied after the lugs are completely dry. A small amount should be used when applying the final coat of epoxy to the lugs. The purpose is to seal the lugs with a thin finish coat. The paper towel is dipped in Tung oil, and this is rubbed into the bamboo to keep the bike weather resistant and to make it shine. An illustration of the secondary manufacturing process chain for HERObike's bamboo bicycle can be seen in Appendix D.

2.5.3 Case study: Dell computers

Michael Dell founded PC's Limited at the age of 19 while he was a premed freshman at the University of Texas with a game-changing vision for how technology should be designed, manufactured and sold (59). The name of the company was later changed to Dell Inc., but everyone refers to the company as 'Dell' (60). The company's goals were very different from those of its competition, and it strove to simplify the process of offering its products to its customers by providing assistance.

Dell's goal of simplifying its offerings is encapsulated in a programme called 'Smart Selection' (61). This is an offering that will be of interest to a large number of Dell's current and potential customers. Today, Dell can literally sell tens of millions of different kinds of configurations driven by its configure to order (CTO) model (62). In the CTO world, every order is custom-made and is built only after the order has been placed. For commercial customers, this means that the typical waiting period from receipt of order to shipment time is around seven to ten days (63). With Smart Selection, Dell prebuilds what it believes will be the most popular configurations, or SKUs, and ships them within 24 hours (64). This can be considered BTO, something Hewlett-Packard and previously Compaq have been doing for a while (61). Large enterprises can even obtain their approved custom software image by adding another 24 hours. This is a monumental step for Dell and one that has other positive outcomes as illustrated below.

There are many advantages to BTO. The first is supply chain and manufacturing; because the builds are very high volume and manufacturing is scheduled in advance, the total supplier and manufacturing cost is much lower (65). CTO manufacturing lines are designed to produce one custom SKU at a time versus BTO lines that are designed to make thousands at a time. This creates an inventory trade-off, but total success is typically driven by how close one is to knowing what one's customers want. Dell's long history of direct sales gives it a wealth of customer information and, as a result, can be a source of competitive advantage (61). If Dell can effectively mine the reported two billion customer conversations that it has per year, this could work out very well.

BTO configurations are easier to service as well; every CTO configuration is unique and so is a service event (65). BTO configurations can be built in volumes of 100 000 each, and as an original equipment manufacturer, one knows exactly what is inside, making it much easier for the customer to do self-diagnosis and fixes. Dell has rolled out new personal computer diagnostics and drivers and downloads that are easier to find and use, again made easier by Smart Selection SKUs (59). This is important because a satisfied self-service customer is a much happier and lower cost one.

2.5.4 Lessons learned around value creation

IKEA is an example of a company benefitting from the use of non-assembled product kits. This approach provides it with a competitive advantage when compared to its competitors in the same industry. IKEA's focus on the value chain as a tool to optimise production and overhead costs can be used by other companies in different industries. Moreover, finalising the price of the product before the design stage forces the design team to use the most resource-efficient materials and design for any given product. These strategies were incorporated into the design of the framework for the purpose of this study.

The bamboo bicycle case studies illustrate how the same product can have different process chains while delivering more or less the same product. However, different process chains influence the cost and time to manufacture the fully assembled product. The skill of the customer also needs to be considered when attempting to sell a product as a non-assembled product kit. This case study also illustrates the need for clear and easy-to-follow instructions for the assembly process. The design and material selection affect the resource efficiency of the final product. This was considered for the framework designed in this study.

The Dell case study illustrates the different ordering configurations that need to be considered when converting a product from a fully assembled product to a non-assembled product kit. The non-assembled product kit offers more freedom for customisation by providing add-ons to be added to the package being shipped to the customer. This strategy could give a company the competitive advantage that it needs to grow in a given industry.

3 RESEARCH METHODOLOGY

The research started with a comprehensive literature review to understand the theory behind the selected topic. Following were case studies that were used to understand the real-world needs and applications of the theory in the previous step. This information was then used to design a resource-efficient framework. The framework was compared to existing approaches with regard to time, cost, waste, quality and energy consumption. All of this was concluded by stating the lessons learned during this research study and by suggesting future research to be done. The research approach and its steps are illustrated in Figure 3.1. Appendix E contains a table illustrating the project progress tracking strategy used to complete this study in the allowed time.

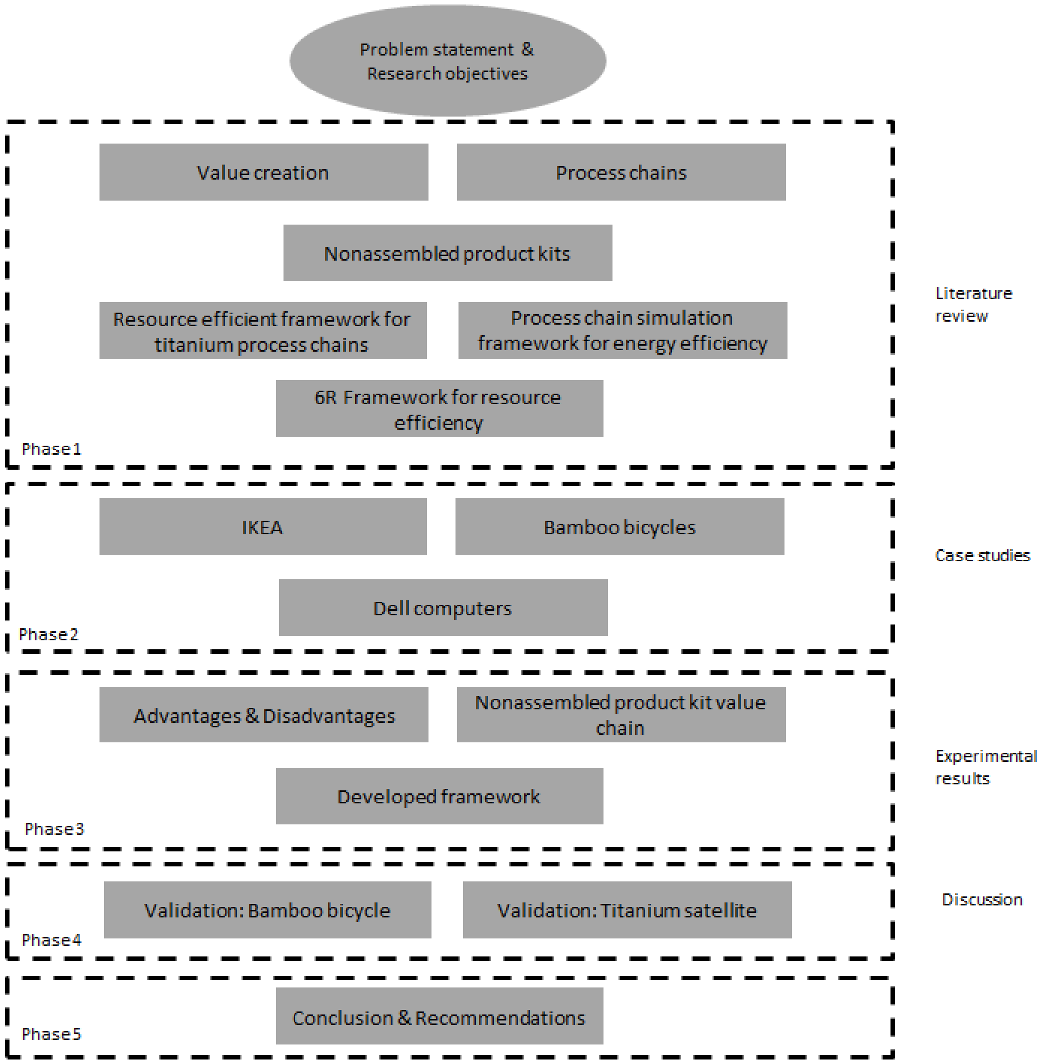


Figure 3.1: Research methodology used to achieve the research objectives for this study

Phase 1: The first phase after the problem statement and research objectives had been defined formed part of the background of and motivation for this study. This phase was executed to understand the literature behind value chains by investigating Porter's value chain and how IKEA impacted the traditional value chain. Process chains form the most important part of any value chain and were investigated with regard to manufacturing time, manufacturing cost, quality, waste and energy consumption. The IKEA effect was also investigated to support the main purpose of this study, which was to evaluate the effect of non-assembled product kits on the resource efficiency of process chains. The first phase of this study also investigated existing resource-efficient process chain frameworks to serve as a benchmark. The resource-efficient framework for titanium process chains, the process chain simulation framework for energy efficiency and the sustainable manufacturing performance measurement framework formed part of this phase.

Phase 2: Case studies of IKEA furniture, Dell computers and bamboo bicycle kits formed part of the second phase of this study. The lessons learned from these case studies were summarised and used for the newly developed framework.

Phase 3: The third phase involved the experimental results, including the advantages and disadvantages and value chain of non-assembled product kits. The framework for the purpose of this study was developed during this phase, including the three phases followed during the design of the framework and the Excel-based tool to be used by the end user.

Phase 4: The fourth phase served to validate the newly developed framework by using existing products that were eligible to be sold as non-assembled product kits. Two bamboo bicycles and a titanium satellite were used as the validation products. The effect on their respective process chains were illustrated with regard to cost, time, waste, quality and energy. The results were also discussed during this phase.

Phase 5: The final phase comprised the concluding remarks and recommendations for future research projects originating from this research.

4 EXPERIMENTAL SETUP AND DESIGN

This chapter shows the experimental results, which include the advantages, disadvantages and value chain of using non-assembled product kits. Based on these results, a new framework was designed for the purpose of this study by modifying an existing framework for resource-efficient process chains. The new framework included an Excel-based tool designed to be as user-friendly as possible. The framework was then validated by incorporating various different products to be considered for selling as non-assembled product kits.

4.1 Advantages and disadvantages of non-assembled product kits

The main objective of this study was to design a framework to be used to determine the effect of non-assembled product kits in the manufacturing process chain. Firstly, it was necessary to identify the advantages and disadvantages of non-assembled product kits compared to the more traditional fully assembled product. The literature from the literature study was used to determine the advantages and disadvantages of non-assembled product kits, as illustrated in Table 4.1.

Table 4.1: The advantages and disadvantages of non-assembled product kits compared to fully assembled products (section supporting the statement)

Non-assembled product kits	
Advantages	**Disadvantages**
Smaller packages required (2.1.3)	No quality control for assembled product (2.5.2)
Lower storage costs (2.1.3)	Not all products qualify (2.5.1)
Lower shipping costs (2.1.3)	
Fewer steps required (2.3.1)	
Increased customer attachment (2.3.1 & 2.3.2)	
Customisable (2.5.3)	

The advantages of selling a product as a non-assembled product kit clearly outweigh the disadvantages. As shown in Table 4.1, not all products are eligible to be sold as non-assembled product kits and this was considered when designing the new framework.

4.2 Non-assembled product kit value chain

The literature mentioned in sections 2.1 and 2.3 was used to define each stage of the value chain for non-assembled product kits and how it differed from the traditional manufacturing value chain. This newly defined value chain is illustrated in Figure 4.1 and was incorporated into the framework designed for the purpose of this study.

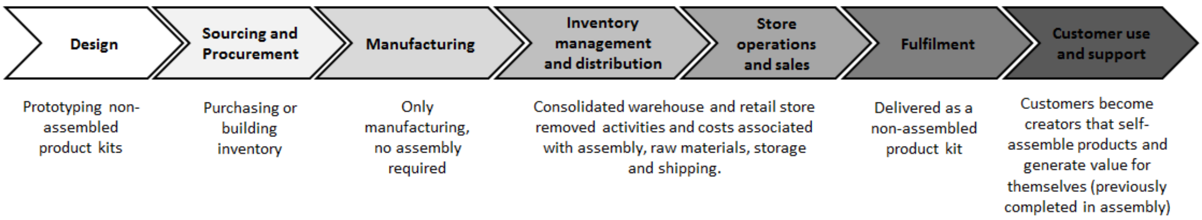


Figure 4.1: Non-assembled product kit value chain

As seen in the non-assembled product kit value chain, the focus of the design stage changed from prototyping products to prototyping non-assembled product kits. This is necessary since the design for a fully assembled product is different from the design for a non-assembled product kit. Non-assembled product kits require new designs for packaging, and the difficulty of the assembly steps needs to be low enough for the customer to complete at home. In some cases, the tools for assembly also need to be added to the product being sold. For the sourcing and procurement stage, most raw materials will be the same as for the fully assembled product, with the necessary tools being the only additional task to be considered for the non-assembled product kit.

The third stage of the value chain only requires manufacturing, seeing that the assembly step of the product's process chain is the customer's responsibility. The non-assembled product kit, like IKEA's value chain, impacts the warehouse and retail stores, therefore removing activities and costs associated with assembly, raw materials, storage and shipping. This has an effect on stages three and four of the non-assembled product kit value chain.

For the fulfilment stage, the package is delivered as a non-assembled product kit including an instruction manual and the necessary tools to be used by the customer to assemble the product. During the final stage of the value chain, the customer uses the fully assembled product and the company offers after-sale support for those who struggle to complete the necessary assembly process.

4.3 Developed conceptual framework

A framework needed to be developed to determine the effect of non-assembled product kits on the resource efficiency of process chains. Rather than developing this framework from scratch, it was decided to use an existing framework that could be modified to fit the needs of this study and in the process solve the research objectives set out at the beginning of this report. The framework in Section 2.4.1 was used as the starting point to develop the new framework for this project.

This framework consists of three phases, starting with resource-conscious production, then progressing to efficiency evaluation and ending with resource-efficient process chains. Many changes were required to suit the needs of the framework for this study, but resource efficiency is a mutual goal for both frameworks, making this the best starting point. The new framework needed to determine the effect of non-assembled product kits on the resource efficiency of process chains of a company. The first step was to modify the existing framework to suit the needs of the new framework before the additional features could be designed. Figure 4.2 illustrates the conceptual decision framework used to develop the new framework for this study.

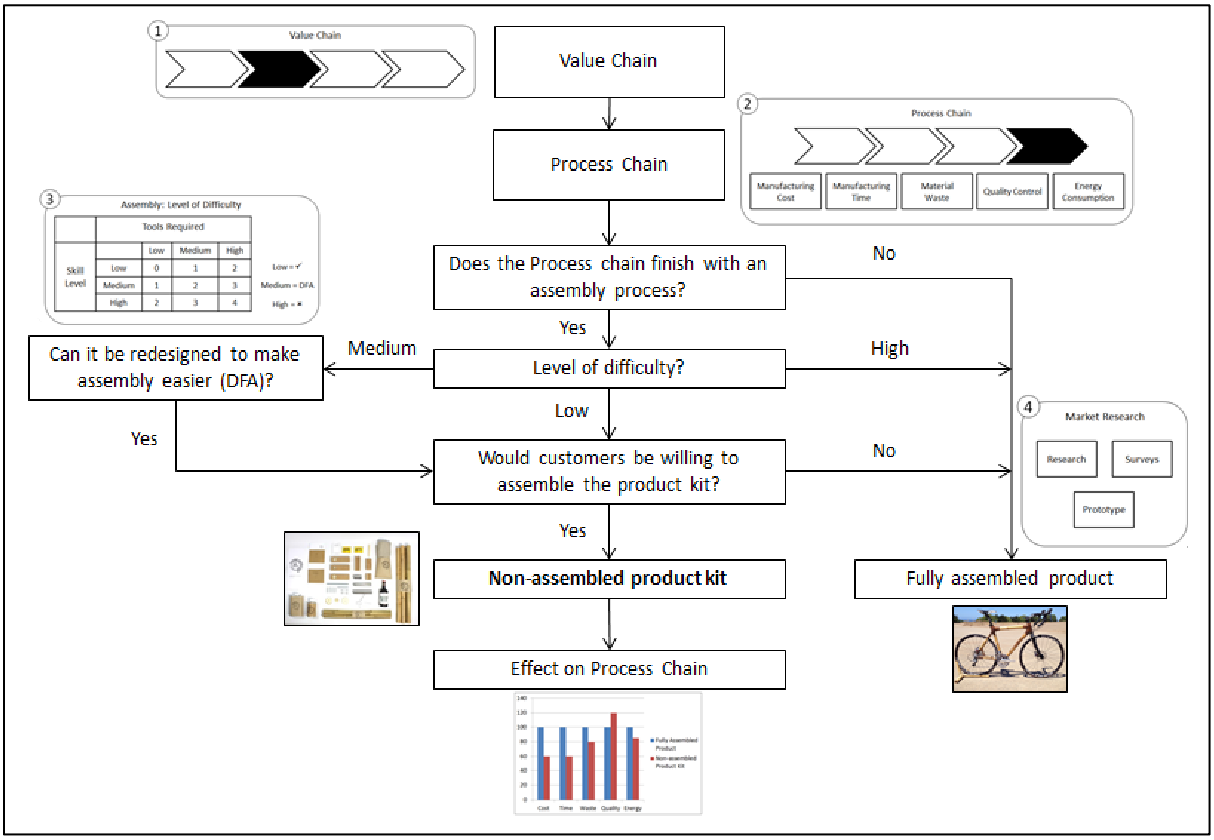


Figure 4.2: Conceptual decision framework for the new framework that was developed

This illustration shows that the user will start the process by developing the value chain and process chain for the product to be evaluated. The value chain serves as the starting point to understand the bigger picture and to show where the process chain fits into the value creation process. The process chain requires the cost, time, waste, quality and energy consumption of each individual step to be used by the framework as the benchmark for comparison at the end of the framework.

The first question being asked by the framework is whether the existing process chain includes an assembly process step. If the assembly process does not exist, the product is better suited to being sold as a fully assembled product; if there is an assembly process, the product moves to the next step of the framework. If successful, the next step is to determine the level of difficulty of the existing assembly process required for the investigated product. This is important because if the difficulty level is too high, customers will not be able to assemble the product at home, making it impossible to transform to a non-assembled product kit. A medium level of difficulty can possibly be altered to lower the level of difficulty, making the product a candidate for a non-assembled product kit. A product with a low level of difficulty automatically moves to the next step of the framework. At this point of the process, it is important to ask whether the customer would be willing to complete this assembly process at home in his/her own time.

The last step of the framework is to determine the effect of transforming the existing product into a non-assembled product kit on the resource efficiency of the process chain. This result will either convince the user to transform his/her product or show that this transformation is not worth the trouble.

The existing framework needed to be redesigned to meet the needs of this study. Three phases were adapted independently to form the newly developed framework to be used to evaluate the effect of non-assembled product kits on the value chain.

4.3.1 Phase A: Minimum requirements

The existing Phase A consists of three steps, including process and part design, design of suitable process chains and process planning. The new framework focuses on designing for assembly rather than on designing for additive manufacturing, subtractive manufacturing or a combination of the two processes. The focus of the new framework, as seen in Figure 4.3, starts with the value chain of an existing product. The value chain is used to identify the importance and the impact of the manufacturing process chain on the entire value chain of a specific product.

The next step requires that the existing process chain of the product be investigated to ensure that the product is eligible to be sold as a non-assembled product kit. If the product is successful in this step, more detail needs to be provided for each step of the process chain. The detail required includes the manufacturing cost, manufacturing time, material waste, quality control and energy consumption.

The third step is used to determine the level of difficulty involved in performing the assembly process required by the process chain. The level of difficulty is measured by determining the tools that are required to perform the task and the level of skill required to perform such a task. The level of difficulty of using different assembly tools is displayed in Table 4.2. These two factors are ranked according to their difficulty by using indications such as low, medium and high. The combined score of these two factors results in one of nine possible difficulty scores for a given product. A combined score of zero or one means that the task is easy enough to be performed by the customer while a combined score of two or three requires alterations to be considered easy enough to be performed by the customer. A combined score of four indicates that the task is too difficult to be performed by the customer and results in a rejection of the product, meaning that the product is not eligible to be sold as a non-assembled product kit.

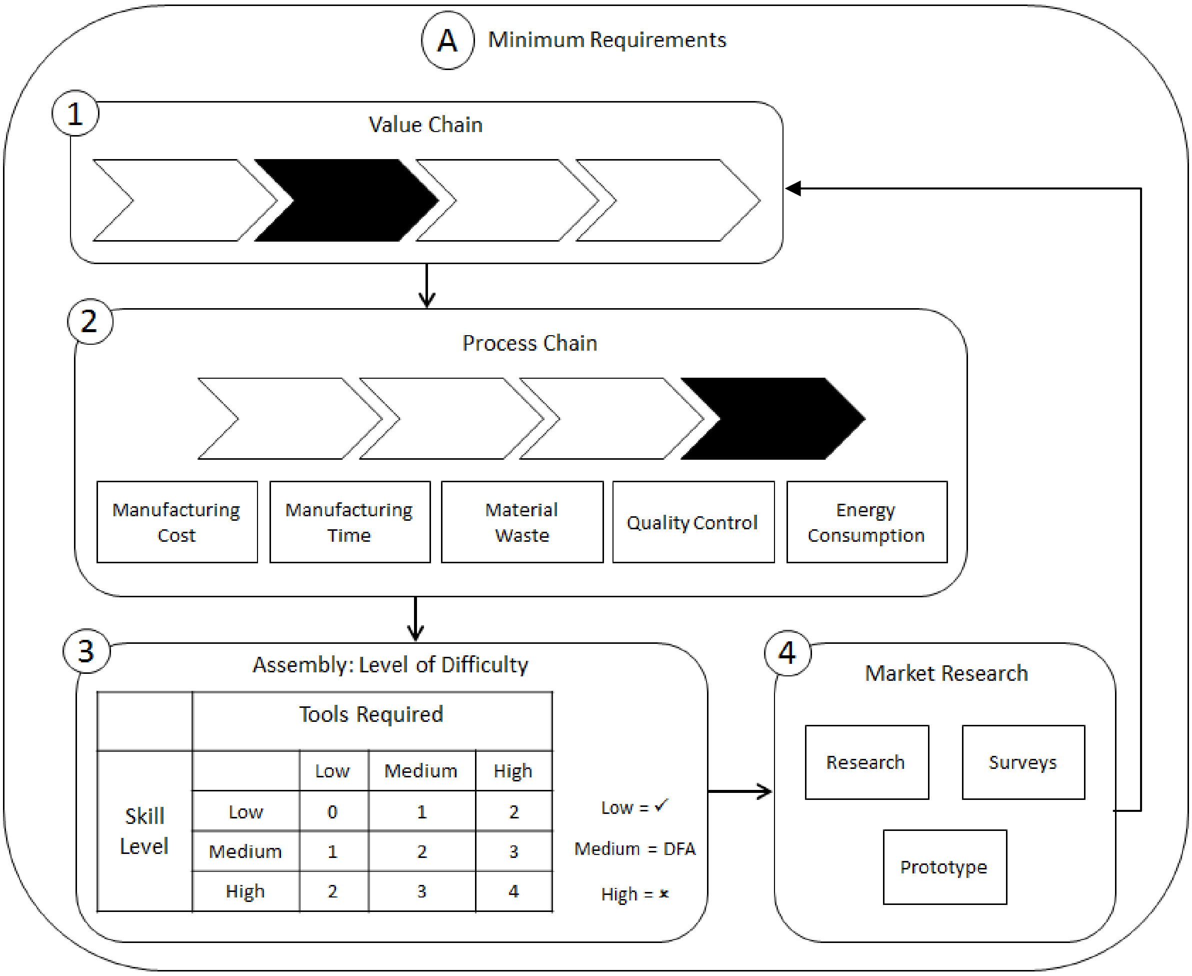


Figure 4.3: Illustration of Phase A for the new framework

Table 4.2: The level of difficulty for the different assembly tools to be used by the customer

	Tool	Difficulty level
1	Hand-held circular saw	High
2	Jigsaw	High
3	Hammer drill	Medium
4	Cordless drill	Low
5	Claw hammer	Low
6	Panel pin hammer	Low
7	Screwdrivers	Low
8	Side cutters	Low
9	Hacksaw	Medium
10	Metal file	Low
11	Pliers	Low
12	Glue gun	Medium
13	Spanner	Low

Step four is used to understand the market of the product being investigated to ensure that the given customer will be willing to perform the required assembly task. This step is completed by doing market research, sending out surveys to the target market and testing prototypes of non-assembled product kits for the product being investigated. If the results from this step indicate that adoption is highly unlikely, it would be best to stay with the fully assembled product, but if the research indicates that the target market will be willing to adopt the product as a non-assembled product kit, the investigated product proceeds to the next phase of the framework.

4.3.2 Phase B: Efficiency evaluation

The second phase is more or less the same for the new framework as both frameworks share a similar objective with this phase. After Phase A, the investigated product is determined to be eligible to be sold as a non-assembled product kit. The purpose of Phase B is to determine the resource efficiency of the new process chain for the product being investigated. A few minor improvements can also be incorporated during this step seeing that the new approach of non-assembled product kits will impact the manufacturing process chain in some way. As illustrated in Figure 4.4, the efficiency of the process chain will be measured with regard to material waste, manufacturing cost, manufacturing time, quality control and energy consumption.

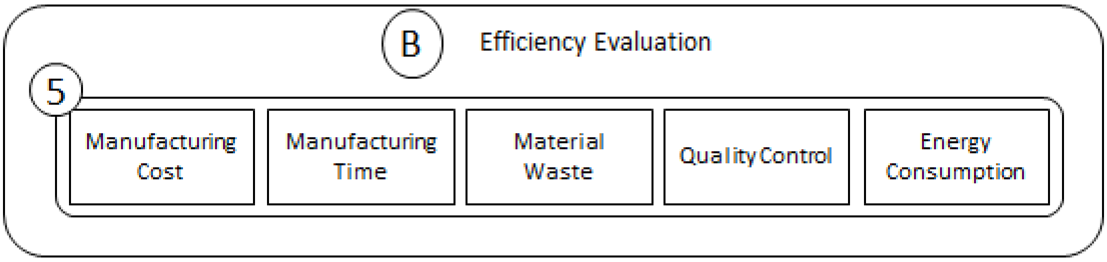


Figure 4.4: Illustration of Phase B for the new framework

The new process chain will then be used for the final phase to determine the impact of the non-assembled product kit on the resource efficiency of the process chain of the investigated product.

4.3.3 Phase C: Value chain impact assessment

The third and final phase of the framework is used to assess the impact on the existing process chain of converting existing products to non-assembled product kits. As illustrated in Figure 4.5, this required the design of an Excel-based Visual Basic for Applications (VBA) user form incorporating all the steps required for this new framework. This not only simplifies the entire process of determining the effect on the process chain but also makes it easier to see the difference in the two process chains, making the decision easier for the company whose product it is.

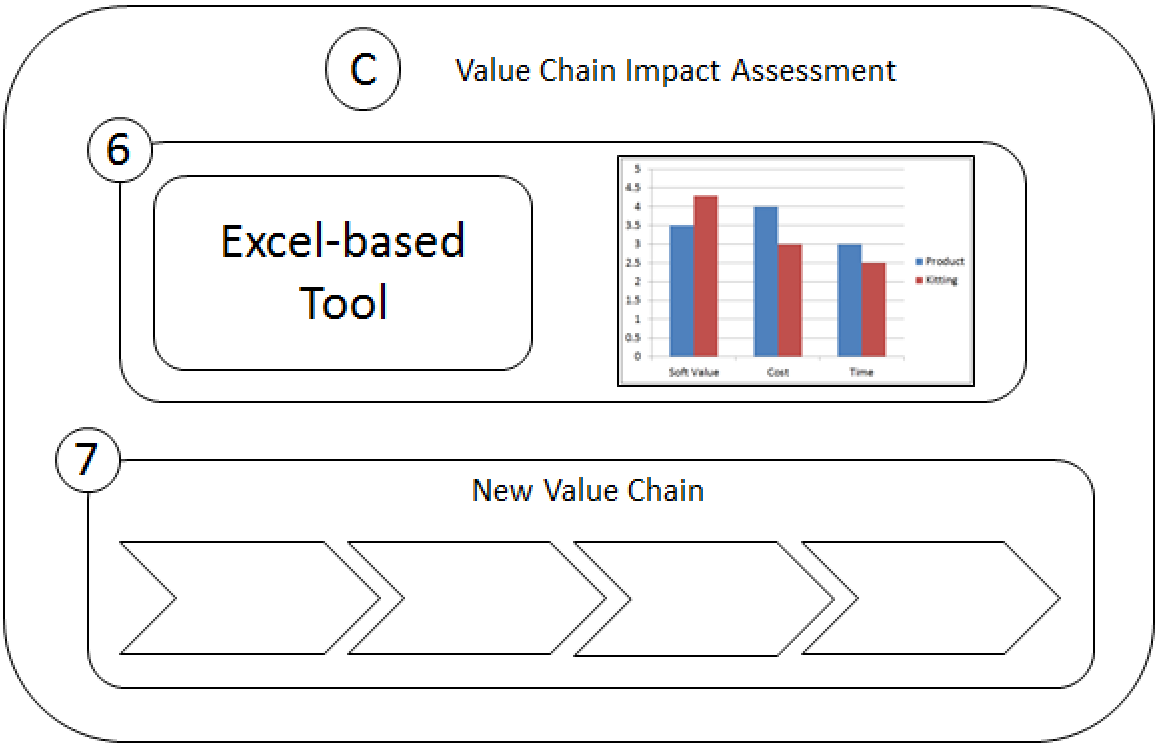


Figure 4.5: Illustration of Phase C for the new framework

Excel was chosen due to its popularity and accessibility and because it is easy to learn. The results from the framework will be displayed in a simple graph illustrating the difference in manufacturing time, cost, quality, waste and energy between the existing process chain and the newly developed process chain. This will be used to determine the effect on the value chain of the investigated product.

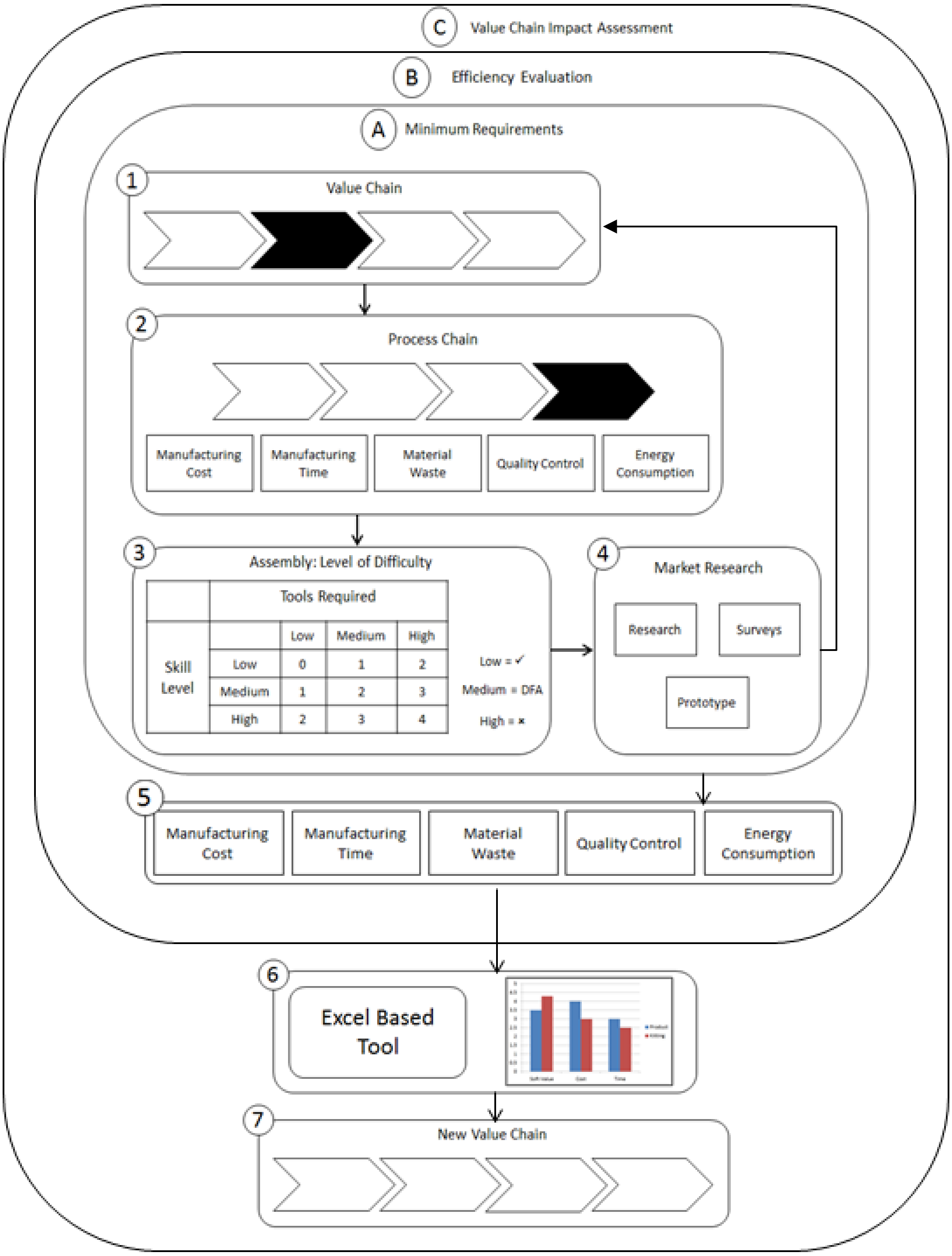


Figure 4.6: Final design of the newly developed framework

As seen in the final design of the new framework illustrated in Figure 4.6, the next step to make the framework a reality was to design the Excel-based tool to be used by a company to investigate the possibility of altering some of its products to be sold as non-assembled product kits.

4.3.4 Excel-based tool

When developing a tool to be used by anyone, it is important to consider the level of user-friendliness and practicality. Therefore, this Excel-based tool was developed for first-time users to easily follow the clearly stated instructions on each user form. The tool was designed to follow a logical layout, making it easy for anyone to follow the necessary steps required to obtain the desired results.

When the user opens the Excel-based tool, the first user form appears with the heading 'Value Chain Input', as illustrated in Figure 4.7. This user form allows the user to select the stages of the value chain that his/her company is involved in, and the data are used to determine whether the company is part of the 'Manufacturing and Assembly' stage. If the company is not part of this stage, an error message will appear, as illustrated in Figure 4.8. This error message, labelled as 'Not Qualified', suggests that the product being investigated is not suitable to be sold as a non-assembled product kit.

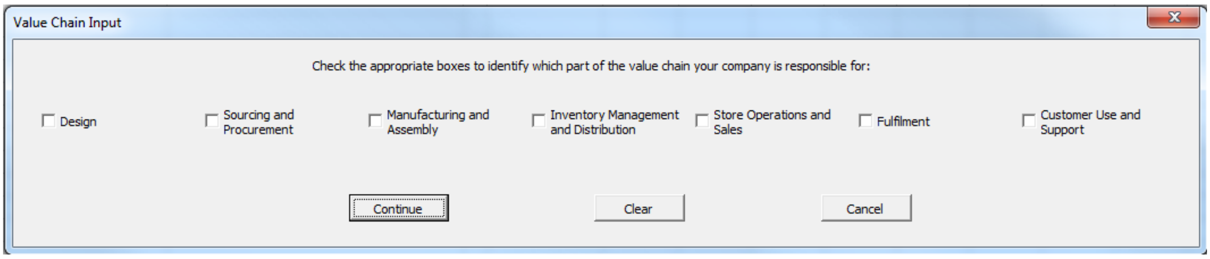


Figure 4.7: Illustration of the first step of the Excel-based tool for the input of the value chain

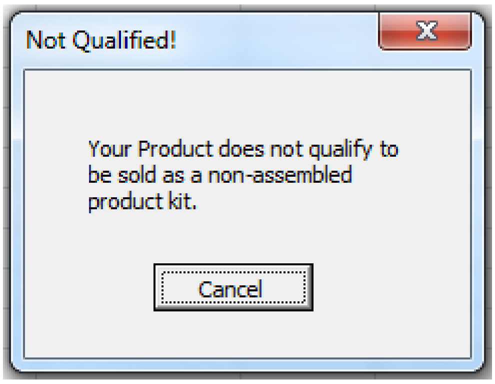


Figure 4.8: Error message for the first step of the Excel-based tool

If the company's value chain includes the manufacturing and assembly stage, the Excel-based tool continues to the next step of the framework. The second user form, as illustrated in Figure 4.9, appears asking the user to identify the steps of a typical manufacturing chain where his/her company is directly involved in. This step is used to identify whether the process chain in question ends with an assembly step for it to qualify to continue to the next step of the framework. If the product is not successful, the same error message will appear as with the first step, as illustrated in Figure 4.8.

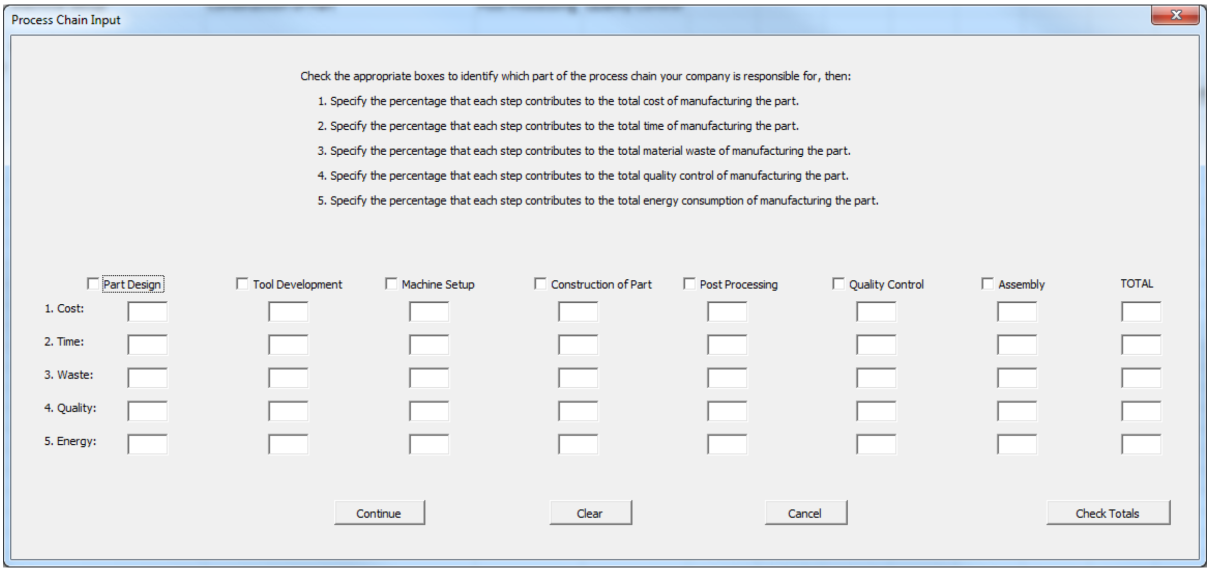


Figure 4.9: Illustration of the second user form asking the user for the process chain input

The user is also required to input the percentage that each step of the process chain contributes to the total cost, time, waste, quality and energy of the manufacturing process of the product being investigated. These data will be used in the last step to compare the new process chain of the non-assembled product kit to the existing process chain specified during this step. The VBA code used to develop the necessary user forms is illustrated in Appendix F.

4.3.5 Equation development

The purpose of the Excel-based tool is to display the effect of using non-assembled product kits on the resource efficiency of process chains. This requires equations to provide an estimation of the measured values for using a non-assembled product kit. These results can then be compared to the original values of using a fully assembled product.

A bamboo bicycle was designed and manufactured at Stellenbosch University, as illustrated in Figure 4.10. This experiment was used to develop the necessary equations to be used by the framework to make an estimation of the new values. The results would give an indication of the effect of using non-assembled product kits and would not present actual values. Section 2.5.2 illustrates the popularity of bamboo bicycles being sold as non-assembled product kits.

Figure 4.10: Finished bamboo bicycle manufactured at Stellenbosch University

This means that we already know that the product can be sold as a non-assembled product kit and that the framework will be successful if it reaches the same conclusion. Figure 4.11 illustrates the process chain used to manufacture the bamboo bicycle at Stellenbosch University.

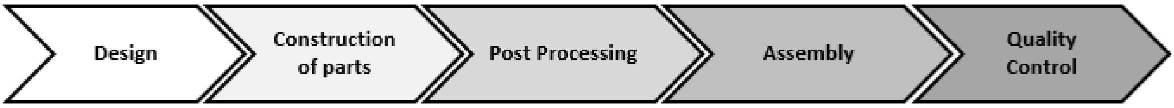


Figure 4.11: Bamboo bicycle process chain used to develop the necessary equations for the framework

The data from the bamboo bicycle experiment were entered into the Excel-based tool, as illustrated in Appendix G. The bamboo bicycle includes a manufacturing and assembly stage in its value chain and proceeded from the first step. The process chain of the bamboo bicycle also makes use of an assembly process, making it eligible for a non-assembled product kit. The cost, time, waste, quality and energy consumption of each step of the fully assembled product process chain were entered, as illustrated in Table 4.3.

Table 4.3: Fully assembled product process chain data for the bamboo bicycle used as the benchmark data for the equations development for the framework

	Design	Construction of parts	Post processing	Assembly	Quality control	Total
Cost	R2 400	R2 585	R440	R2 255	R220	R7 900
Time	480 min	240 min	120 min	784 min	60 min	1 684 min
Waste	0%	50%	15%	25%	10%	100%
Quality	40%	10%	20%	20%	10%	100%
Energy	0.8 kWh	2.8 kWh	1.2 kWh	1.6 kWh	0.6 kWh	7 kWh

The assembly process requires only an air tool and nonelectrical hand tools. The required skill level to fibreglass the joints is given a Number 2 rating; thus, the level of difficulty of assembly for the bamboo bicycle is a two. This means that the assembly process is acceptable for customers to perform but only customers who have the necessary skill and time to perform the required steps. The non-assembled product kit process chain for the bamboo bicycle is illustrated in Figure 4.12.

Figure 4.12: Non-assembled product kit process chain for the bamboo bicycle

This new process chain requires fewer steps than the existing process chain because the assembly step converts to a subassembly step and quality control is no longer possible for the fully assembled product. The data for the new non-assembled product kit process chain are illustrated in Table 4.4.

Table 4.4: Non-assembled product kit process chain data for the bamboo bicycle

	Design	Construction of parts	Post processing	Subassembly	Total
Cost	R2 400	R2 585	R440	R715	R6 140
Time	480 min	240 min	120 min	60 min	900 min
Waste	0%	50%	15%	10%	75%
Quality	40%	10%	20%	10%	80%
Energy	0.8 kWh	2.8 kWh	1.2 kWh	0.8 kWh	5.6 kWh

The total cost of the existing process chain, R7 900, was used as the benchmark for comparison. The total cost of the new process chain excluded the cost of the assembly process as the product was considered to be sold as a non-assembled product kit. However, it will not be possible to outsource the entire assembly step to the customer without providing the necessary materials required and in some cases also some of the required tools to perform this step. Using these factors as guidelines, equation (11) was developed to determine the total cost of the new process chain:

$$New\ C_{manufacturing} = C_{manufacturing} - \left(\frac{2}{3}\right)(C_A) - C_Q \qquad (11)$$

C_A is the cost of assembly and C_Q is the cost of the quality control step of the process chain being investigated.

The total time of the existing process chain was used as the benchmark for comparison and was 1 684 min. The total time of the new process chain excluded the labour time for the assembly step but included the time for packing the non-assembled product kit. This resulted in equation (12) being developed to calculate the new manufacturing time of the process chain:

$$New\ T_c = T_c - \left(\frac{9}{10}\right)(T_A) - T_Q \tag{12}$$

T_A is the total assembly time and T_Q is the total time for the quality control step of the process chain being investigated.

The total manufacturing waste of the existing process chain was used as the benchmark for comparison and was therefore set to be 100%. The total manufacturing waste of the new process chain excluded the waste produced by the assembly step from the old process chain. This resulted in the following formula being developed to calculate the new manufacturing waste of the process chain:

$$New\ W_T = 100 - \left(\frac{3}{5}\right)(W_A) - W_Q \tag{13}$$

W_T is the total waste of the process chain, W_A is the waste for the assembly step and W_Q is the waste for the quality control step of the process chain being investigated.

The total manufacturing quality of the existing process chain was used as the benchmark for comparison and was therefore set to be 100%. The total manufacturing quality of the new process chain excluded the quality control for the fully assembled product, making it impossible for the company to ensure that the customer assembled the product correctly. This means that the quality of the final product could be worse as a non-assembled product kit than when the fully assembled product was manufactured entirely in the factory. This resulted in the following formula being developed to calculate the new manufacturing quality of the process chain:

$$New\ Q_T = 100 - \left(\frac{1}{2}\right)(Q_A) - Q_Q \tag{14}$$

Q_T is the total quality of the process chain, Q_A is the quality of the assembly step and Q_Q is the quality of the quality control step of the process chain being investigated.

The total manufacturing energy consumption of the existing process chain was used as the benchmark for comparison and was therefore set to be 100%. The total manufacturing energy consumption of the new process chain excluded the energy consumed by the assembly step from the old process chain. This resulted in the following formula being developed to calculate the new manufacturing energy consumption of the process chain:

$$New\ E_T = 100 - \left(\frac{1}{2}\right)(E_A) - E_Q \tag{15}$$

E_T is the total energy consumption of the process chain, E_A is the energy consumption of the assembly step and E_Q is the energy consumption of the quality control step of the process chain being investigated.

These formulas were used as a benchmark for other products being evaluated by this framework to determine the effect on the resource efficiency of their respective process chains. The results of the bamboo bicycle experiment applied to the framework are illustrated in Figure 4.13.

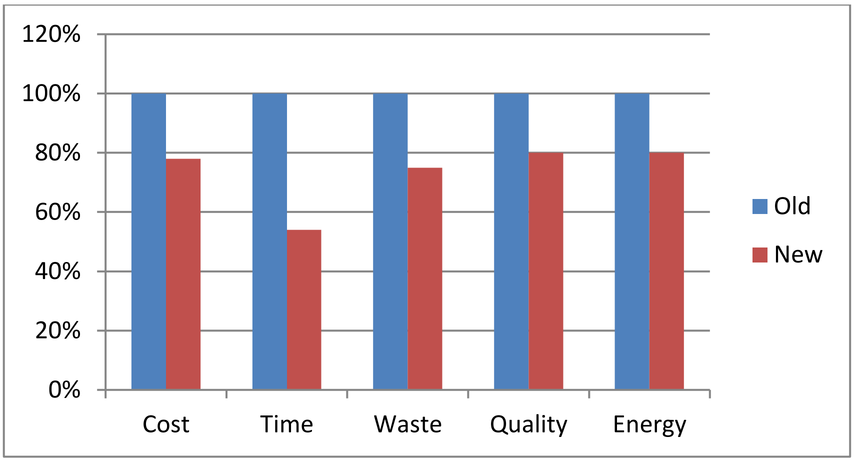


Figure 4.13: Results of the bamboo bicycle experiment applied to the framework

A framework is worthless if it is not validated and if it is not ensured that it functions correctly and achieves its purpose. The next chapter is used to validate the newly developed framework.

5 RESULTS AND DISCUSSION

This chapter illustrates the results obtained from the experimental setup and design explained in the previous chapter. This illustration includes the experiments to validate the developed framework to determine its accuracy in predicting the effect of using non-assembled product kits on the resource efficiency of process chains.

5.1 First validation of the framework: Bamboo Bicycle Club

As seen in section 2.5.2.1, Bamboo Bicycle Club designed and manufactured a bamboo bicycle frame as illustrated in Figure 5.1. The data was gathered for the process chain used to manufacture this bamboo bicycle and was used to validate the framework designed for the purpose of this study.

Figure 5.1: Illustration of the bamboo bicycle designed and manufactured by the Bamboo Bicycle Club

The bamboo bicycle was applied to the developed framework, and its progress through the framework will be illustrated step- by- step in the following section.

5.1.1 Step 1: Value chain input

The first step of the framework requires the value chain input for the product being investigated. This bamboo bicycle was designed and manufactured by the Bamboo Bicycle Club and then sold via an online platform to its customers. Therefore, the value chain of the bamboo bicycle include the first three stages, as well as inventory management and customer support, as seen in Figure 5.2.

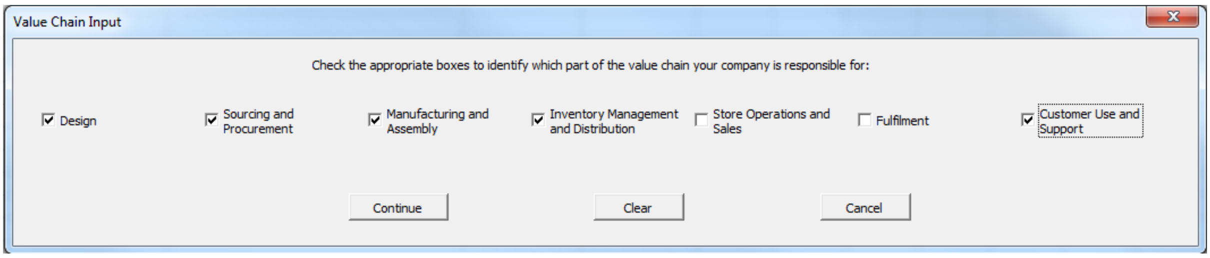


Figure 5.2: Illustration of the value chain input for Step 1 of the framework for BBC's bamboo bicycle

The most important result obtained from this step is that the value chain includes the manufacturing and assembly stage, as illustrated above. This means that the bamboo bicycle successfully progresses from the first step of the framework.

5.1.2 Step 2: Process chain input

The second step of the process chain requires the process chain input for the product being investigated. The process chain of the bamboo bicycle also includes an assembly process making it eligible for a non-assembled product kit. The cost, time, waste, quality and energy consumption of each step of the process chain are entered as illustrated in Figure 5.3 below.

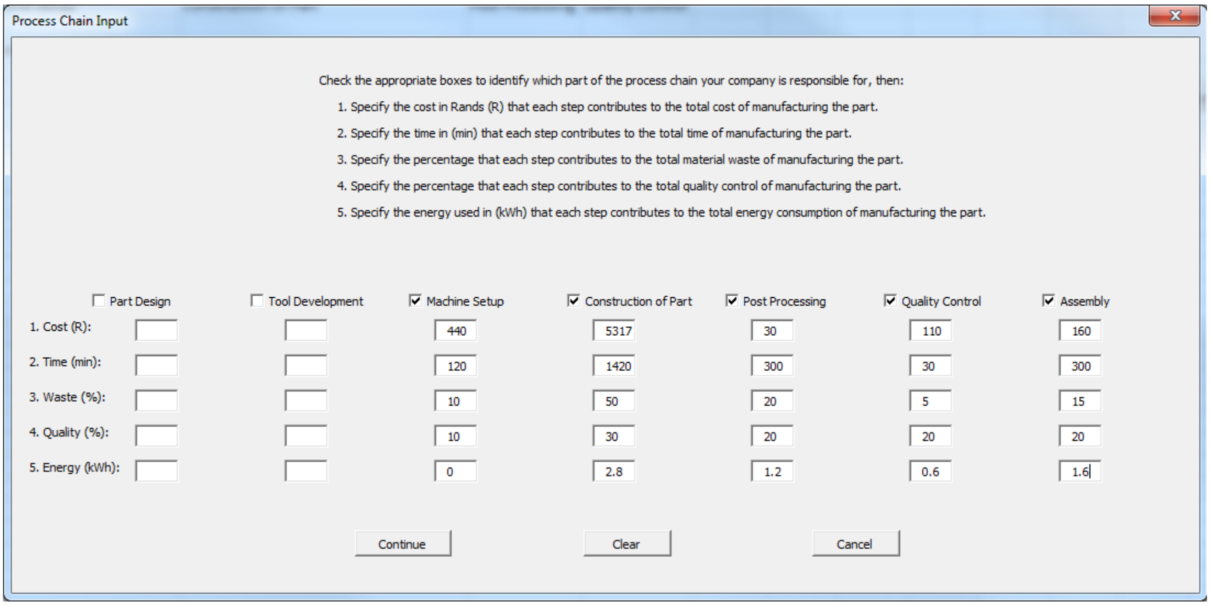


Figure 5.3: Illustration of the process chain input for Step 2 of the framework for the bamboo bicycle manufactured by the Bamboo Bicycle Club

The bamboo bicycle process chain includes all the steps from the traditional process chain, except the tool development step.

5.1.3 Step 3: Level of difficulty of assembly

This bamboo bicycle was designed to be as light as possible while using the most resource efficient materials available. However, the bamboo bicycle frame was assembled with the use of fibreglass which requires a certain skill, but all the necessary materials can easily be included into the non-assembled product kit. The customer support stage of the value chain becomes important to ensure that customers assemble the product correctly, making the quality of the end-product acceptable. The level of difficulty of assembly was acceptable to sell this product as a non-assembled product kit.

5.1.4 Step 4: Market research

The popularity of bamboo bicycles was illustrated in Section 2.5.2. and already supports the idea of selling bamboo bicycles as non-assembled product kits. Therefore, the market research was considered to be completed and was not to be repeated in this section.

5.1.5 Step 5: Resource efficiency calculation

The equations used in Section 4.3.5. were applied to the data provided by the second step of the framework for the process chain input. The calculations are displayed below:

$$\begin{aligned} New\ C_{manufacturing} &= C_{manufacturing} - \left(\frac{2}{3}\right)(C_A) - C_Q \\ &= 6057 - \left(\frac{2}{3}\right)(160) - 110 \\ &= R\ 5894 \end{aligned}$$

$$\begin{aligned} New\ T_c &= T_c - \left(\frac{9}{10}\right)(T_A) - T_Q \\ &= 2160 - \left(\frac{9}{10}\right)(300) - 30 \\ &= 1806\ min \end{aligned}$$

$$\begin{aligned} New\ W_T &= 100 - \left(\frac{3}{5}\right)(W_A) - W_Q \\ &= 100 - \left(\frac{3}{5}\right)(15) - 5 \\ &= 86\% \end{aligned}$$

$$\begin{aligned} New\ Q_T &= 100 - \left(\frac{1}{2}\right)(Q_A) - Q_Q \\ &= 100 - \left(\frac{1}{2}\right)(20) - 20 \\ &= 70\% \end{aligned}$$

$$\begin{aligned} New\ E_T &= 6.2 - \left(\frac{1}{2}\right)(E_A) - E_Q \\ &= 6.2 - \left(\frac{1}{2}\right)(1.6) - 0.6 \\ &= 4.8\ kWh \end{aligned}$$

These equations are calculated manually for illustrative purposes, but will be done in the background when running the final framework.

5.1.6 Step 6: Results

The answers obtained from the previous steps are used for the illustration of the resource efficiency of the newly developed process chain. The results of the bamboo bicycle experiment are displayed in Figure 5.4 and will be discussed in the following section.

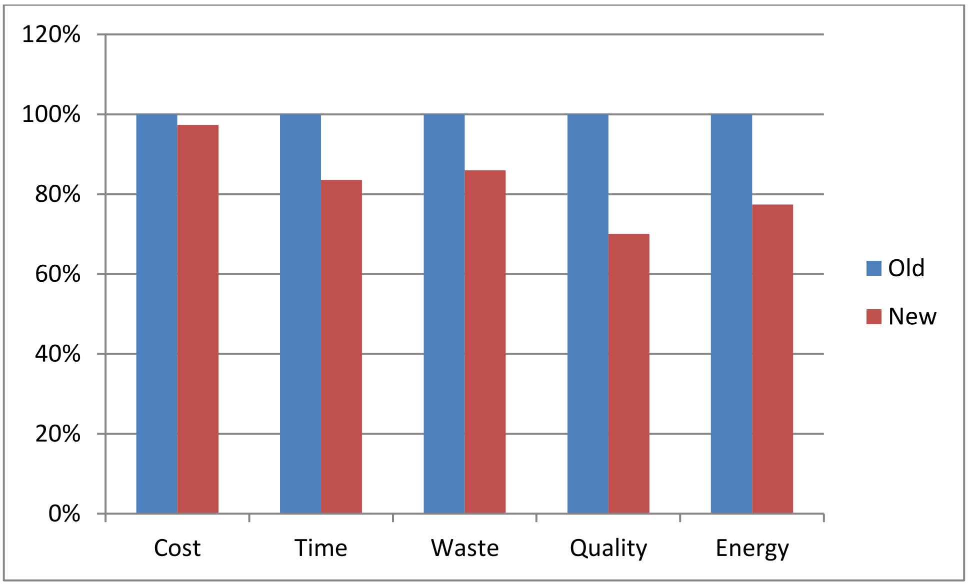


Figure 5.4: Results of BBC's bamboo bicycle applied to the framework

The last section of this chapter discusses the results obtained by this validation experiment for the newly developed framework to determine the effect on the resource efficiency of the process chain when using non-assembled product kits.

5.2 Second validation of the framework: HeroBike

As seen in section 2.5.2, HeroBike designed and manufactured a bamboo bicycle frame as illustrated in Figure 5.5. The data was gathered for the process chain used to manufacture this bamboo bicycle and will be used to validate the framework designed for the purpose of this study.

Figure 5.5: Illustration of the bamboo bicycle designed and manufactured by HeroBike

The bamboo bicycle was applied to the developed framework, and its progress through the framework will be illustrated step- by- step in the following section.

5.2.1 Step 1: Value chain input

The first step of the framework requires the value chain input for the product being investigated. This bamboo bicycle was designed and manufactured by HeroBike and then sold via an online platform to their customers. Therefore, the value chain for their bamboo bicycle includes the first three stages, as well as inventory management and customer support, as seen in Figure 5.6.

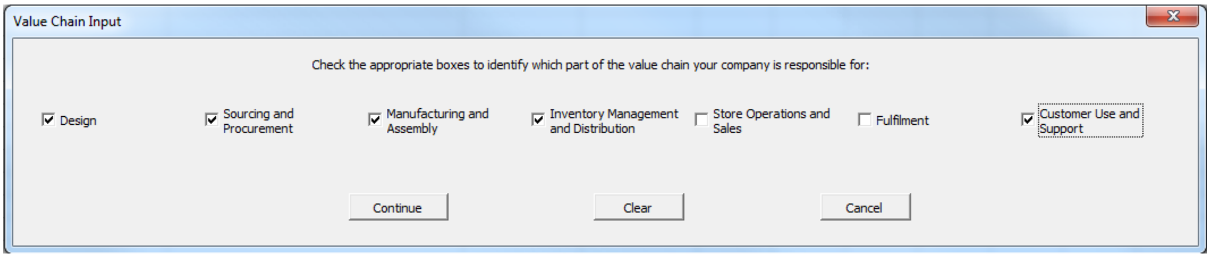
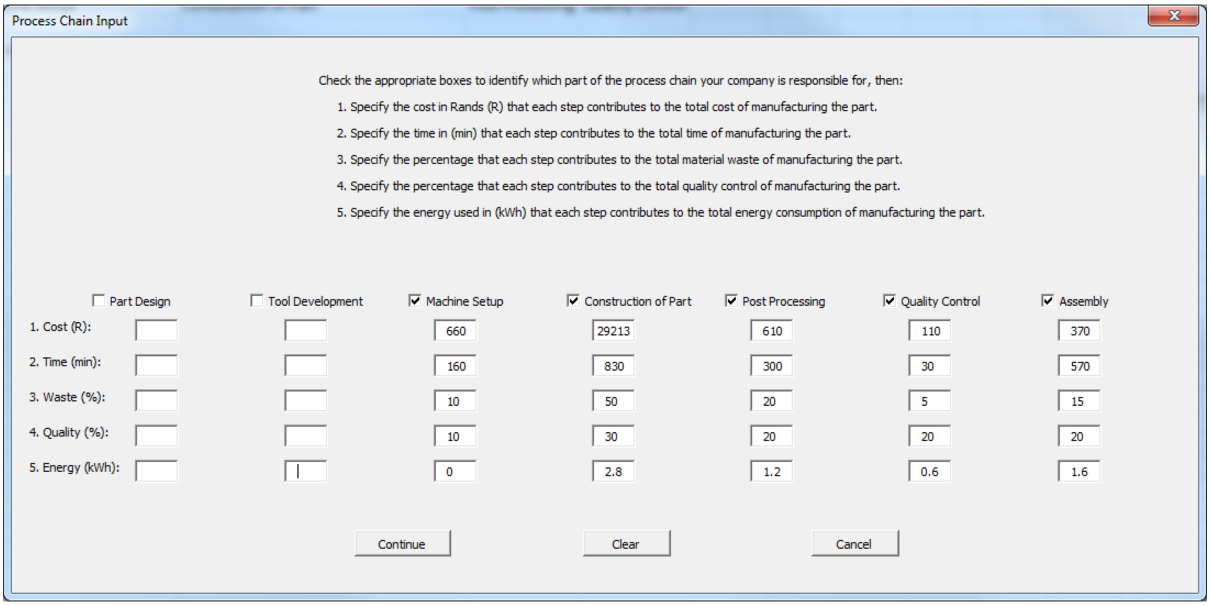


Figure 5.6: Illustration of the value chain input for Step 1 of the framework for HeroBike's bamboo bicycle

The most important result obtained from this step is that the value chain includes the manufacturing and assembly stage, as illustrated above. This means that the bamboo bicycle successfully progresses from the first step of the framework.

5.2.2 Step 2: Process chain input

The second step of the process chain requires the process chain input for the product being investigated. The process chain of the bamboo bicycle also includes an assembly process making it eligible for a non-assembled product kit. The cost, time, waste, quality and energy consumption of each step of the process chain are illustrated in Figure 5.7.


Process Chain Input

Check the appropriate boxes to identify which part of the process chain your company is responsible for, then:

1. Specify the cost in Rands (R) that each step contributes to the total cost of manufacturing the part.
2. Specify the time in (min) that each step contributes to the total time of manufacturing the part.
3. Specify the percentage that each step contributes to the total material waste of manufacturing the part.
4. Specify the percentage that each step contributes to the total quality control of manufacturing the part.
5. Specify the energy used in (kWh) that each step contributes to the total energy consumption of manufacturing the part.

	☐ Part Design	☐ Tool Development	☑ Machine Setup	☑ Construction of Part	☑ Post Processing	☑ Quality Control	☑ Assembly
1. Cost (R):			660	29213	610	110	370
2. Time (min):			160	830	300	30	570
3. Waste (%):			10	50	20	5	15
4. Quality (%):			10	30	20	20	20
5. Energy (kWh):			0	2.8	1.2	0.6	1.6

Continue | Clear | Cancel

Figure 5.7: Illustration of the process chain input for Step 2 of the framework for the bamboo bicycle from HeroBike

The bamboo bicycle process chain includes all the steps from the traditional process chain, except the tool development step.

5.2.3 Step 3: Level of difficulty of assembly

This bamboo bicycle was designed to be as light as possible while using the most resource efficient materials available. However, the bamboo bicycle frame was assembled with the use of fibreglass which requires a certain skill, but all the necessary materials can easily be included into the non-assembled product kit. The customer support stage of the value chain becomes important to ensure that customers assemble the product correctly, making the quality of the end-product acceptable. The level of difficulty of assembly is acceptable to sell this product as a non-assembled product kit.

5.2.4 Step 4: Market research

The popularity of bamboo bicycles is illustrated in Section 2.5.2. and already supports the idea of selling bamboo bicycles as non-assembled product kits. Therefore, the market research is considered to be completed and will not be repeated in this section.

5.2.5 Step 5: Resource efficiency calculation

The equations used in Section 4.3.5. were applied to the data provided by the second step of the framework for the process chain input. The calculations are displayed below:

$$\begin{aligned} New\ C_{manufacturing} &= C_{manufacturing} - \left(\frac{2}{3}\right)(C_A) - C_Q \\ &= 30963 - \left(\frac{2}{3}\right)(370) - 110 \\ &= R\ 30606 \end{aligned}$$

$$\begin{aligned} New\ T_c &= T_c - \left(\frac{9}{10}\right)(T_A) - T_Q \\ &= 1920 - \left(\frac{9}{10}\right)(570) - 30 \\ &= 1377\ min \end{aligned}$$

$$\begin{aligned} New\ W_T &= 100 - \left(\frac{3}{5}\right)(W_A) - W_Q \\ &= 100 - \left(\frac{3}{5}\right)(15) - 5 \\ &= 86\% \end{aligned}$$

$$\begin{aligned} New\ Q_T &= 100 - \left(\frac{1}{2}\right)(Q_A) - Q_Q \\ &= 100 - \left(\frac{1}{2}\right)(20) - 20 \\ &= 70\% \end{aligned}$$

$$\begin{aligned} New\ E_T &= 6.2 - \left(\frac{1}{2}\right)(E_A) - E_Q \\ &= 6.2 - \left(\frac{1}{2}\right)(1.6) - 0.6 \\ &= 4.8\ kWh \end{aligned}$$

These equations were calculated manually for illustrative purposes, but will be done in the background when running the final framework.

5.2.6 Step 6: Results

The answers obtained from the previous steps are used for the illustration of the resource efficiency of the newly developed process chain. The results of the bamboo bicycle experiment are displayed in Figure 5.8 and will be discussed in the following section.

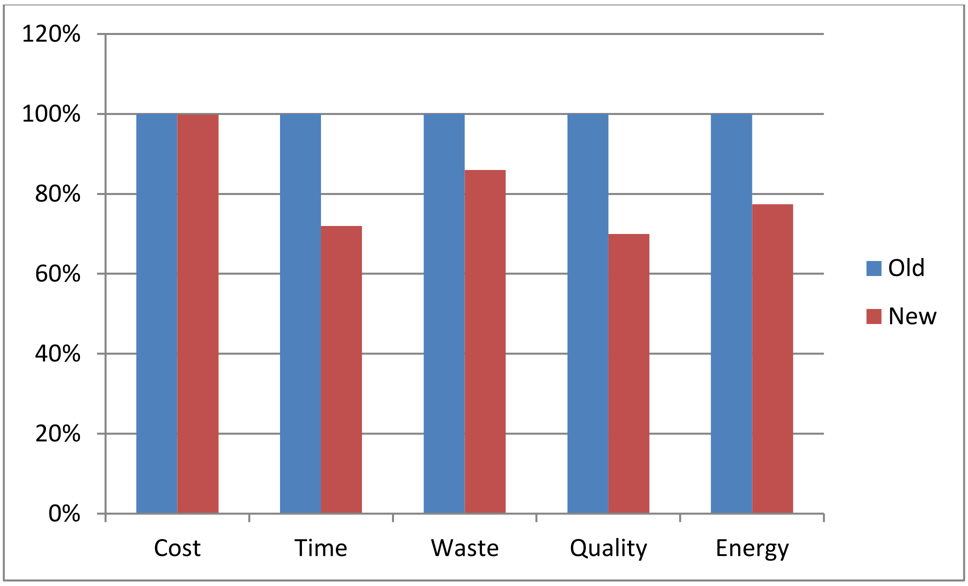


Figure 5.84: Result of HeroBike's bamboo bicycle applied to the framework

The last section of this chapter is used to discuss the results obtained by this validation experiment for the newly developed framework to determine the effect on the resource efficiency of the process chain when using non-assembled product kits.

5.3 Third validation of the framework: Titanium satellite

A CubeSat was designed and manufactured at Stellenbosch University, as illustrated in Figure 5.9. A CubeSat is a 10-cm cube with a mass of up to 1.33 kg and is known as a 1U design. Designs of up to 3U are known to orbit the earth as illustrated in Figure 5.9. The manufactured CubeSat focuses on the outside of the satellite and includes the side panels and rails. The customer can install various types of equipment within the frame and requires the frame to be easy to assemble and disassemble. Therefore, this product is an excellent candidate to validate the developed framework. The framework will determine the effect on the resource efficiency of the process chain if the product is sold as a non-assembled product compared to selling it as a fully assembled product.

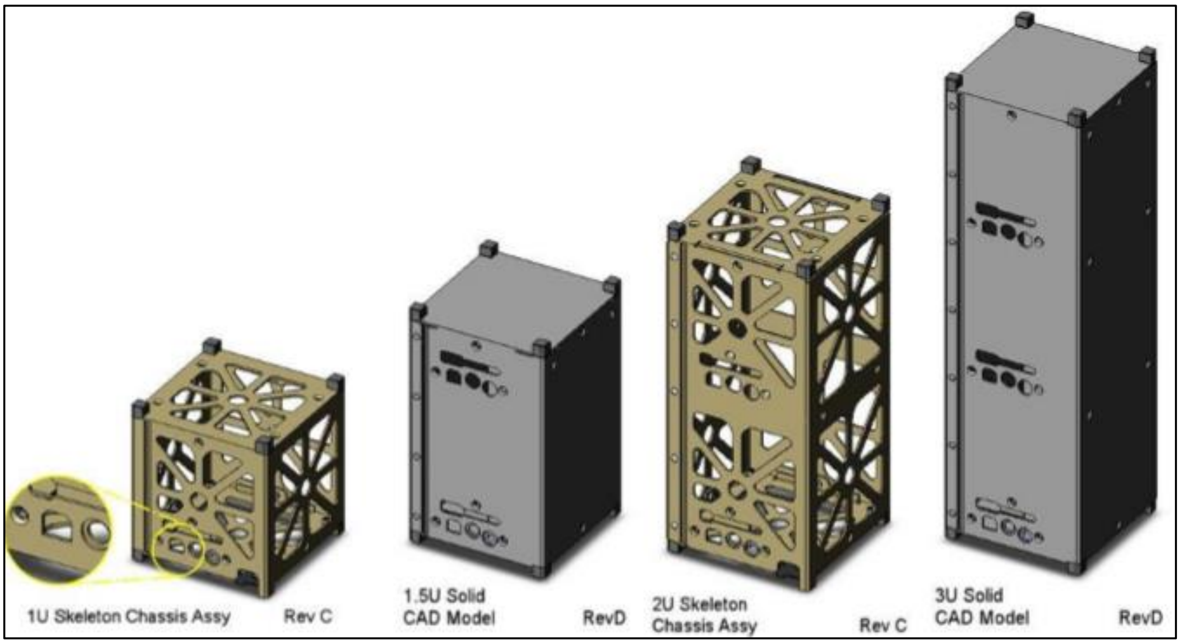


Figure 5.9: Illustration of the CubeSat and the different sizes ranging from a 1U to a 3U (66)

The titanium satellite was applied to the developed framework, and its progress through the framework will be illustrated step by step in the following sections.

5.3.1 Step 1: Value chain input

The first step of the framework requires the value chain input for the product being investigated. This satellite was designed and manufactured at Stellenbosch University and does not form part of the value chain of a typical retail store. The value chain for the titanium satellite only includes the first three stages, as seen in Figure 5.10.

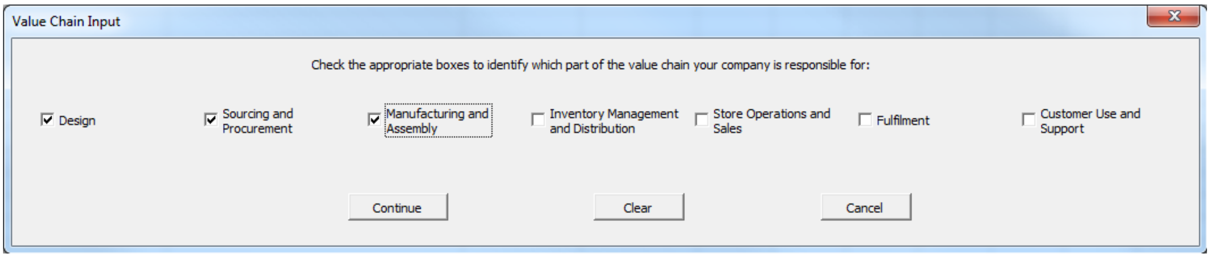


Figure 5.10: Illustration of the value chain input for Step 1 of the framework for the titanium satellite

The most important result obtained from this step is that the value chain includes the manufacturing and assembly stage, as illustrated above. This means that the titanium satellite successfully progresses from the first step of the framework.

5.3.2 Step 2: Process chain input

The second step of the process chain requires the process chain input for the product being investigated. The process chain of the titanium satellite also includes an assembly process making it eligible for a non-assembled product kit. The cost, time, waste, quality and energy consumption of each step of the process chain are illustrated in Figure 5.11.

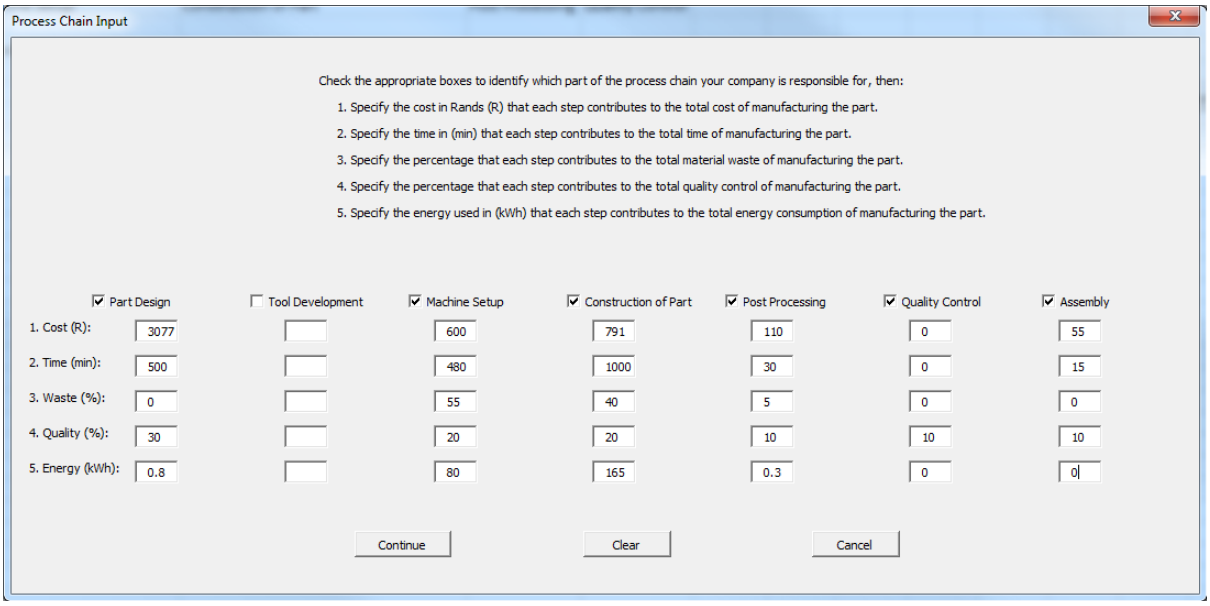


Figure 5.11: Illustration of the process chain input for Step 2 of the framework for the titanium satellite

The titanium satellite process chain includes all the steps from the traditional process chain except the tool development step.

5.3.3 Step 3: Level of difficulty of assembly

This satellite was designed to be as light as possible while using the most resource-efficient materials available. Therefore, the assembly process makes use of sliding fit methods, eliminating the need for screws and welding steps. The design requirements include the customer's need to easily assemble and disassemble the satellite to be able to work on the components added to the inside of the frame. This means that the titanium satellite does not require any extra tools to be assembled and is considered to have a level of difficulty of assembly acceptable to the customer.

5.3.4 Step 4: Market research

The CubeSat concept has become very popular, in university groups as well as for researchers, space agencies, governments and companies (67). CubeSats offer a fast and affordable way for a wide array of stakeholders to be active in space and allow for a fast innovation cycle (67). Clyde Space is an example of a company recognised as a world-leading innovator and supplier of CubeSats and small satellite systems (68). Clyde Space customers include international universities, commercial companies and government organisations. Figure 5.12(a) illustrates a 1U CubeSat designed and manufactured by Clyde Space.

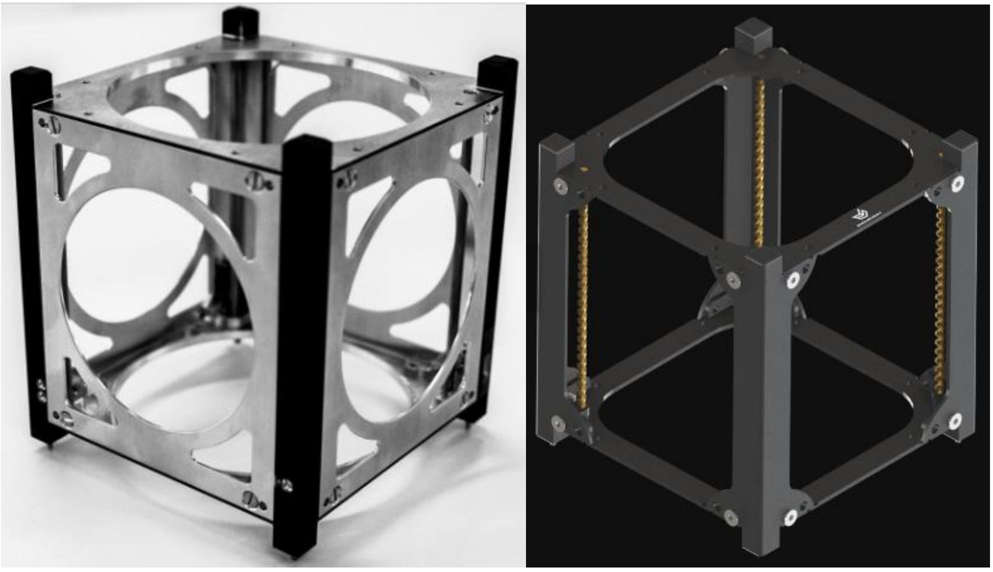


Figure 5.12: Illustration of a 1U CubeSat designed and manufactured by (a) Clyde Space and (b) EnduroSat

Figure 5.12(b) illustrates a 1U CubeSat designed and manufactured by EnduroSat. This CubeSat is manufactured from aluminium 6061 and weighs less than 100 g. The market research illustrates the popularity of CubeSats and the increasing demand for more resource-efficient process chains to manufacture these CubeSats. It also shows the importance of designing a CubeSat that is easy to assemble for the customer to retrofit the satellite with customised hardware and software.

5.3.5 Step 5: Resource efficiency calculation

The equations used in Section 4.3.5. were applied to the data provided by the second step of the framework for the process chain input. The calculations are displayed below:

$$New\ C_{manufacturing} = C_{manufacturing} - \left(\frac{2}{3}\right)(C_A) - C_Q$$
$$= 4\ 633 - \left(\frac{2}{3}\right)(55) - 0$$
$$= \text{R4 596}$$

$$New\ T_c = T_c - \left(\frac{9}{10}\right)(T_A) - T_Q$$
$$= 2\ 025 - \left(\frac{9}{10}\right)(15) - 0$$
$$= 2\ 012\ \text{min}$$

$$New\ W_T = 100 - \left(\frac{3}{5}\right)(W_A) - W_Q$$
$$= 100 - \left(\frac{3}{5}\right)(0) - 0$$
$$= 100\%$$

$$New\ Q_T = 100 - \left(\frac{1}{2}\right)(Q_A) - Q_Q$$
$$= 100 - \left(\frac{1}{2}\right)(10) - 10$$
$$= 85\%$$

$$New\ E_T = 100 - \left(\frac{1}{2}\right)(E_A) - E_Q$$
$$= 100 - \left(\frac{1}{2}\right)(0) - 0$$
$$= 100\%$$

These equations were calculated manually for illustrative purposes, but will be done in the background when running the final framework.

5.3.6 Step 6: Results

The answers obtained from the previous steps are used for the illustration of the resource efficiency of the newly developed process chain. The results of the titanium satellite experiment are displayed in Figure 5.13 and will be discussed in the following section.

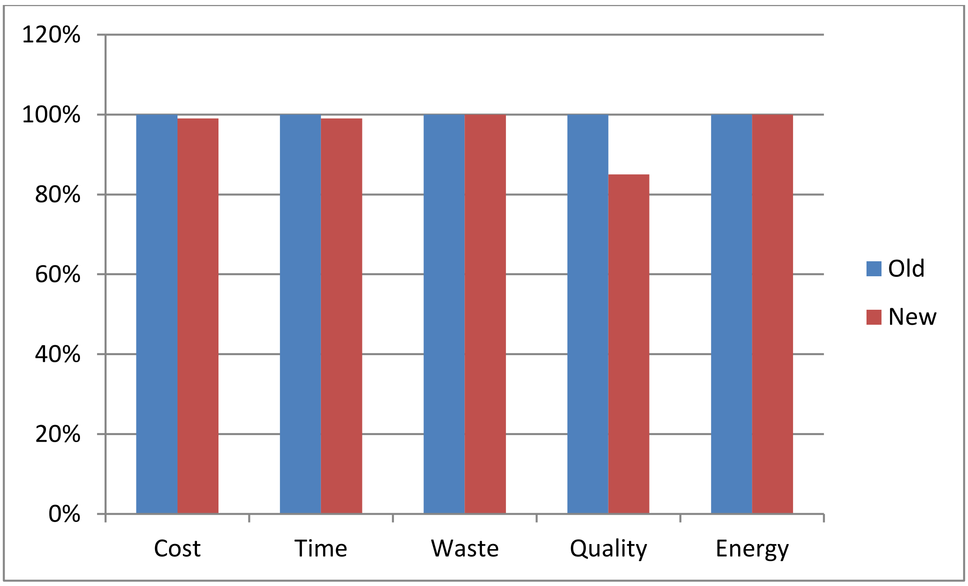


Figure 5.13: Results of the titanium satellite experiment applied to the framework

The next section discusses the results obtained by this validation experiment for the newly developed framework to determine the effect on the resource efficiency of the process chain when using non-assembled product kits.

5.4 Discussion

This section discusses the results obtained from the experiments performed for the purpose of this study. This is an attempt to clarify the findings obtained and to gain further understanding about the results to form the most accurate conclusions for the final chapter of this report.

An extensive literature review provided the advantages and disadvantages of using non-assembled product kits and clearly illustrated that the advantages outweighed the disadvantages. This result supported the use of non-assembled product kits and proved that the project could deliver valuable results for the manufacturing industry. This result is also the answer to one of the research objectives described in the first chapter.

The second step of the experimental setup illustrated the value chain when using non-assembled product kits. The impact at each stage of the value chain shows the implications of using non-assembled product kits compared to fully assembled products using the traditional value chain. Through the comparison of this value chain to IKEA's value chain in Section 2.1.3, it becomes clear that the newly developed value chain shares some of the same advantages incorporated by IKEA. This proves that if a company is able to convert a product to be sold as a non-assembled product kit, this simple conversion can provide it with the necessary competitive advantage to outperform its competition.

The resource-efficient framework for titanium process chains was used as the starting point for the development of the new framework due to the similarities between the frameworks. Due to a difference in the main focus of the two frameworks, many changes were required. The old framework focused only on titanium process chains while the new framework is able to incorporate different materials but is more focused on the assembly step of the process chain rather than the entire process chain. An additional design goal of the new framework was to make it as easy to understand as possible. If a framework becomes too complicated, it becomes useless if the person using the framework is unable to benefit from the full potential thereof. The conceptual decision framework was developed to provide the design with an easy-to-follow guideline for the purpose of the framework. This resulted in a user-friendly framework with an Excel-based tool to eliminate any unnecessary errors by the potential user.

The bamboo bicycle experiment was used for the development of the equations to be used by the framework to determine the resource efficiency of the new process chain. Specific equations for the cost, time, waste, quality and energy consumption were developed. These equations serve as a guideline to be used for future products being investigated by the framework for which the data for a non-assembled product kit are not readily available.

With the equations, the new framework was complete and ready to be validated by products to determine the accuracy of the results obtained. The bamboo bicycle manufactured by Bamboo Bicycle Club was used as the first validation study. The results were automatically generated and compared by using the same graph as previously illustrated. The results show a decrease in the total manufacturing cost, time, waste, quality and energy consumption. The most significant improvement is the 18% decrease in the required manufacturing time. The only negative part was the 26% decrease in quality control due to the assembly step being outsourced to the customer.

The bamboo bicycle manufactured by HeroBike was used for the second validation study and the results show a similar trend than the first validation study. The most significant change was the 24% decrease in manufacturing time of the process chain. Again, the quality control decreases with 30% which needs to be addressed by customer support.

A titanium CubeSat was used for the third validation study of the newly designed framework. Only the data from the existing process chain were entered into the framework by using the Excel-based tool. When one compares the raw data of the titanium satellite to that of the bamboo bicycle, it becomes clear that the bamboo bicycle has a much more intensive assembly process than the satellite. The comparison showed that the framework successfully illustrated that the titanium CubeSat should be sold as a non-assembled product kit. Due to the low intensity of the assembly step for the titanium CubeSat, the results were very close and there does not exist a clear distinction between the old and new process chain. However, the market research suggests that the CubeSat should be sold as a non-assembled product kit to enable customers to retrofit the product. It should be noted that the results are not specific and are only an indication of the effect of using non-assembled product kits on the process chain of a product being investigated.

This means that non-assembled product kits should rather not be used if the compared results are too close to make a clear distinction between the old and the new process chains. This effect is also just a representation of the effect on the process chain with the main focus on the assembly step of the process chain and does not consider the effect on the rest of the process chain for the product being investigated. Converting a product from a fully assembled product to a non-assembled product kit will probably have an impact on other stages of the process chain than just the assembly step. New designs will be required, and inventory and transportation will be affected. These wider effects need to be investigated before committing to converting products to non-assembled product kits.

5.5 Evaluate research objectives

At the beginning of this research paper four research objectives were defined to determine the scope of the study and the requirements to answer the problem statement.

Table 5.1: Checklist to determine if all objectives were met by the research study, with the section(s) supporting each research objective.

Research objective	Completed (Yes/No)	Supporting section(s)
1. Identify the advantages and disadvantages of selling fully assembled products versus non-assembled product kits.	Yes	4.1
2. Develop a framework to evaluate the impact of using non-assembled product kits compared to using fully assembled products on the resource efficiency of process chains.	Yes	4.3
3. Validate the framework with manufacturing research experiments.	Yes	5.1 & 5.2 & 5.3
4. Make recommendations for future studies leading from this research.	Yes	5.4 & 6

Table 5.1 illustrates that all the research objectives set out for this research study have been met satisfactorily. The next chapter will be used to conclude the findings from this research study.

6 CONCLUSION

In order for companies to stay competitive, they need to invest in more efficient strategies and change their approach to manufacturing to fulfil the customer's needs. Customers request more variety and options while still seeking for the lowest prices. To keep costs at a minimum, several different aspects and strategies can be analysed and maybe implemented. Therefore, this study attempted to determine the effect of using non-assembled product kits on the process chain of the product being investigated.

The literature review provided the researcher with enough understanding about the underlying concepts to develop a resource-efficient framework for manufacturing process chains. There are a handful of companies that benefit from the use of non-assembled product kits, namely IKEA, the Bamboo Bicycle Club, HERObike and Dell. The advantages of using non-assembled product kits include smaller packages required, lower storage costs, lower shipping costs, fewer steps required, increased customer attachment and improved customisability. The only disadvantages of using non-assembled product kits are that the manufacturer is unable to perform quality control on the final assembled product and that not all products qualify to be sold as non-assembled product kits.

The framework made use of a bamboo bicycle manufactured at Stellenbosch University. All the required data were available and were used to develop the necessary equations to be used by the framework to determine the effect on the resource efficiency of the process chain. These equations are only based on assumptions and are to be used as an indication of the effect on the existing process chain and not a specific outcome to be obtained if the product is converted to a non-assembled product kit.

The validation studies used two bamboo bicycles and a titanium satellite also manufactured at Stellenbosch University to determine the accuracy of the results obtained from using the equations developed during the first experiment. The results showed that the framework could successfully give an indication of the effect of using non-assembled product kits on the resource efficiency of the manufacturing process chain. However, this result is focused on one stage of the value chain and mainly focuses on the assembly step of the process chain. Therefore, further investigation needs to be performed to determine the effect of non-assembled product kits on the rest of the manufacturing process chain and the effect on the value chain before making use of non-assembled product kits. This could possibly be investigated in future studies leading from this report.

This framework is more valuable for new designs and new products being developed. In this case, a company can quickly determine the effect of designing the product either as a fully assembled product or as a non-assembled product kit. Thereafter, it will be able to tailor the manufacturing process chain to fit the needs of the desired product from the start.

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ADDENDUM A: EXCEL-BASED TOOL FOR THE RESOURCE-EFFICIENT FRAMEWORK FOR TITANIUM PROCESS CHAINS

The Excel-based tool developed by Richard Girdwood for the resource-efficient framework for titanium process chains is illustrated in this appendix. Illustrations of each step of the process are displayed, as well as an example of the output obtained from the framework.

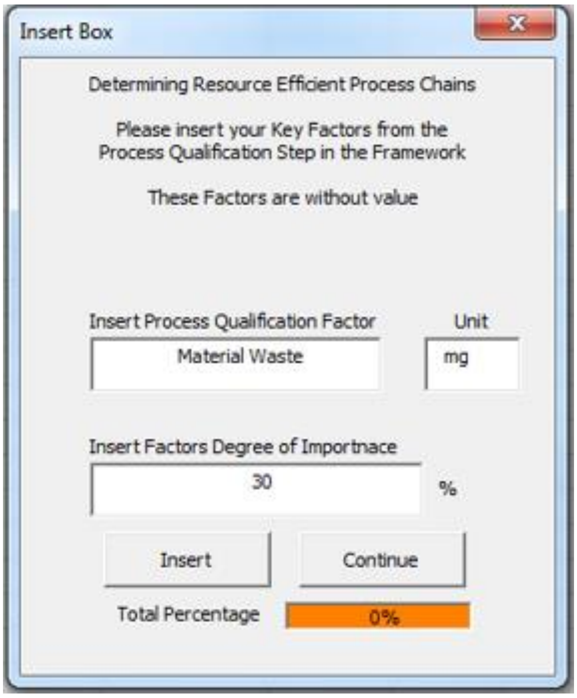

Figure A1: User form 1 of the Excel-based tool developed for the resource-efficient framework for titanium process chains

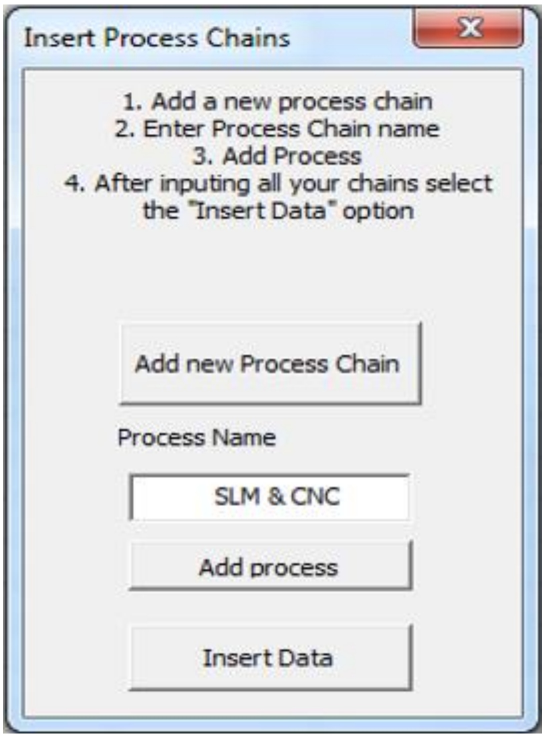

Figure A2: User form 2 of the Excel-based tool developed for the resource-efficient framework for titanium process chains

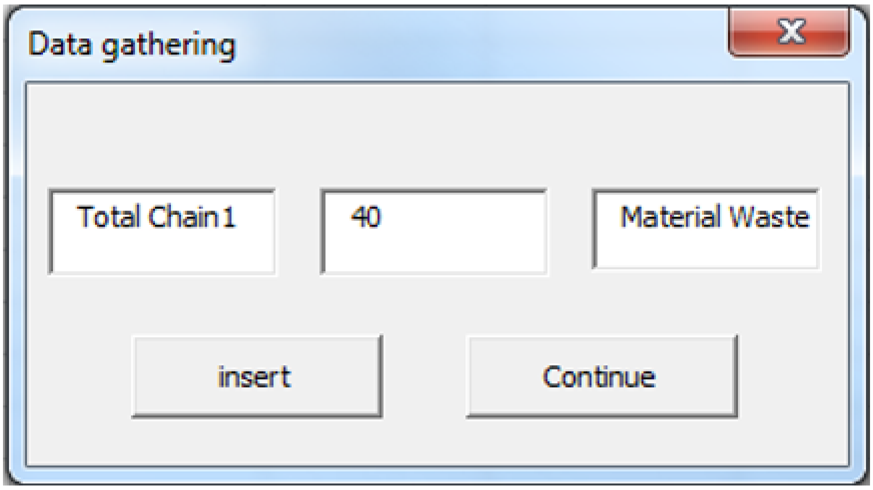

Figure A3: User form used to input the evaluation data for the resource-efficient framework for titanium process chains

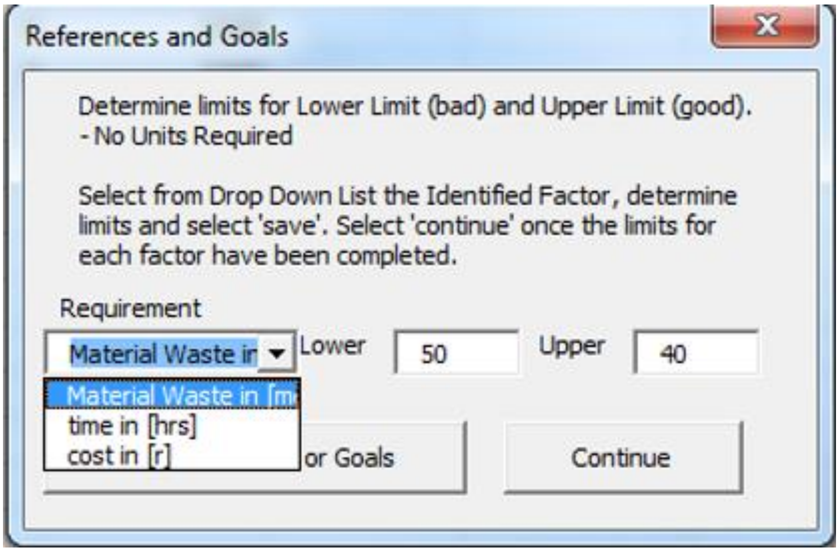

Figure A4: User form used to reference the limits of the data for the resource-efficient framework for titanium process chains

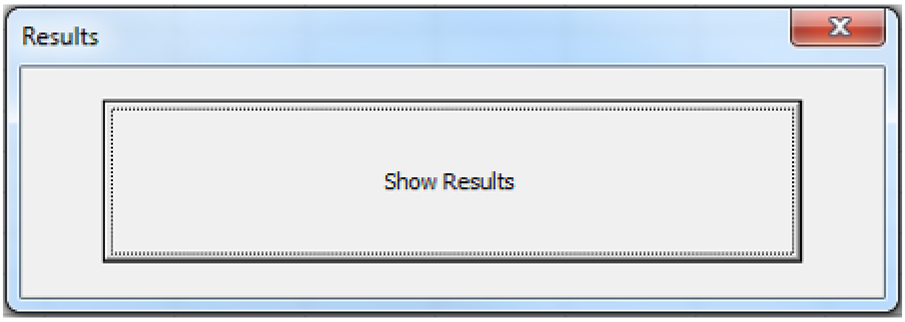

Figure A5: Final user form for the process evaluation for the resource-efficient framework for titanium process chains

Score Process Chains

Process Chain 1	5.99
Process Chain 2	6.3
Process Chain 3	7.01

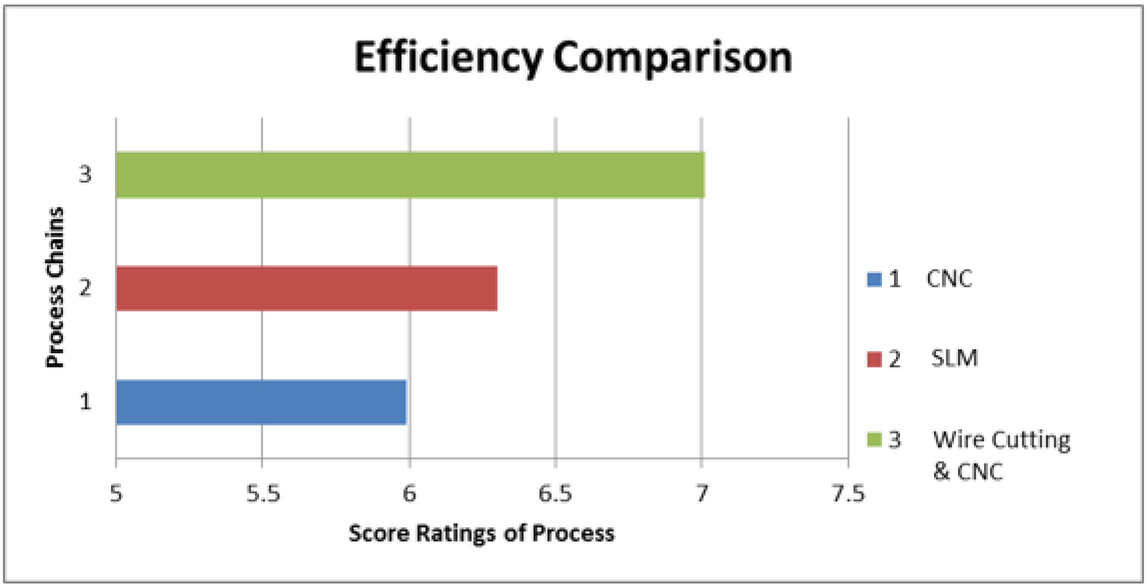

Figure A6: Example of how the results for the resource-efficient framework for titanium process chains are displayed

ADDENDUM B: EXAMPLES OF IKEA FURNITURE SOLD AS NON-ASSEMBLED PRODUCT KITS

This appendix illustrates some of the products that IKEA offers its clients to be self-assembled at home.

Figure B1: Illustration of an IKEA table

Figure B2: Illustration of a) an IKEA Malm dressing table and b) an IKEA Gersby bookcase

ADDENDUM C: BAMBOO BICYCLE CLUB SECONDARY MANUFACTURING PROCESS CHAIN FOR A BAMBOO BICYCLE

The secondary manufacturing process chain for the bamboo bicycle manufactured by the Bamboo Bicycle Club is illustrated in this appendix. The cost and time for each step of the process are also included in the illustration. The total cost to manufacture the bamboo bicycle, including the primary manufacturing activities, is R6 057. The total manufacturing time to manufacture the bicycle, including the primary manufacturing activities, is 2 160 min.

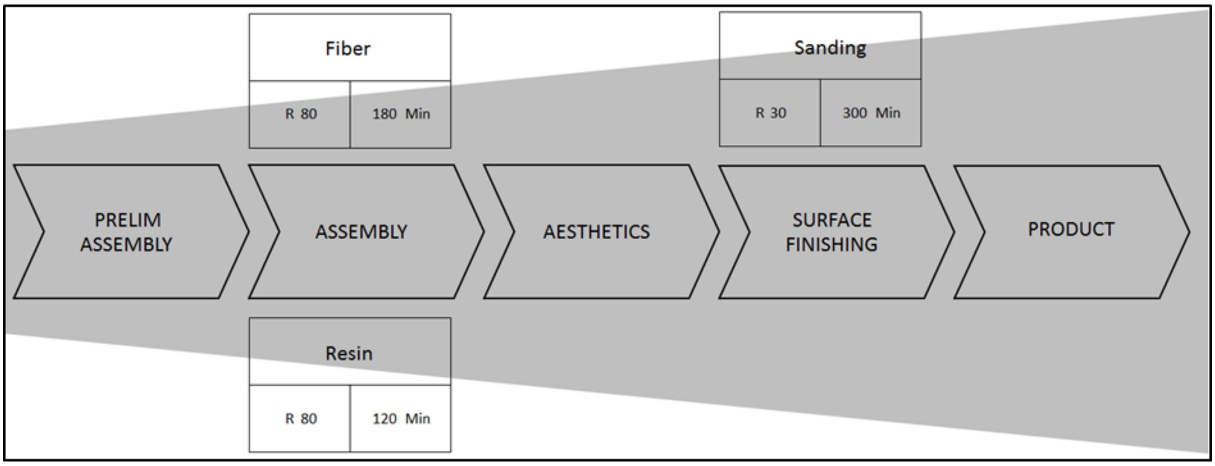

Figure C1: Secondary manufacturing process chain for the bamboo bicycle manufactured by the Bamboo Bicycle Club, including the cost and time of each process step

ADDENDUM D: HEROBIKE SECONDARY MANUFACTURING PROCESS CHAIN FOR A BAMBOO BICYCLE

The secondary manufacturing process chain for the bamboo bicycle manufactured by HERObike is illustrated in this appendix. The cost and time for each step of the process are also included in the illustration. The total cost to manufacture the bamboo bicycle, including the primary manufacturing activities, is R30 963. The total manufacturing time to manufacture the bicycle, including the primary manufacturing activities, is 1 920 min.

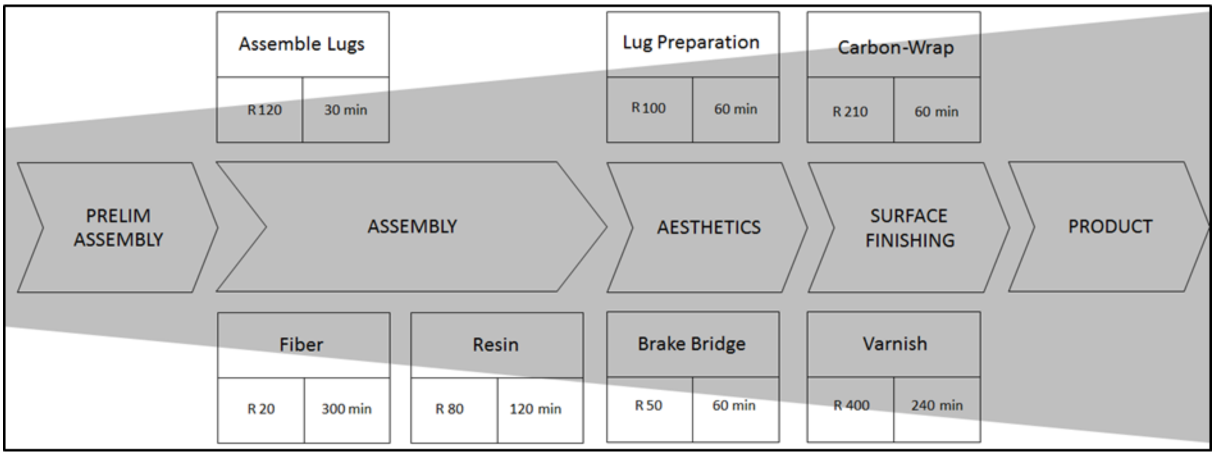

Figure D1: Secondary manufacturing process chain for the bamboo bicycle manufactured by HERObike, including the cost and time of each process step

ADDENDUM E: RESEARCH PROJECT PROGRESS MANAGEMENT

A table that shows all the tasks that had to be completed to finish the study within the required time is illustrated in this appendix.

Table E1: All the required tasks to complete this research study and the progress of each task

Evaluating the effect of non-assembled product kits on the process chain				
Task	**Description**	**% Complete**	**Required**	**Notes**
1	Abstract	100%	Finish body of report	Round off at the end.
2	List of figures	100%	Finish body of report	Remember to ensure that figure numbering is correct.
3	List of tables	100%	Finish body of report	Remember to ensure that table numbering is correct.
4	Glossary and nomenclature	100%	Finish body of report	
5	Introduction	100%	6, 7, 8, 9 & 10	
5.1	Problem statement	100%	Background	
5.2	Project scope	100%	Problem statement	
5.3	Research objectives	100%	Problem statement	
5.4	Report layout	100%	Research methodology	
6	Value creation	100%		
6.1	Porter's value chain	100%		Part of intro for value chains.
6.2	Manufacturing value chain	100%		
6.3	IKEA value chain	100%		
6.4	AM value chain	100%		
7	Manufacturing process chain	100%		
7.1	Manufacturing cost	100%		
7.2	Manufacturing time	100%		
7.3	Material waste	100%		
7.4	Energy consumption	100%		
7.5	Quality control	100%		
8	Non-assembled Product kits	100%		
8.1	IKEA effect	100%		

8.2	Customer engagement	100%		
8.3	Design for assembly	100%		
9	Resource-efficient frameworks	100%		
9.1	Resource-efficient framework for titanium process chains	100%		
9.2	Process chain simulation for energy efficiency	100%		
9.3	6R framework for resource efficiency	100%		
10	Case studies	100%		
10.1	IKEA furniture	100%		
10.2	Bamboo bicycles	100%		
10.3	Dell computers	100%		
10.4	Lessons learned	100%	10.1–10.3	
11	Research methodology	100%	Report layout	
12	Results and discussion	100%		
12.1	Advantages and disadvantages	100%	6, 7, 8, 9 & 10	
12.2	Non-assembled product kits value chain	100%	6, 7, 8, 9 & 10	
12.3	New framework design	100%	9.1., 9.2 & 9.3	
12.4	Validation: Bamboo bicycle kit experiment	100%	10.2	
12.5	Validation: Titanium satellite experiment	100%	12.3 & 12.4	
12.6	Discussion	100%	12	
13	Conclusion	100%	All	
14	Referencing	100%	6, 7, 8, 9 & 10	
15	Appendices	100%	All	
		100%		

ADDENDUM F: VISUAL BASIC FOR APPLICATIONS CODE USED TO DEVELOP THE EXCEL-BASED TOOL FOR THE NEW FRAMEWORK

The VBA code used to develop the user forms for the newly developed framework is illustrated in this appendix.

```
Private Sub CancelButton_Click()

Unload Me

End Sub
```

```
Private Sub ClearButton_Click()

Call UserForm_Initialize

End Sub
```

```
Private Sub ContinueButton_Click()
Dim emptyRow As Long

'Make Sheet1 active
Sheet1.Activate

'Determine emptyRow
emptyRow = WorksheetFunction.CountA(Range("A:A")) + 1

'Transfer information

If CheckBox1.Value = True Then Cells(emptyRow, 1).Value = CheckBox1.Caption
If CheckBox2.Value = True Then Cells(emptyRow, 2).Value = CheckBox2.Caption
If CheckBox3.Value = True Then Cells(emptyRow, 3).Value = CheckBox3.Caption
If CheckBox4.Value = True Then Cells(emptyRow, 4).Value = CheckBox4.Caption
If CheckBox5.Value = True Then Cells(emptyRow, 5).Value = CheckBox5.Caption
If CheckBox6.Value = True Then Cells(emptyRow, 6).Value = CheckBox6.Caption
If CheckBox7.Value = True Then Cells(emptyRow, 7).Value = CheckBox7.Caption

Call CancelButton_Click

If CheckBox3.Value = False Then ValueChainCancel.Show

If CheckBox3.Value = True Then ProcessChainUserForm.Show

End Sub
```

```
Private Sub UserForm_Initialize()

'Uncheck DataCheckBoxes
CheckBox1.Value = False
CheckBox2.Value = False
CheckBox3.Value = False
CheckBox4.Value = False
CheckBox5.Value = False
CheckBox6.Value = False
CheckBox7.Value = False

End Sub
```

Figure F1: VBA code used to develop the first user form for the value chain input

```
Private Sub CheckTotals_Click()

Call TextBox36_Change
Call TextBox37_Change
Call TextBox38_Change
Call TextBox39_Change
Call TextBox40_Change

End Sub
```

```
Private Sub ContinueButton_Click()

Dim emptyRow As Long

'Make Sheet1 active
Sheet1.Activate

'Determine emptyRow
emptyRow = WorksheetFunction.CountA(Range("A:A")) + 2

'Transfer information

If CheckBox1.Value = True Then Cells(emptyRow, 1).Value = CheckBox1.Caption
If CheckBox2.Value = True Then Cells(emptyRow, 2).Value = CheckBox2.Caption
If CheckBox3.Value = True Then Cells(emptyRow, 3).Value = CheckBox3.Caption
If CheckBox4.Value = True Then Cells(emptyRow, 4).Value = CheckBox4.Caption
If CheckBox5.Value = True Then Cells(emptyRow, 5).Value = CheckBox5.Caption
If CheckBox6.Value = True Then Cells(emptyRow, 6).Value = CheckBox6.Caption
If CheckBox7.Value = True Then Cells(emptyRow, 7).Value = CheckBox7.Caption

emptyRow = WorksheetFunction.CountA(Range("A:A")) + 3

Cells(emptyRow, 1).Value = TextBox1.Value
Cells(emptyRow, 2).Value = TextBox2.Value
Cells(emptyRow, 3).Value = TextBox3.Value
Cells(emptyRow, 4).Value = TextBox4.Value
Cells(emptyRow, 5).Value = TextBox5.Value
Cells(emptyRow, 6).Value = TextBox6.Value
Cells(emptyRow, 7).Value = TextBox7.Value

emptyRow = WorksheetFunction.CountA(Range("A:A")) + 4

Cells(emptyRow, 1).Value = TextBox8.Value
Cells(emptyRow, 2).Value = TextBox9.Value
Cells(emptyRow, 3).Value = TextBox10.Value
Cells(emptyRow, 4).Value = TextBox11.Value
Cells(emptyRow, 5).Value = TextBox12.Value
Cells(emptyRow, 6).Value = TextBox13.Value
Cells(emptyRow, 7).Value = TextBox14.Value
```

Figure F2: VBA code for the second user form for the newly developed framework Part 1

```
Private Sub TextBox36_Change()

Dim Total1 As Double
    Total1 = 0
    If Len(TextBox1.Value) > 0 Then Total1 = Total1 + CDbl(TextBox1.Value)
    If Len(TextBox2.Value) > 0 Then Total1 = Total1 + CDbl(TextBox2.Value)
    If Len(TextBox3.Value) > 0 Then Total1 = Total1 + CDbl(TextBox3.Value)
    If Len(TextBox4.Value) > 0 Then Total1 = Total1 + CDbl(TextBox4.Value)
    If Len(TextBox5.Value) > 0 Then Total1 = Total1 + CDbl(TextBox5.Value)
    If Len(TextBox6.Value) > 0 Then Total1 = Total1 + CDbl(TextBox6.Value)
    If Len(TextBox7.Value) > 0 Then Total1 = Total1 + CDbl(TextBox7.Value)

    TextBox36.Value = Total1

End Sub
```

```
Private Sub TextBox37_Change()

Dim Total2 As Double
    Total2 = 0
    If Len(TextBox8.Value) > 0 Then Total2 = Total2 + CDbl(TextBox8.Value)
    If Len(TextBox9.Value) > 0 Then Total2 = Total2 + CDbl(TextBox9.Value)
    If Len(TextBox10.Value) > 0 Then Total2 = Total2 + CDbl(TextBox10.Value)
    If Len(TextBox11.Value) > 0 Then Total2 = Total2 + CDbl(TextBox11.Value)
    If Len(TextBox12.Value) > 0 Then Total2 = Total2 + CDbl(TextBox12.Value)
    If Len(TextBox13.Value) > 0 Then Total2 = Total2 + CDbl(TextBox13.Value)
    If Len(TextBox14.Value) > 0 Then Total2 = Total2 + CDbl(TextBox14.Value)

    TextBox37.Value = Total2

End Sub
```

```
Private Sub TextBox38_Change()

Dim Total As Double
    Total = 0
    If Len(TextBox15.Value) > 0 Then Total = Total + CDbl(TextBox15.Value)
    If Len(TextBox16.Value) > 0 Then Total = Total + CDbl(TextBox16.Value)
    If Len(TextBox17.Value) > 0 Then Total = Total + CDbl(TextBox17.Value)
    If Len(TextBox18.Value) > 0 Then Total = Total + CDbl(TextBox18.Value)
    If Len(TextBox19.Value) > 0 Then Total = Total + CDbl(TextBox19.Value)
    If Len(TextBox20.Value) > 0 Then Total = Total + CDbl(TextBox20.Value)
    If Len(TextBox21.Value) > 0 Then Total = Total + CDbl(TextBox21.Value)

    TextBox38.Value = Total

End Sub
```

Figure F3: VBA code for the second user form for the newly developed framework Part 2

ADDENDUM G: BAMBOO BICYCLE DATA USED FOR THE EQUATION DEVELOPMENT

The secondary manufacturing process chain for the bamboo bicycle manufactured by Stellenbosch University is illustrated in this appendix. The cost and time for each step of the process are also included in the illustration. The total cost to manufacture the bamboo bicycle, including the primary manufacturing activities, is R2 200. The total manufacturing time to manufacture the bicycle, including the primary manufacturing activities, is 3 831 min.

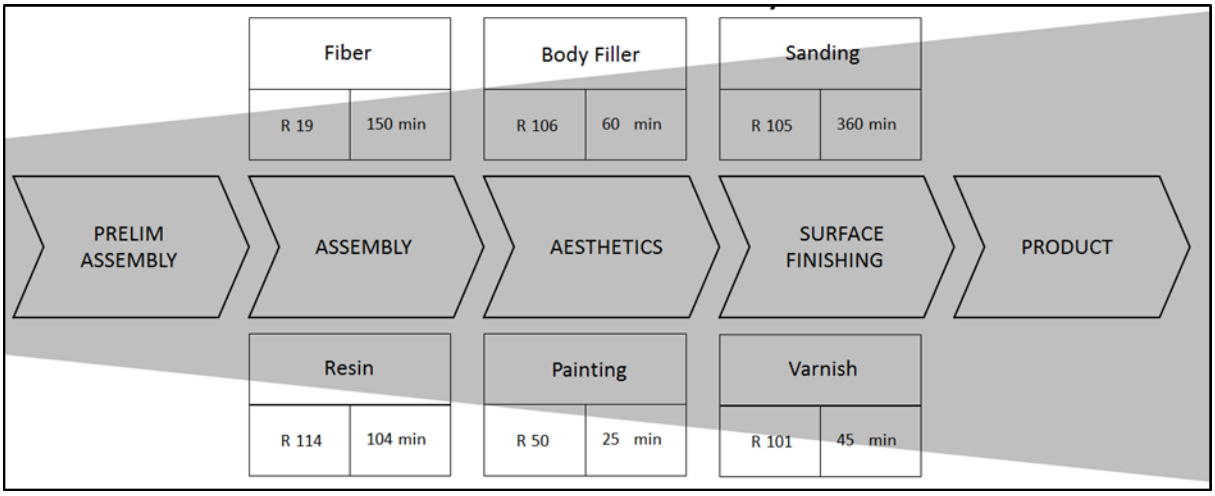

Figure G1: Secondary manufacturing process chain for the bamboo bicycle manufactured by Stellenbosch University, including the cost and time of each process step

The data for each step of the manufacturing process chain was captured during the actual manufacturing process of the bicycle. The time was calculated with the use of time studies of each step performed during the manufacturing process. The manufacturing cost for each step was calculated by adding the cost of the material used to the cost of the labour for the duration of each step.