LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
School of Technology
Mechanical Engineering

Patricia Nyamekye

ENERGY AND RAW MATERIAL CONSUMPTION ANALYSIS OF POWDER BED FUSION. CASE STUDY: CNC MACHINING AND LASER ADDITIVE MANUFACTURING

Examiners: Professor Antti Salminen
Professor Risto Soukka

Supervisors: D. Sc. Heidi Piili

M. Sc. Maija Leino

ABSTRACT

Lappeenranta University of Technology
School of Technology
LUT Mechanical Engineering
Mechanical Engineering
Patricia Nyamekye

ENERGY AND RAW MATERIAL CONSUMPTION ANALYSIS OF POWDER BED FUSION. CASE STUDY: CNC MACHINING AND LASER ADDITIVE MANUFACTURING

Master's thesis

108 pages, 66 figure, 16 tables, 5 appendices

Examiners: Professor Antti Salminen
Professor Risto Soukka

Keywords: Laser, additive manufacturing, CNC machining, power, energy, time, specific energy consumption, utilisation, efficiency, efficacy.

Laser additive manufacturing (LAM), known also as 3D printing, is a powder bed fusion (PBF) type of additive manufacturing (AM) technology used to manufacture metal parts layer by layer by assist of laser beam. The development of the technology from building just prototype parts to functional parts is due to design flexibility. And also possibility to manufacture tailored and optimised components in terms of performance and strength to weight ratio of final parts. The study of energy and raw material consumption in LAM is essential as it might facilitate the adoption and usage of the technique in manufacturing industries.

The objective this thesis was find the impact of LAM on environmental and economic aspects and to conduct life cycle inventory of CNC machining and LAM in terms of energy and raw material consumption at production phases.

Literature overview in this thesis include sustainability issues in manufacturing industries with focus on environmental and economic aspects. Also life cycle assessment and its applicability in manufacturing industry were studied. UPLCI-CO2PE! Initiative was identified as mostly applied exiting methodology to conduct LCI analysis in discrete manufacturing process like LAM. Many of the reviewed literature had focused to PBF of polymeric material and only few had considered metallic materials. The studies that had included metallic materials had only measured input and output energy or materials of the process and compared to different AM systems without comparing to any competitive process. Neither did any include effect of process variation when building metallic parts with LAM.

Experimental testing were carried out to make dissimilar samples with CNC machining and LAM in this thesis. Test samples were designed to include part complexity and weight reductions. PUMA 2500Y lathe machine was used in the CNC machining whereas a modified research machine representing EOSINT M-series was used for the LAM. The raw material used for making the test pieces were stainless steel 316L bar (CNC machined parts) and stainless steel 316L powder (LAM built parts).

An analysis of power, time, and the energy consumed in each of the manufacturing processes on production phase showed that LAM utilises more energy than CNC machining. The high energy consumption was as result of duration of production. Energy consumption profiles in CNC machining showed fluctuations with high and low power ranges. LAM energy usage within specific mode (standby, heating, process, sawing) remained relatively constant through the production. CNC machining was limited in terms of manufacturing freedom as it was not possible to manufacture all the designed sample by machining. And the one which was possible was aided with large amount of material removed as waste. Planning phase in LAM was shorter than in CNC machining as the latter required many preparation steps.

Specific energy consumptions (SEC) were estimated in LAM based on the practical results and assumed platform utilisation. The estimated platform utilisation showed SEC could reduce when more parts were placed in one build than it was in with the empirical results in this thesis (six parts).

ACKNOWLEDGEMENTS

My utmost praise goes to Almighty God for how far he has brought me. Baba, I say glory be to your Holy Name.

I will also like to express my sincere appreciation to my examiners Professor Antti Salminen and Professor Risto Soukka for the valuable ideas, advice, comments and suggestions towards the completion of this thesis. My heartfelt gratitude goes also to D.Sc. Heidi Piili and M.Sc. Maija Leino for the roles of advisors. I am very thankful for all the comments to this thesis as well as answers to my questions. I was never alone during difficult moment as you (Heidi) were always there to assist me in times of challenge and dismay. To Ville Matilainen, Ilkka Poutiainen, Jari Selesvuo and Juho Ratava I say thank you for all the assistance during the LAM and CNC machining experiments. Your readiness were overwhelming. Further thanks go to all my course teachers for the unmeasurable knowledge I received during my studies. From Mechanical, industrial management, energy, chemical and language departments. This thesis was possible as a result of all knowledge gained.

My gratefulness also goes out to all of my Family members, my pastor Rev. Sere-Yeboah Mensah and my friends (Martin, Appiah, Daniel, Eddie, Kingsley, Joshua, Atta, Frank (Franki) and Prince to mention but a few) for the encouragement and motivations towards the achievement of this thesis. A special thanks to Charles Nutakor who has always been there to help me go through both personal and academic issues. I have had swing moods sometimes but you understood me soo well and supported me regardless the temperament. A friend in whom I also find brotherly love and care. Thank you for been a true friend Charles.

To you my lovely son, Brian Nana Adu Appiah, (my reason for living) I dedicate this thesis to. I pray the good Lord preserves us all to see many blesses in our lives.

Thank You All!

Patricia Nyamekye
Lappeenranta 13th of March 2015.

CONTENTS

Appendix I	Representation of Contribution of manufacturing on GDP.
Appendix II	Representation of UPLCI! CO2PE! Initiative frame work and system boundary unit identification.
Appendix III	Representation of PUMA 2500Y specifications.
Appendix IV	Power, time, energy, mass and volume of material results in CNC machining.
Appendix V	Power, time, energy, mass and volume of material results in LAM.

LIST OF SYMBOLS, UNITS AND ABBREVIATIONS

Symbol	**Unit**	**Explanation**
Σ (i, n)	-	Summation from term one (i) to last term (n)
ϱ	kg/cm^3	Density
ϱ316L	kg/cm^3	Density of stainless steel grade 316L
E^3	-	Signifies sustainability
e	-	Exponential
E_{CNC}	MJ (kwh)	Total energy used to machine one test piece
$Ecutting$	MJ (kwh)	Energy consumed to cut-off test piece
E_{con}	MJ (kwh)	Estimated energy consumed as per part
$E_{drilling}$	MJ (kwh)	Energy consumed for drilling
E_{LAM}	MJ (kwh)	Total energy consumption in LAM
$E_{outside}$	MJ (kwh)	Energy consumed during the outside turning
E_{inside}	MJ (kwh)	Energy consumed during internal turning
$E_{milling}$	MJ (kwh)	Energy consumed during milling
E_{method}	MJ (kwh)	Energy consumed in each manufacturing method
E_{tool}	MJ (kwh)	Energy consumed for tools change
E_{total}	MJ (kwh)	Total energy used to produce test pieces
$E_{heating}$	MJ (kwh)	Energy used to heat and create inert atmosphere
$E_{processing}$	MJ (kwh)	Energy used for recoating, scanning, platform travels etc.
E_{sawing}	MJ (kwh)	Energy used to saw work pieces from platform
f	mm/min	Feed rate
L (1,2,3)	-	Line 1, line 2 line 3
m_d	*kg*	Deposited mass
m_r	kg	Removed mass
N_2	-	Nitrogen
O_2	-	Oxygen
P_{avg}	W	Power average
P_{CNC}	W	Power value during a CNC machining
$P_{process}$	W	Average power value in each process

$P_{standby}$	W	Power used for activities such as preparation, etc.
$P_{heating}$	W	Power used to heat and create inert atmosphere
P_{sawing}	W	Power used to saw work pieces from platform
P_{kw}	W	Power
p_v	V	voltage
STL	-	CAD file format that translates 3D model to acceptable format for AM systems
S1	-	Spindle motor
S2	-	Rotating tool motor
t	s	Time
$t_{process}$	s	Time taken to perform each manufacturing phase
$V_{removed}$	cm^3	Volume of removed material
V_{input}	cm^3	Volume of starting material
V_{part}	cm^3	Volume of final part
vi	cm^3	Volume of each test part
v_{TOT}	cm^3	Total volume of all six test pieces
X-axis	-	Movement of axis perpendicular to Z- axis
Y-axis	-	Movement of axis perpendicular to X axis and Z axis
Z-axis	-	Movement axis parallel with the spindle

Unit	**Explanation**
µ	Micro
µm	Micro meter
cm^3	Cubic centimeter
J	Joule
kg/cm^3	Kilogram per cubic centimeter
kg	Kilogram
kJ	Kilo joules
kW	Kilowatt
kWh/kg	Kilo watt hour per kilogram
kWh/cm^3	Kilo watt hour per cubic centimeter

l	Liter
mg/s	Milligram per second
min	Minutes
MJ	Mega joule
MJ/kg	Mega joule per kilogram
MJ/cm^3	Mega joule per cubic centimeter
mm	Millimeter
mm/min	Millimeter per minute
MPa	Mega Pascal
ms	Millisecond
Mtoe	millions of tonnes of oil equivalent
MW	Mega watt
rpm	Revolutions per minute
s	Seconds
W	Watt

Abbreviation	**Explanation**
3D	Three-dimensional model
AM	Additive manufacturing
AMAZE	Additive Manufacturing Aiming Towards Zero Waste and Efficient Production of High-Tech Metal Products
AISI	American Iron and Steel Institute
CNC	Computer numeric control
CO_2	Carbon dioxide
CO_2PE!	Cooperative effort on process emissions in manufacturing
DED	Direct energy deposition
DFM	Design for manufacture
DMD	Direct metal deposition
DMLS	Direct metal laser sintering
EU	European Union
EC	European Commission

ECU’s	Energy consuming units
G-code	Controlling programming language that inform the movement of parts and tool in numerical control machining systems.
GDP	Gross domestic product
LAM	Laser additive manufacturing
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
LS	Laser sintering
MDGs	Millennium development goals
M&S	Manufacturing and service
NC	Numerical control
OECD	Organization for economic cooperation and development
PBF	Powder bed fusion
PLM	Product life management
SBD	Sustainability business development
SDGs	Sustainable development goals
SEC	Specific energy consumption
SETAC	Society of Environmental Toxicology and Chemistry
SLM	Selective laser melting
SLS	Selective laser sintering
TCA	Trichloroethane
UN	United Nations
UNEP	United Nation’s environment program
UPLCI	Unit process life cycle inventory

INTRODUCTION

1 OVERVIEW TO THIS THESIS

1.1 Background

The revolution from agriculture-based to manufacturing-based economy for greater yields has remained reliable approach to improve the standard of living in many developing countries. This trend of development has enhance healthy competition in industrialised nations (Manyika et al., 2012). The activities of manufacturing sector contribute to the economy and wellness of many countries. As raw materials are converted into finished consumer goods or intermediate goods by fabricating or assembling components to satisfy the needs of people. The outputs of manufacturing activities generate substantial percentage of employment for personal, regional and national development. Manufacturing industries also support economic strength with specific share in Gross Domestic Product (GDP) (Olakunle, 2010).

However, many manufactory activities account largely to present-day global environmental problems. Many negative environmental damage are introduced into the environment in the process of fabricating and assembling products. A lot of studies have been conducted on the negative impacts traditional processes like machining, welding, forging and casting have on the environment and natural resource. The ecosystem suffer from either the massive amount of raw materials, energy and process aids (liquids, gases) used to manufacture parts or related emissions. Some of the aftermath are natural resources depletion and increased pollutants released into the atmosphere either as solid, gas or liquid. This has raised lots of concerns on different levels in several corporations.

Maintaining a balance of the usage and re-usage or re-cycling of resources must be retained in order to safeguard the environment (Batterham, 2003). Present relevant discussions in many organizations (e.g. EU) are centred on these damages caused to the environment by manufacturing and other industrial sectors. The existence and profusion of carbon dioxide

(CO_2) and other greenhouse gases (GHGs) pose a danger to the universe. Notably the levels of GHGs that continue to increase remain a threat to human and the ecosystem. It is however challenging as the problems that exist in the world appear unsolvable by level of thinking that created them. Thus finding new ideas to identify and develop resource efficient practices may offer a solution to these resource imbalances. This objective is achievable since the advancement of science and technology has given a steady increase of efficient and effective processes in producing goods and services (Batterham, 2003; Gutowski et al., 2006).

New techniques are anticipated to diminish negative impact like emission of toxic substance from manufacturing activities into the environment. The few ecological footprint reduction tool designs suit conventional processes like milling and turning. As such there exist few tools and methods to identify the potential environment benefit in present and emerging manufacturing processes like LAM. One of such tool that exist to overcome such shortfall is a lifecycle model, CO_2PE! Initiative. This initiative was developed to carter for the inefficiencies in measuring benefits in discrete manufacturing processes (Duflou et al., 2011).

Energy consumption in industrial sector differ from place to place as well as yearly. In 2007, industrial sector was the highest single consumer of energy with 27.9 % within EU-27[1] (EC, 2010). The sector was also responsible for 51.0 % of energy consumption and 25.0 % of CO_2 emissions globally (Iogen Corporation, 2014; Jancovici, 2013) in 2012. It is interesting to note however that, these consumptions vary yearly and from country to country with OECD[2] countries consuming more than non-OECD countries (EC, 2014a).

The share of energy consumption per sector within Europe and other advanced states were reviewed. Figure 1 and 2 exhibit the share of energy consumed per sector for the years 2005, 2010, 2011 and 2012 within EU-28[3].

---

[1] The EU-27 was an economic and political partnership between 27 European countries.

[2] Organization for Economic Cooperation and Development

[3] The EU-28 is an economic and political partnership between 28 member states.

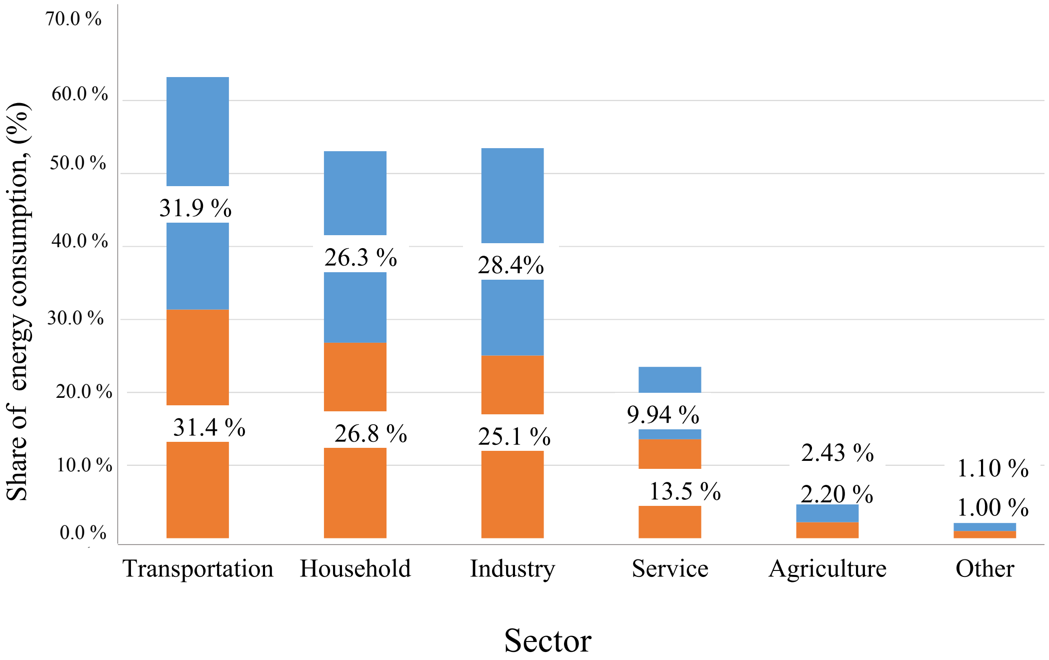


Figure 1. Share of total energy consumption by sector within EU-28 for 1) orange 2010 and 2) blue 2005 (European Union, 2014).

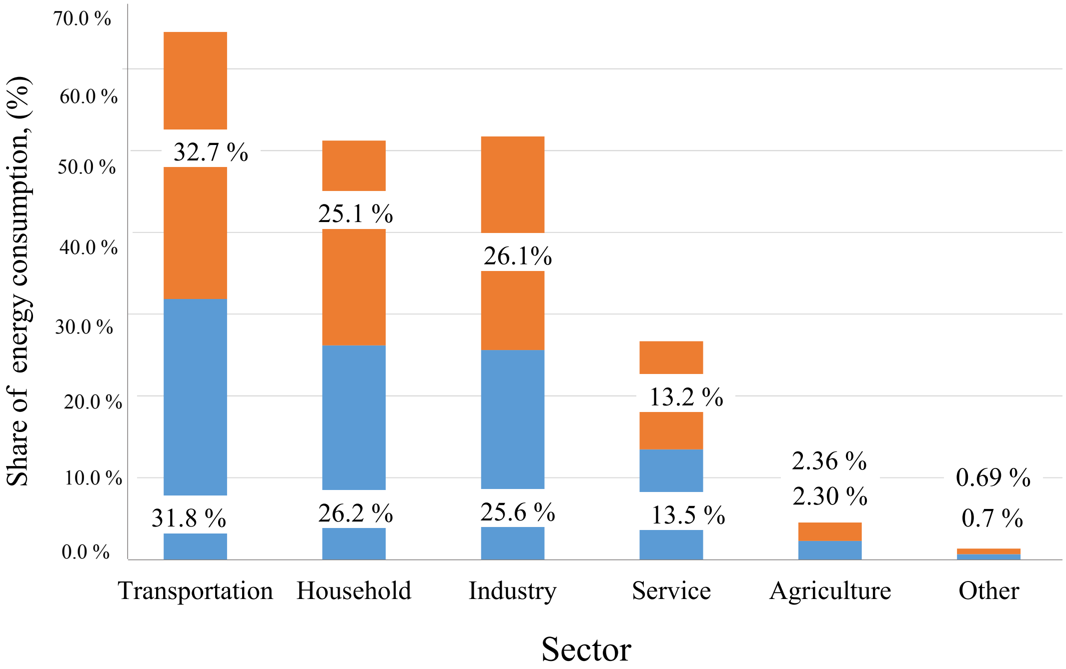


Figure 2. Share of total energy consumption by sector within EU-28 for 1) orange 2011 and 2) blue 2012 (European Union, 2014).

The percentages amongst the various sectors show an ununiformed consumption of energy. Transportation remain with the highest share the all the considered years as shown in Figures

1 and 2. The share of industry for the compared years demonstrates discrepancies with 28.4 % for 2005; 25.1 for 2010; 26.1 % for 2011 and 25.6 % for 2012. Total energy consumption per sectors in EU-28 was about 1160 Mtoe in 2005 and 2010, 1108 Mtoe in 2011 and 1104 Mtoes in 2012. A comparison of the energy usage for these years show about 7.9 Mtoe declination. The total energy consumed by industrial was 290.7 Mtoe in 2010 and 282.8 Mtoe in 2012. In 2011 only about 1.3 Mtoe reduction of energy consumption (289.4 Mtoe) in relation to 2010 value was saved. A higher decline of energy consumption can be seen from 2005 to 2010 as about 39.0 Mtoe energy saving was realised. (European Union, 2014) The European Commission believes that these reductions have been possible with the replacement of olden, unproductive engineering activities and other infrastructure notwithstanding the improved economic activity. These reductions might have also effected as a result of energy efficient policies implemented by European Commission (EC, 2014a) or ecological trend in manufacturing activities.

Figures 3 and 4 show energy consumption variations among some industrialised economics (Finland; Russia and EU-27) for the years 2007 and 2009 (EC, 2014a; Statistics Finland, 2008). Figure 3 illustrates energy consumption per sector in Finland for 2008.

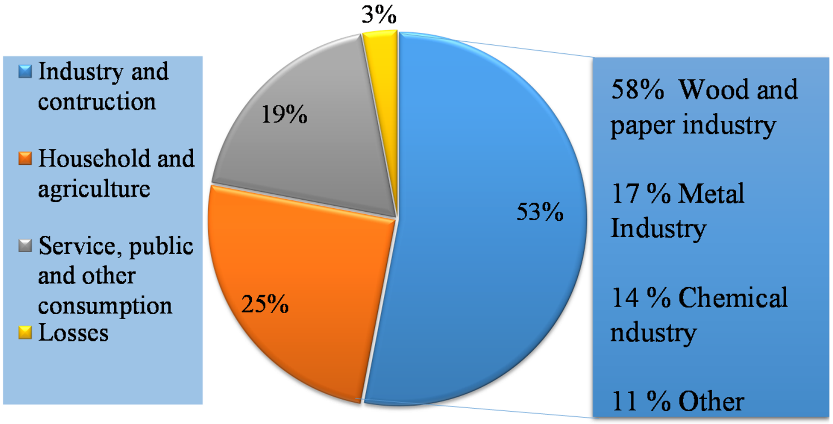
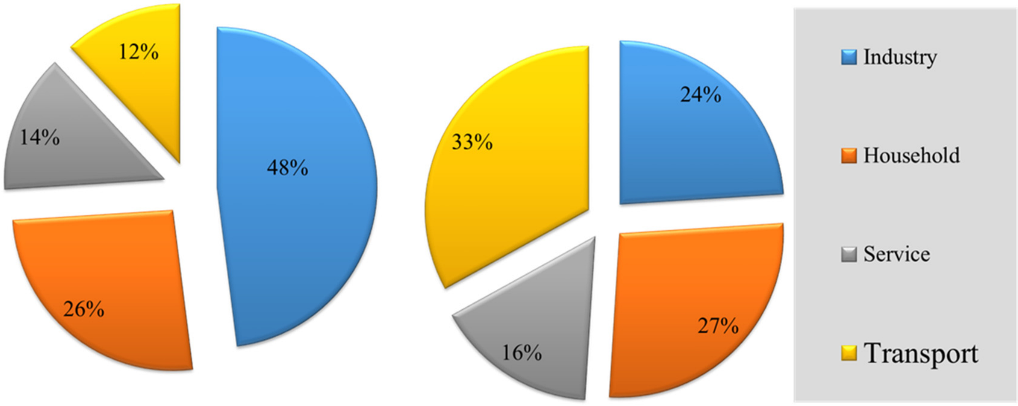


Figure 3. Share of energy consumption by 1) sector and 2) within industry of Finland in 2007 (Statistics Finland, 2008).

As it can be seen from Figure 3 the energy consumption within industry are subdivided into various manufacturing sectors with the metal industry consisting the second energy consumption source in Finland. Figure 4 shows the share of energy consumption for Russia and EU-27 in 2009.



Share of energy consumption per sector a) Russia b) EU-27

Figure 4. Energy consumption in Russia and EU-27 in 2009 (EC, 2014a).

As it can be seen from Figure 4 industrial sector accounts for variable percentage of energy consumption depending on the region or country considered. As it accounts for a larger share of energy consumption in Russia with 48.0 % in 2009 it accounted for 24.0 % in EU-27.

1.2 Research problem and objectives

Presently, an increase of material and resource inefficiencies appear worrisome in manufacturing industries. This is as a result of the many laws emerging from various sectors to govern its activities due to their quota to negative environmental impacts like global warming. Countries and nations are jointly developing rules and laws to ensure minimisation of such effects. The UN, EU and other leading organisations have all expressed interest and are taking steps to control emissions released into the atmosphere. The United States and China recently revealed their approach to achieving such targets. An announcement was made in November 2014 of their joint post-2020 effort (UN, 2014).

Many have questioned emissions and resource efficiencies in the manufacturing industry as it constitutes as one of the main material and energy-related consumption segments (UNEP, 2011). The need to develop efficient and effective manufacturing processes amongst other reasons are necessary to salvage the earth and its inhabitants. The United States in an efforts to overcome resource inefficiencies acknowledges the benefit of mass customization, improved supply chain and lower lifecycle energy related systems like laser assisted processes. LAM is one of the existing techniques that might offer manufacturing sector the path to more fast, efficient, and cost-effective production. As such it is considered as part of future manufacturing technologies towards resource efficiency, due to their characteristic of high productivity, agility and flexibility. (Yoon et al., 2014; Cohen et al., 2014; Klocke et al., 2014; Nyrhilä, 2014; Morrow et al., 2007)

An evaluation of the performance of modern technologies (e.g. LAM) in terms environmental and economic benefits may help improve current shortfalls in manufacturing activities. Thus conducting LCI with empirical methods according to ISO standards to highlight the potentials and improvement of manufacturing unit process might facilitate the acceptability and adoption of LAM.

This thesis had two main objectives as:

1. Find the impact of LAM on environmental and economic aspects and
2. Conduct life cycle inventory (LCI) analysis of LAM in comparison with CNC machining.

The study of the impact of LAM on environment and economy and possible ways to improve productivity may foster an appreciation of its contribution to sustainability. This thesis was thus carried out in order give numerical comparisons of energy and raw material usage and generated waste as well as efficiency improvement in LAM with experimental test. Parts were produced using LAM and with a replaceable process (CNC machining). The execution of this thesis was directed by three main questions:

1. Does LAM provide environmental benefits in industrial processes?
2. Does LAM provide economic benefits?
3. How does productivity improve in LAM?

The main stipulated outcomes after a successful completion of this thesis were:

1. To offer experimental values of energy and material consumption of both processes,
2. To demonstrate the advantages of LAM to manufacturing flexibility.
3. To provide appreciation of the efficiency and efficacy of both CNC machining and LAM.

1.3 Research methodology

The methods were used to find answers to the research questions of this master's thesis were literature review and experiment studies. There are two main sections: 1) literature review and 2) experimental part of this thesis. Firstly, an overview of relevant literature regarding CNC machining and LAM, sustainability in manufacturing and life cycle assessment are discussed. A description of the experimental study performed to examine the energy and raw material consumption in CNC machining and LAM is also detailed. Results, conclusions and recommendations for further studies are also offered.

1.4 Outlines of this thesis

This thesis was limited to CNC machining and LAM to manufacture direct metal components. The advantages and disadvantages of LAM with regards to environmental and economic aspects were studied based on existing literature. Raw material, electrical energy and related fluid consumption during production phase of each process form the basis of comparison in the experimental study. The empirical study of this thesis was narrow to the production phase due to the enormous information on the entire value chain. However, a comparative assertion to determine the more efficient process in terms of environment and economy was presented with the literature review. Figure 5 shows areas included in this thesis for both manufacturing processes.

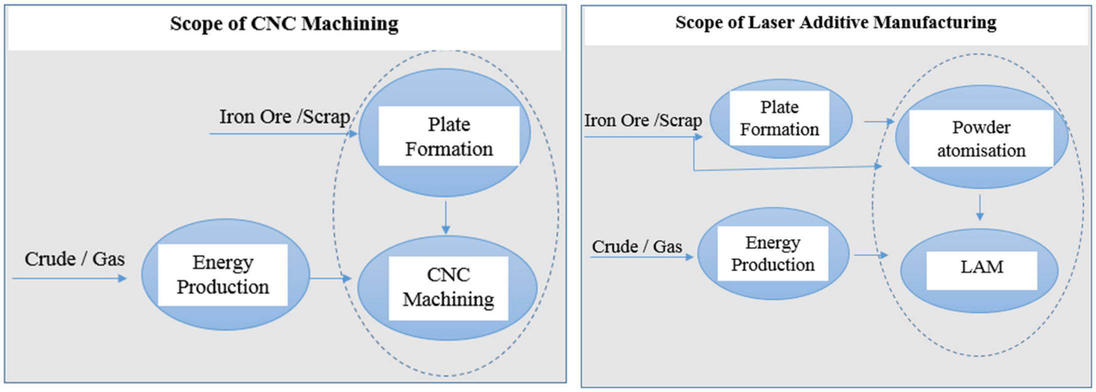


Figure 5. Scope used for the literature review in this thesis.

Figure 5 represents the scope within which literature review of this thesis was done. An overview of previous studies relating to energy and material usage during the production; making of the raw materials as well as sustainability issues in terms of environment and economical aspects were deliberated. The experimental study was limited to the production phase of both process. The limitation of experimental study are shown later in experimental part in this thesis.

LITERATURE REVIEW

2 SUSTAINABLE DEVELOPMENT

Sustainable manufacturing and services oriented businesses have become vital issue in recent years. This is as the result of the many negative impact such as global warming, acid rain, ozone layer depletion and several pollutions the eco-system is exposed to (Conserve Energy Future, 2015). Another factor that might have demanded such change could be ascribed to the increased awareness about environmental issues to the consumer. The modern drift of customers' choice centres on ecology which has stimulated companies for competitive advantage (EC, 2011). Also environmental needs and rules compliance cost imposed on companies is other reason to this trend (Gunasekaran and Spalanzani 2012).

Servitisation[4] and product life management (PLM[5]) are concepts in industrial engineering management that support companies to offer and track products and services through their life cycle (Lee, 2011; Anon., 2011). These ideas are expected to remain in manufacturing companies and be developed for many years to come if sustainability is to be maintained. It is no doubt that this will be maintained as sustainability initiatives presently play an important role in the success of firms (Deloitte Development LLC, 2010). The adoption of sustainability by manufacturing and service organisations is geared towards conservation of natural resources against misuse, and in a quest for higher productivity and attractiveness. This trend includes reverse logistics[6] to safeguard natural resources and protect the environment (Manyika et al., 2012). The sustainability of products, processes and services has become a worldwide phenomenon; due to the pressure around ecological advancement, environmental legislations, increased cost of living and growing numbers of population.

---

[4] According to Neely. (2008) "servitisation is defined as the process of providing a service offering to key product lines: from maintenance and upgrades to training and end of life disposal".

[5] According to Anon. (2011) "PLM is a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise, and spanning from product concept to end of life-integrating people, processes, business systems, and information".

[6] According to Kim et al. (2006) "Reverse logistics can be defined as the logistics activities all the way from used products no longer required by the customer to products again usable in the market".

According to WCED (1987) “sustainability is meeting the needs of the present generation without compromising the ability of future generations to meet their own needs”. According Sikdar. (2003) “sustainability can be said to achieve when material and social conditions for human health and the environment are maintained or improved over time without exceeding the ecological capabilities that support them”. Whereas sustainable development refer to any techniques, means or processes that lead to the realisation of the sustainability goal. Figure 6 shows the interactive sustainability metrics signifying it as interaction of three pillars integrated as one system. (Sikdar., 2003)

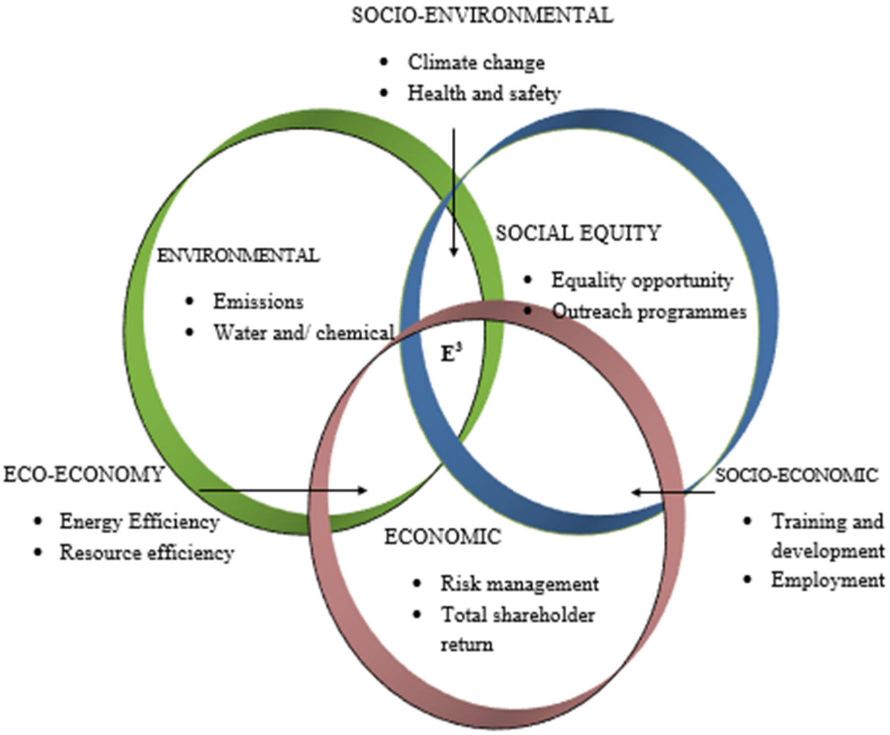


Figure 6. Representation of sustainability metric (Sreenivasan and Bourell, 2009).

As it is shown in Figure 6 sustainability is illustrated to be based on three key pillars (social, economy, and environment) with further subsections (eco-economy, socio-economy, socio-environmental). The area indicated as “E^3” implies that sustainability is achievable when all of environment, social equity and economic impact issues are fulfilled. The goal of sustainable development may not be achieved with neither economic profitability, environmental efficiencies nor social balances only. It requires an all-inclusive as a triple bottom line approach to its attainment as Figure 6 illustrates.

The definition of sustainability given by WCED (1987) has been argued on the basis that the future generations as well as the earth are at risk as the people develop thus caring for environment and people alone is not enough but earth and its system must be included. It is suggested that the mere extension of the Millennium Development Goals (MDGs) is inefficient and that measures to support also earth systems like waterways and biosphere as well reduce poverty are essential towards achieving of sustainable development goals (SDGs). The view is that the over decade model (see Figure 6) that has served both the UN and other nations is flawed due to its failure of giving a true reflection of reality. A new definition is thus proposed in carter for this inadequacy.

According to Griggs al. (2013) “sustainability development is development that meets the needs of the present while safeguarding earth’s life-support system, on which the welfare of current and future generations depends” It is becoming imperative to safeguard the earth, safety and welfare of those alive today and prepare for those yet to come. Shyamsundar noted that, “as the global population increases towards nine billion people sustainable development should be seen as an economy serving society within Earth’s life support system, not as three pillars” (IGBP, 2013). Figure 7 illustrate the new integrated approach of the three pillars (Earth’s life support, society and economy) of sustainability.

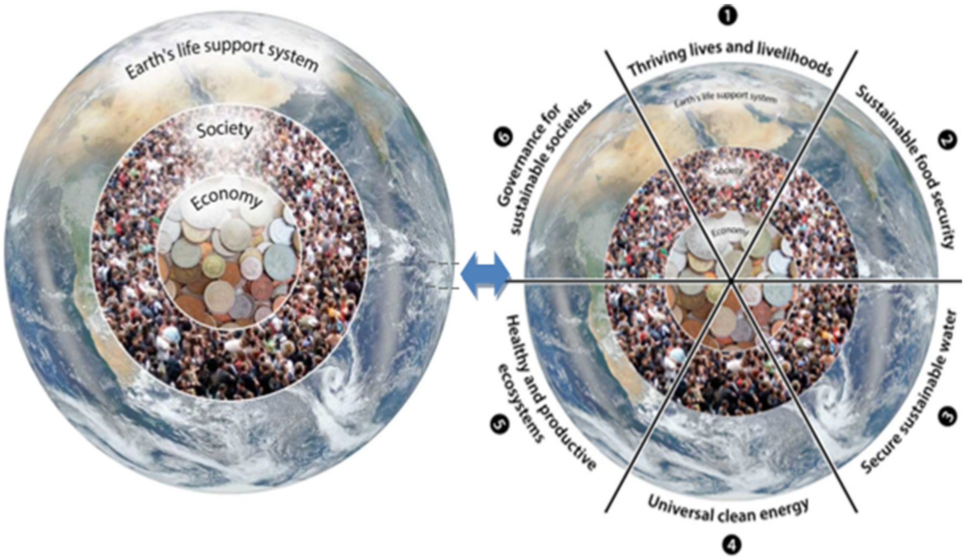


Figure 7. Sustainability pillars placed as integrated sectors for sustainable development (IGBP, 2013).

As it can be observed from Figure 7, six goals are proposed to be achieved with this new approach. It alleged that can this might help over the tensions that have continually remained in countries. For example, economic gains have been satisfied whiles the environment suffer and political struggling remain in an effort to link global environmental concerns with poverty tackling (UNEP, 2011).

Sustainability, agile supply chain and customised products are increasingly becoming fundamentals of competition in manufacturing industries.

Gunasekaran and Spalanzani (2012) in their study have presented sustainable business development (SBD) to focus on manufacturing, production and supply chain systems. In the study it was identified that safeguarding natural resource will require companies understanding of the importance of the reuse and recycling of products as well as their advantage of increased efficiency (Gunasekaran and Spalanzani 2012). Figure 8 illustrates SBD in manufacturing and service (M&S) companies as revealed in the study.

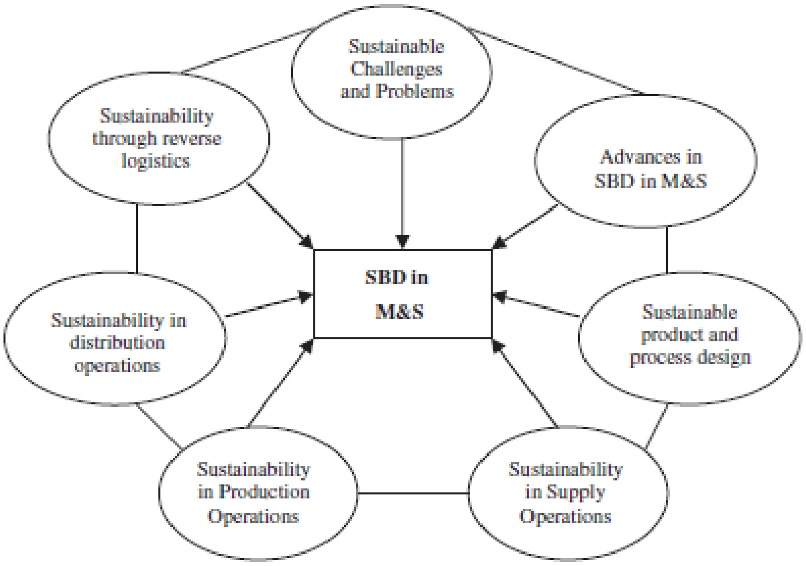


Figure 8. Sustainable business development in manufacturing and services (Gunasekaran and Spalanzani 2012).

As depicted in Figure 8 sustainability in manufacturing is definitely necessary to be built on all the seven major blocks. According to Gunasekaran and Spalanzani. (2012) “sustainability in production operations should result in flexibility, customization, alertness, reliability, cost reduction as well as high quality products and services”. The study maintain that all of these and other attributes of products and services depends upon effective production processes and supply chains, inventory turnover, process control, capacity utilization, work-in-process inventory with reduced scrap rates. However sustainability from environmental perspectives require minimal waste, minimum energy use, safety and wellbeing of employees.

Most traditional processes however often impose these negative impacts on both natural and non-natural resources (Manyika et al., 2012). Developing and adapting to processes, materials and systems that offer manufacturing companies the option to effective operations is inevitably essential. Thus there have been many new innovations in manufacturing industry thought of as theoretically or practically capable to such negative impact on earth's life support system.

Morrow et al. (2007) have demonstrated with a case study some environmental and economic impacts of direct metal deposition (DMD) processes. Laser based DMD is described as one of the promising manufacturing methods in terms of resource efficiency. It is alleged that these techniques might reduce part of the negative effect in manufacturing sectors as well as reduce tooling needed. It was revealed that DMD with laser for remanufacturing products may result in higher efficacy through their lifetime than conventional manufacturing under specified use. For instance building low solid-to-cavity volume ratio mould with DMD are potentially least environmentally burdensome. Contrarily, fabricating a high solid-to-cavity volume ratio mould which does not require a lot of finish processes with CNC machining may be much beneficial to the environment.

In another view LAM is labelled as one of the existing environmental friendly processes that is capable of saving materials and energy usage. The possibility to creating complex and customised parts and to omit coolant or lubrication liquid which emit pollutant often in manufacturing was also emphasised. Also it is believed that there could be an additional advantage I excess heat could be transferred for water-cooling in buildings (Bechmann, 2014).

According to Morgan. (2013) David Jarvis of ESA in an interview has also revealed that AMAZE has expressed their ambition of having metallic satellite printed as one unit with LAM process. It is believed that having parts as built as one unit may eliminate the need of welding or bolting and in effect reduce cost. Production budget is expected to reduce by half as well as improve strength and reduced weight of part. These benefits of LAM indicate a dual benefit if adopted to as both the ecology and economy could be improved.

2.1 Impact of CNC machining and LAM on the environment

Most of the literature reviewed in terms of environment of AM processes included only laser based processes. However other studies compared AM with other manufacturing processes such as injection moulding and machining. Other sections of reviews that have compared conventional process with AM have merely limited studies to polymeric material without much said of metallic production. In a study conducted by Baumers et al. (2011) an empirical results of various metallic AM processes were presented. Laser and electron beam based processes for metallic and polymeric powder were investigated. The study showed that a good capacity utilisation in LAM may improve resource efficiency and enhanced customised production which may result in reduction of negative environmental impacts.

Yoon et al. (2014) in a study have compared AM, and traditional processes like injection moulding and machining (e.g. milling and drilling) processes like. The study was limited to energy consumption in producing polymeric parts. It was revealed that AM processes were among the strongly highlighted advance manufacturing initiatives proposed by the USA government for energy efficiency. In their study, AM processes were identified as the most energy intensive process among the three processes studied. The specific energy consumption (SEC[7]) recorded for the AM were high. The SEC for AM process was about a 100-fold higher than that of compared processes. Despite the low SEC for both traditional processes compared to AM CNC machining was described as subtractive manufacturing process that uses vast quantity of energy to remove large mass of start-up material in order to produce parts (Yoon et al., 2014).

---

[7] According to FEDCO. (2014) “SEC a parameter used to evaluate energy efficiency.in kW-hr or MJ of electrical energy consumed in producing kg or cm3 of product”.

2.1.1 Impact of CNC machining and LAM on raw material usage

The production of the metallic plate and powder used in CNC machining and LAM often start from same form of material. The process flow begins with casted ingots in a ratio of about 5 to1 of scrap and sponge or pig iron. Melting of metal is done to form uniform solution with additional purification through ladle refining, re-melting and re-casting to precise structure. A post processing performed before making plates, slabs or blocks with by forging or rolling. Powder metal may be achieved with two processes. It may be done either by atomising the finished plate or slabs into powder, a process termed as indirect atomization. Conversely a straight powder production from the melted scrap and ore iron without necessary the plate formation is achievable with direct atomization. (Morrow et al., 2007). Figure 9 illustrates process flow of metallic ingot and powder production.

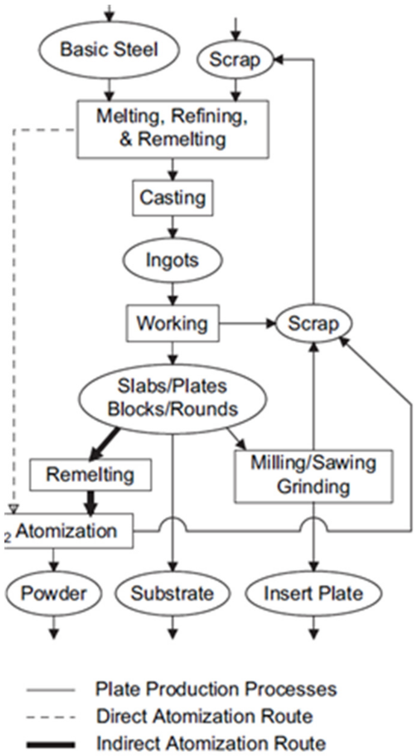


Figure 9. Raw material production processes for metallic powder, plate or slab (Morrow et al., 2007).

Some amount of material losses can be expected with all paths though a higher lost can be anticipated with the plate formation and indirect atomization flow paths. Figure 9 presumes more material loss in the plate or indirect routes as scrap which are however recycled as raw material. It is undoubtable that during the various intermediate phases, some amount of materials are lost either on surfaces of moulds or during the re-melting.

In a case study to investigate fabrication of an airplane bracket has shown that using indirect atomised powder saves both raw material and energy. The embodied energy for producing the ingot was given as 918 MJ/kg which indicates that indirect atomization was utilised. About 95 % of starting material needed for machining a bracket was saved using LAM. It was also shown in the study that the SEC required to atomise powder for AM WAS about 1.10 MJ/kg lower than the needed energy for primary processing in machining (U.S. Department of Energy, 2014).

LAM, strongly support material and resource efficiency with a higher degree of part flexibility. Building parts with LAM can guarantee the wise usage of material and resources in that no additional fixtures or jigs often necessary in CNC machining are required. LAM offer also the possibility of almost direct re-use of leftover powder with minimal treatment. The use of LAM will reduce waste by about 90 % of raw material and offer option of reusing excess powder in new build (Fraunhofer ILT, 2013). LAM has the potential of almost 94 % of raw material utilisation during part building not considering the powder losses. (Salminen, 2014)

2.1.2 Impact of CNC machining and LAM on energy consumption

The rate at which energy is consumed in fabricating products remain one of the basis for environmental concern in manufacturing processes. The SEC required for the production of raw material needed in CNC machining (plate) and LAM (powder) was compared in the study by Morrow et al. (2007) for H13 steel plates and H13 steel. Figure 10 shows the energy consumption associated with the production these raw materials.

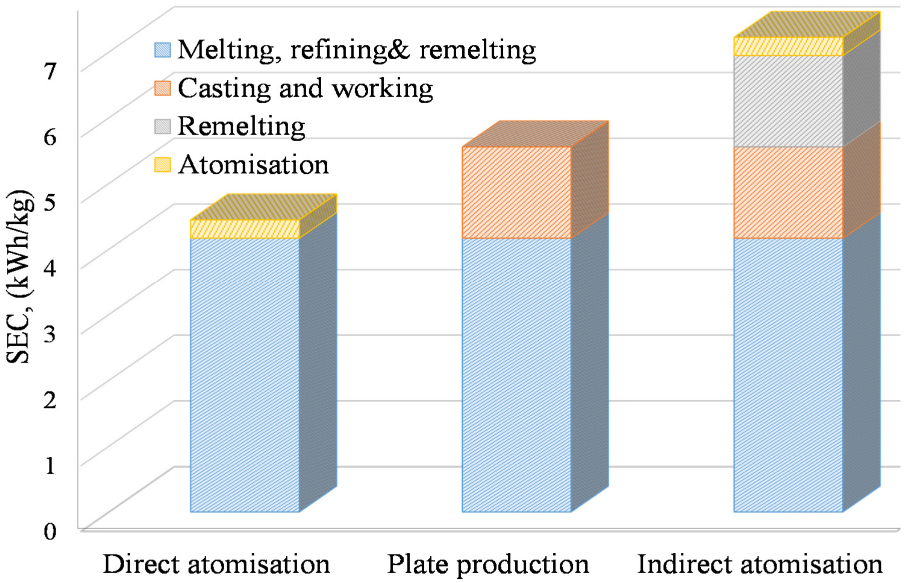


Figure 10. SEC of material production pathways (Redrawn from Morrow et al., 2007).

As seen it can be seen from Figure 10, the specific energy required for producing powder with indirect atomization is high. It required about 25 % more SEC to that of the plate production which consumes about 5.6 kWh/kg. SEC for the plate production was about 20 % more in value than the required amount used for direct atomization. One may expect that powder produced with direct atomization flow chart may be used frequently as both material and energy consumption are relatively low. Instead, the study revealed that powder utilisation was high with indirect atomised powder thus it was often preferred to the former (Morrow et al. 2007). This issue needs further studies however.

Another study to investigate the environmental impact of machining proves that rate of energy consumption in CNC machining process are almost constant irrespective of the production outcome. The electrical demand per part appeared independent on the material removal rate for metal machining. The type of material seemed to have an effect on the energy usage. This indicate higher energy would be required for machining virgin materials than recycled ones. (Dahmus and Gutowski, 2004)

In a similar study to compare energy consumption in machining processes it was revealed that the air cutting[8] and actual cutting of different materials are almost the same with little or no variations Figure 11 represents the power demanded for machining three different materials in watts (Diaz et al. 2011).

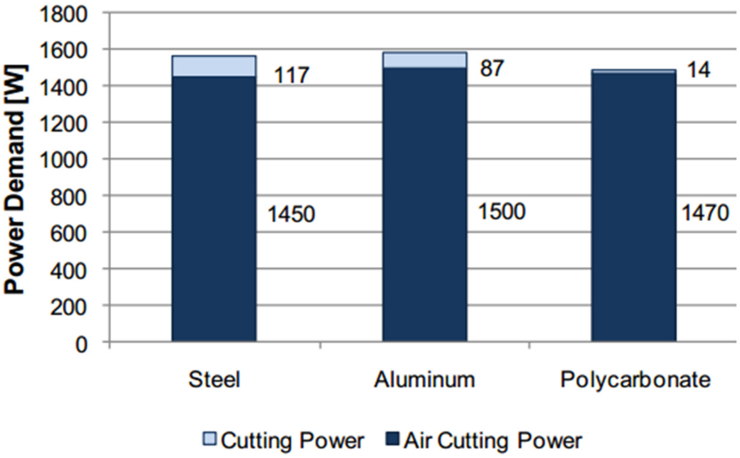


Figure 11. Power demand of NV1500 DCG for steel, aluminium, and polycarbonate work pieces (Diaz et al., 2011).

Figure 11 indicate a constant energy usage in machining the three different materials as power values are almost same. The difference in materials minimally can affect the total cutting energy. This implies that the total embodied energy of CNC machining processes can to very small extent be controlled whereas energy usage in LAM often can be meticulous by increasing number of parts.

The trend of energy consumption for any AM processes remain unpredictable. This is due to likelihood of variance in build volume, density and height or heating and cooling of different systems affecting consumption rate. It was revealed in the study by Baumers et al. (2011) that capacity utilisation affects strongly the SEC required to lay one kilogram of material. This was confirmed by the results of their experimental studies designed for a full and single builds. The SEC for the fully filled LAM was 66.9 kWh/kg and single parts was 99.2 kWh/kg (Baumers et al., 2011).

The results of energy related articles on metallic LAM reviewed in this thesis from different systems are summarised in Table 1. Almost all the conducted studied involved metallic LAM

---

[8] The state of running the programmed cutting code without tool touching work piece.

with other processes or same process with different materials. Table 1 represents the summarised SEC valves for metallic parts with laser based additive manufacturing processes.

Table 1. Energy consumption rates for three LAM process (Baumers et al., 2011).

Technology	**Energy consumption**	**Methodology**	**References**
LS	107–144 [MJ/Kg]	Energy consumption not empirically measured	Luo et al., 1999
DMLS	115-202 [MJ/kg]	Single part build experiments	Mognol et al., 2006
LS	52.2 [MJ/kg]	Empirical energy results not reported	Sreenivasan and Bourell, 2009.
LS	130 [MJ/kg]	Full build experiments	Kellens et al., 2010a and 2010b
SLM	96.8[MJ/Kg]		
SLM	112-140 [MJ/kg]	Based on single part and full build tests	Baumers et al., 2010
DMLS	241–340 [MJ/kg]	Single part and full build experiments	Baumers et al., 2011

Table 1 indicates variations in energy consumption of laser assisted additive manufacturing processes. None of the different studies showed same energy consumption. The varieties in results in Table 1 could be attributed to the dissimilar conditions and LAM systems with which the various test were performed: 1) build orientations, 2) form of part (net or hollow) and 3) machine used. The total energy consumed in the studies are summations of all energy used for warming, cooling and actual building of parts.

The dissimilarity of SEC recorded by Kellens et al (2010a and 2010b) is remarkable considering the fact that both used full build. The energy consumption of 129.73 MJ/kg Kellens et al. (2010a) fall within values of 107.39-144.32 [MJ/kg]. Luo et al. (1999) even the latter was not based on empirical study.

The energy efficiency of AM is very debatable as many studies have shown higher energy consumed with the process. Some school of thoughts believed that the less material and process time used to manufacture a part compensate for these high energy usage. Whereas others maintain that the many peripheral required by machine tools must be included in the different energy considerations (Drizo and Pegna, 2006).

2.1.3 Health and ecosystem risk of CNC machining and LAM

Manufacturing processes release emissions and toxic waste into the environment in the course of fabricating parts. These emissions or toxics often endanger the lives of people and the ecosystem. CNC machining processes use high volume of process fluids that aid either in cooling or lubrication. This often are required to resist and assist corrosion and chip removal. Also high amount of water may be used to clean workshop of spills. Many studies have shown that workers are endangered as result of constant exposure to these as well as other related risks. Workers in machine shops are exposed to lots of these liquids which may be toxic when in contact with the human body. Waste fluids often disposed into waste streams may flow into waterways, if not properly controlled. These fluids may endanger human and can result even in chronic disease (Avram et al., 2011). Also chemicals used as additives (e.g TCA) with these cutting fluids might contribute to high levels in ozone depletion as well as high acidification levels that disturb aqua life.

Another significant impact of these fluids include water footprints that may result from direct water or indirect water usage as raw material, energy generation or supplementary aid during production. Thus environmental considerations cannot be judged based on energy and emissions but also other environmental impacts such as freshwater extraction, consumption and pollution. The degree of waste or harmful substance released into these water determine the extent to which they affect the environment or to which they can be treated back into useful water. About 10.0 % of freshwater withdrawal in United States of America IS consumed by Industrial activities (Ogaldez et al., 2012).

Machining processes that are generally characterised with generation of waste like dust often expose people to health risk. This is because there could be piled up of inhaled dust that can cause problems in respiratory system. This affect the quality of air in the environment and may be transferred outside the manufacturing company if not handled carefully.

Nonetheless, there are equally health risk in LAM process that may threaten lives of human and the environment. The fine grain input powder may be inhaled or diffused into the skin if proper protective clothing are not used. The process gas (Nitrogen) as well as the purged gas (Oxygen) may pose as threats to human too. Other forms of injuries may also be incurred during the post processing of part as more often than not they are needed to complement the built parts.

However, a study by Avram et al. (2011) indicate that environmental considerations could be addressed in manufacturing processes by reducing the amount of hazards and resource consumption. This was based on the fact that not all criteria to be considered towards a simultaneous improvement in manufacturing process often are possible. (Avram et al., 2011).

Many of the studies about effectiveness in LAM have mainly focused on the environmental aspects. However, there are potential economic benefits that can be achieved with the process thus the inclusion of the economic aspect into future studies must be encouraged.

2.2 Impact of CNC machining and LAM on economy

The output of the manufacturing sector contributes a specific share to GDP of nations (see appendix I). The per capita income of nations per year is determined collectively with its activities and that of other sectors (Manyika et al., 2012). New job opportunities are created in manufacturing sectors as the EU and other international countries continue to monitor activities its activity for improved efficiency with less emissions released into the atmosphere. Manufacturing industry have been categorised into five main sectors (see appendix 1) and each has a specific criteria to its success. As some depend on labour or knowledge others consider transportation, proximity to customers a critical issue to their success. The largest (34.0 %) global manufacturing value added segment are automotive, machinery, equipment, chemical and pharmaceuticals require close proximity to markets. This perhaps could be the reason behind a greater adoption of LAM such sectors.

The changes in manufacturing processes towards more ecological friendliness could perhaps be motivated by the many concerns of environmental friendliness which on the other hand have reduced cost of operation within companies or nations. Also the implementation of strict regulations in terms of emission, workers exposures hazards and material usage have supported such trend as companies stiff to eliminate or reduce any extra cost due to emissions. Also companies are equipped with higher competitive advantage in the areas of

(Duflou et al., 2012):

1. Energy saving,
2. Raw material consumption,
3. First to achieve cost efficient product take-back systems,
4. Reduced liability and compliance cost,
5. First to achieve product compliance,
6. Supply chain requirement.

2.2.1 Material and resources efficiencies on economy

In terms of raw material and other resource consumption, LAM techniques gives a higher savings potential as process aids like auxiliary liquids and moulds are excluded with right utilisation of raw material. The use of such process may reduce the costs of production and substantially cut turnover times. The minimal use of process aids in LAM in large extent help companies to save money and time.

A study of the economics of LAM using a method based on build time estimation showed otherwise. The processing time along with the mass of material consumed, are identified as the main variables in several cost models (Baumers et al. 2012; Baumers et al. 2011; Ruffo and Hague 2007). The study according to Barmers el al. (2012) presented a cost structure studies of LAM. The study publicised that the administration, production overheads and labour costs per hour are approximately 41 % of the total indirect machine costs per hour. The conclusion of study indicated that if the payback period for the LAM machine at 364406.80 € was set at 8 years and the machine operates 5000 h/year the machine cost will be about 16.68 €/h. This shows that economy in LAM processes in terms of cost improvements to sustainable development will perhaps be effective at a lower price.

As companies are required to pay for excess emissions produced within the EU emission trading systems, any means of reducing emissions levels is sure a great monetary benefit as less or no liability compliance fees will be paid (Duflou et al., 2012) and any unused rights of emissions be traded to other companies (EC, 2014b). This is particularly important in aerospace, where any additional kilograms of weight could result in additional cost of fuel over the life time of aircrafts (Reeves, 2014). Some studies have shown LAM has the potential to reduce the weight per plane with reduction in carbon dioxide emissions as well as lower energy consumption (EOS, 2014). Judging from this there is no hesitation that printing metallic parts with LAM will improve the economic benefits of aircraft companies.

In order to increase aero engine economic and ecological efficiency, current focus of research in LAM is to enhance thermal effectiveness of built parts. Fabrication with LAM may enable reduction of production cost with improved efficiencies in aviation industries as nearly net shapes are achievable to build parts in small scale (Gasser et al., 2010). This eliminates cost of mould or fixtures needed for conventional processing even if it would be possible to build such shapes. This is why the aviation industry is one of the frontiers to embrace new methods and materials towards efficient and effective productions. This potentially may promote manufacturing trade in terms of LAM as more single parts with reduced weight may be preferred by aircraft industries.

A case study to investigate the manufacturing of aerospace bracket with an additive manufacturing has shown material and economic impact. The study showed that the adoption of material efficient (like powdered) processes can result in about 95 % material utilization and about 50 % of manufacturing cost in aviation sector. (Dehoff et al., 2013)
EOS, Filton branch England and Airbus Group innovations compared in a collaborative study the lifecycle of two critical technologies rapid investment casting and laser additive manufacturing (LAM) of stainless steel bracket for Airbus A380. The study showed that cost and negative environmental impact reduction is achievable with the use of resource efficient processes. Especially in the aviation sector as any kilo savage of material for a long-range aircraft amounts to tons of emission saving during their use phase.

Medical sectors are adopting to LAM processes also as trend of individuality is on the rise in the health sector. The complexity of implants with specific requirements to suit individual needs of patient for instance has increased. The use of compactible materials requires high flexibility in production which conventional processes often may be limited.

The use of LAM potentially may promote economic gains than CNC machining as the latter often require the use of tool inserts and fixture for accuracy and precision. Special designs of mill and powerful enough motors often are required to over possible resistance during material removal. A compromise of accuracy may be present in CNC machining as tools and fixtures cost may be high. This could marginally be absent in LAM as there is no need of such tools in fabricating parts. Building metallic parts directly from powder with laser has the potential of improving resource and economic benefits.

In other study an estimation of cost of individual price of parts in combined manufacturing using LAM process it was revealed that, the application of combined manufacturing reduces production cost. This was shown with a reduced manufacturing and set up time which also influences the production cost. The study showed that further cost reductions could be realised if powerful laser could be stimulated to improve productivity as scanning time remain the main driver of cost in LAM (Rickenbacher et al., 2013).

Advantages of LAM technology outweigh that of CNC machining enormously, however, it is still considered mediocre to CNC machining in certain aspects of production, especially in terms of batch size, imperfections and some instance cost. A study by Huang et al. (2012) claim that the investment cost of LAM are high. Which could be in the range of 5000 to about 50000 euros for higher-end models. It is also shown in the study that additional cost for post processing remain a setback in LAM processes as built parts may have rough and ribbed surface that may require post processing for correction. LAM process is limited by part size or batch size as building times are influenced by their variations. Larger sizes or more batch volume is proven by studies to affect total operating cost in manufacturing processes (Huang, et al., 2012; Fraunhofer ILT 2013).

It is claimed in another study that along the layering of powdered to build functional parts, supports structures are generated depending on the shape of the product. The removal of these structures may increase the total building time and may incur extra cost. The study however revealed that the economic benefit of LAM is released with increase complexity of parts in comparison to other conventional processes. Cost and time for assembly parts are omitted with an increase of choice to combine several parts in one build is possible. Manufacturing units in bulk elaborates resource and energy saving with the process. The study also opine that the traceability of the process for self-labelling gives an additional advantage of reduced cost. About 98 % of unused power in LAM are reusable as revealed in the study (Aliakbari, 2012).

Another study on these methods used to build digital model into physical work piece using high energy photons-light-as a tool have shown other economic benefit of LAM. Figure 12 shows the effect of lot size and degree of complexity of conventional processes against digital photonic production (DPP[9]). (Fraunhofer ILT 2013).

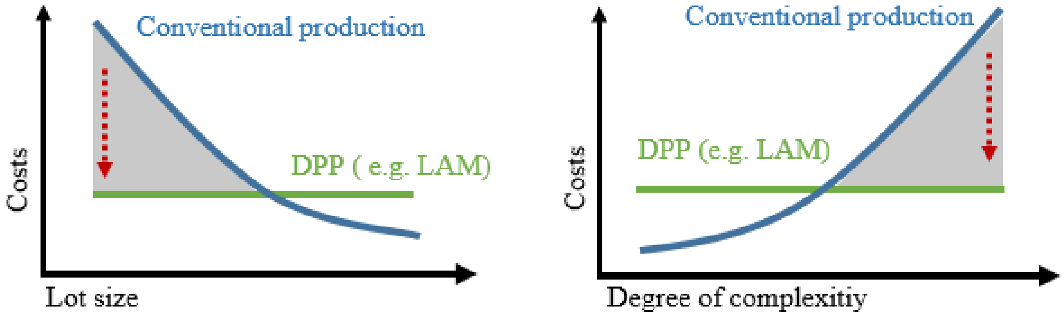


Figure 12. Digital Photonic Production offers benefits both in small series and complex products (redrawn from Fraunhofer ILT 2013).

The Figures 12 indicate that the LAM offer economic benefit in two ways. Firstly, the cost of production is lesser when smaller lot sizes are made whereas, conventional production (e.g. CNC machining) reduces cost of production as lot size increases. Secondly, LAM is preferred to CNC machining when complexity of the product is sufficiently high as in the medical and aviation sectors. Cost of producing highly complex parts with conventional processes have major role in increasing production cost. The elimination of these drawbacks in conventional processing like machining may be possible with LAM (Piili et al., 2013). LAM can replace small series or unique production, for example casting and reduce costs and time to market. When analysing the LAM manufacturing process, it becomes evident that the complexity of the product does not increase the cost. For example a solid feature compared to a netted structure reduces material melted thus can reduce the cost of production in terms of raw material price.

---

[9] According to The Optical Society. (2012) “DPP is used to denote light-assisted manufacturing processes such as High Power ultrashort Lasers, Laser Additive Manufacturing and Laser Micro/Nano Fabrication by Fraunhofer ILT group”.

The efficacy and efficiency of resource in manufacturing processes can be quantifiable based on the consumption rate of material and energy. (Avram et al., 2011). As production costs are related to both direct and indirect energy and material usage, engineers in LAM can debate that, LAM can upraise economic balances in manufacturing. It can be argued also that the cost of waste disposal in CNC machining imposes extra burden to manufacturing companies. Manufacturing companies often incur also extra cost in controlling the emissions as such dust control to avoid or minimise spread out of dust into working area and the environment.

2.2.2 Supply chain efficiency in economy

The supply chain systems in institutions change from time to time as the organizational statues and the desires of customers change (Chopra and Meindl, 2010). Supply chain is a concept that has emerged in companies as an outcome of high costs, short product cycles and the continuous customers' needs. This new approach was adopted to manufacturing businesses to minimise downtimes that could impend manufacturing and delivering schedules as well further negative impacts on market shares of companies. (Chopra and Meindl, 2010). This thought has only been in existence for the past three decades it form integral part of most businesses. In a quest to reduce costs with improved service level whilst satisfying the demands of customers, this system of managing supply chains has become essential. An ecological competitions in firms with maximisation of supply chain surplus are preserved due to its effectiveness and efficiency. Considering the fact that the basics of inter-company competition have shift from other reasons to be based on agility and customer satisfaction in industries like manufacturing. A well-managed configuration of a supply chain is one of the key elements for attractiveness in manufacturing industries.

The value chain in manufacturing companies in recent times are becoming increasingly long and complicated making it more vulnerable than ever before. As a result its supply chain has become occur over long and broadened scope with an increasingly complex relations. These shifts require highly coordinated flows of goods, services, information and money in manufacturing firms within and across national boundaries (Mentzer et al., 2001).

It is shown in a case study that excellent supply chains are characterised with delivering of high quality to consumers' request, efficient converting of inputs into outputs and improvement of asset utilisation e.g. leveraging inventory and working capital. (Perumal, 2006). The managing of spare parts supplies in manufacturing must also focus to reduction of operating cost without altering the demand and wishes of customers to a satisfactory level. However, there may be challenges that might oppose the achievement of these goals. One challenge that has remained persistent over time is the unpredictability of demand. Especially delivery delays for new product launches on which data of parts failure rates may be not be readily available to operations. A higher inventory is usually kept as an option to overcome this challenge (Lindemann, et al., 2013).

Additional burden as a result of parts specification change or outmoded customers' need may increase unused parts that might be recycled or end up at landfills. Another challenge is the need to support the old clients as well as new ones. This responsibility can in large extent require management to keep large unit stocking in order to meet the pre-and after sale request or changes. As a result management may have larger workforce, parts and tools to overseer simultaneously. Having a potentially all-inclusive process flow that can ease some of these burdensome in companies is a sure yardstick welcoming idea. All of these characteristics of a good supply chain and mitigation of such problems that might hinder smooth operations in manufacturing firms may be achievable with LAM.

The analyses of sustainable developments are tied to manufacturing and transportation operation (Nyman and Sarlin, 2013). The elimination of additional process aids like cutting liquids with LAM may reduce partly the financial burden on manufacturing companies. A greater control of delivery time could also be offered as decentralization of manufacturing companies are potentially supported by LAM. Having local production stations possibly may close the gap between customers and manufacturers that might eliminate present inefficiencies in supply chain dynamics within manufacturing industries. This might result in a smaller workforce to be manage as the usual inventory in manufacturing will be minimised or dissolved (Lindemann, et al., 2013; Nyrhilä, 2014).

A case study has shown that the value proposing of AM processes like LAM, can be based on a three-bottom axis of speed, quality and cost in comparison to conventional processes (Eaton, 2014). In cost considerations, time to manufacture parts is essential. Any loss of time as result of less quality work might rise production cost. This in essence may increase time and cost as correcting defects will require additional time and impose excess cost. In determining the value prepositioning, the study considered:

1. Application and material cost,
2. Part quality,
3. Lead time,
4. Production volume and quality and
5. Tooling and part cost.

Figures 13 illustrates impact of additive manufacturing processes on product life cycle, lead-time and cost of production.

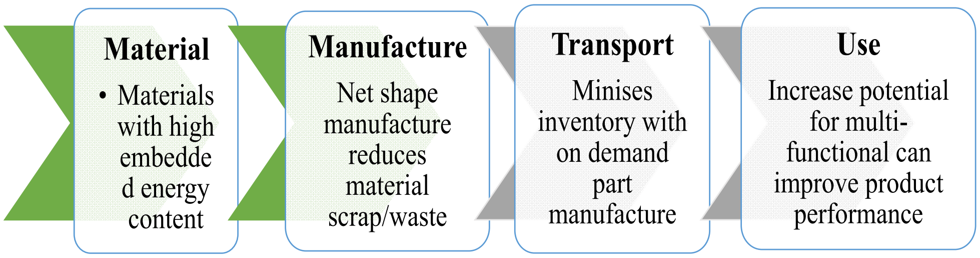


Figure 13. Potential benefit of LAM on product life cycle (redrawn from U.S. Department of Energy, 2014).

Figures 13 indicates that effectiveness and agility of LAM may offer manufacturing firms an opportunity to on-demand production. This predict a transformed supply chains with fast delivery time for less expensive products with as fewer resources will be consumed.

3 LIFE CYCLE ASSESSMENT

The collection and evaluation of the environmental aspects and impacts that relate with a product, service or production systems can be termed as Life cycle assessment (LCA) (Guinee, 2002). LCA has been developed to produce the most scientific information about environmental impacts to a decision making process. According to EPA. (2015) the main focus of an LCA are:

1. “Compiling an inventory of relevant energy and material inputs and environmental releases,
2. Evaluating the potential environmental impacts associated with identified inputs and releases,
3. Interpreting the results to help you make a more informed decision”.

LCA enable accurate quantification of environmental impact of the global system assessment based on different standard unlike methods other environmental impact assessment methods such as carbon Assessment and Design for Environment (Bourhis et al., 2013). The normalization of the former is ensured by SETAC and UNEP under ISO 14044 2006 and ISO 14040 2006 standards.

According to Guinee. (2002) LCA methodology includes four main stages as:

1 “Goal and scope definition,
2 Inventory analysis (LCI),
3 Impact assessment (LCIA),
4 Interpretation of results”.

Figure 14 is presents LCA frame based on ISO 14040.

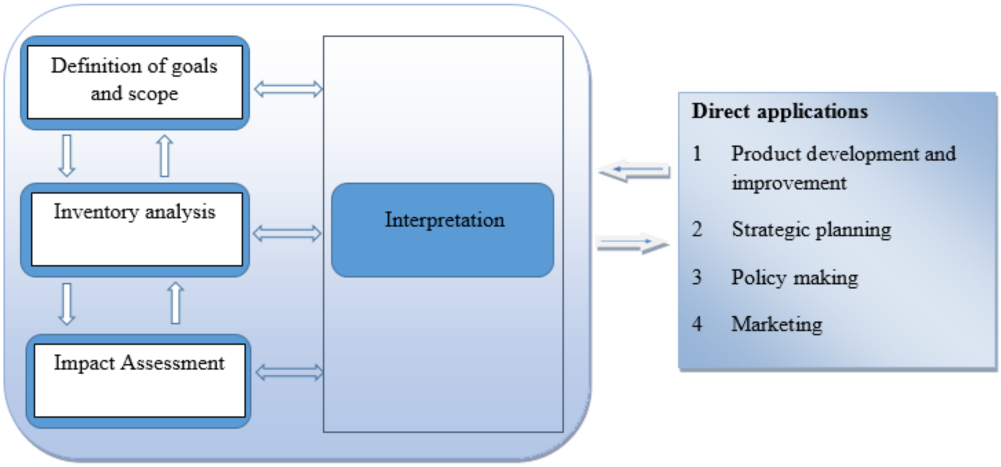


Figure 14. ISO standard (Guinee, 2002).

During the goal and scope definition LCA, primary section of options are made to define the scope of the study. The inventory analysis may include resource used, energy consumed, emissions, and/or final products. The impact assessment phase is done to scrutinise all information from the inventorying. All identified impact to the environments are documented also at this phase of the LCA. Quantitative measure are assigned also to influencing environmental in this phase. All identified categories and effects are quantified in terms of a common unit for specific category. The last phase of the procedure involves analysing and evaluating of results. The degree to which each of the identified elements affect the environment is itemised according to impact category (hot spot). Any suggestions and conclusions are also given in this phase.

3.1 CO$_2$PE! UPLCI! Initiative

Cooperative effort on process emissions in manufacturing, CO$_2$PE! Initiative, is a collective effort of manufacturing companies, students and other stakeholders. According to Kellens et al. (2012a), the goal organisation “has as an objective to coordinate international efforts aiming to document and analyse the environmental impacts of a wide range of current and emerging manufacturing processes, and to provide guidelines to reduce these impacts”.

Figure 15 represents the proposed LCA-like model to ensure correct documentation and interpretation life cycle assessment.

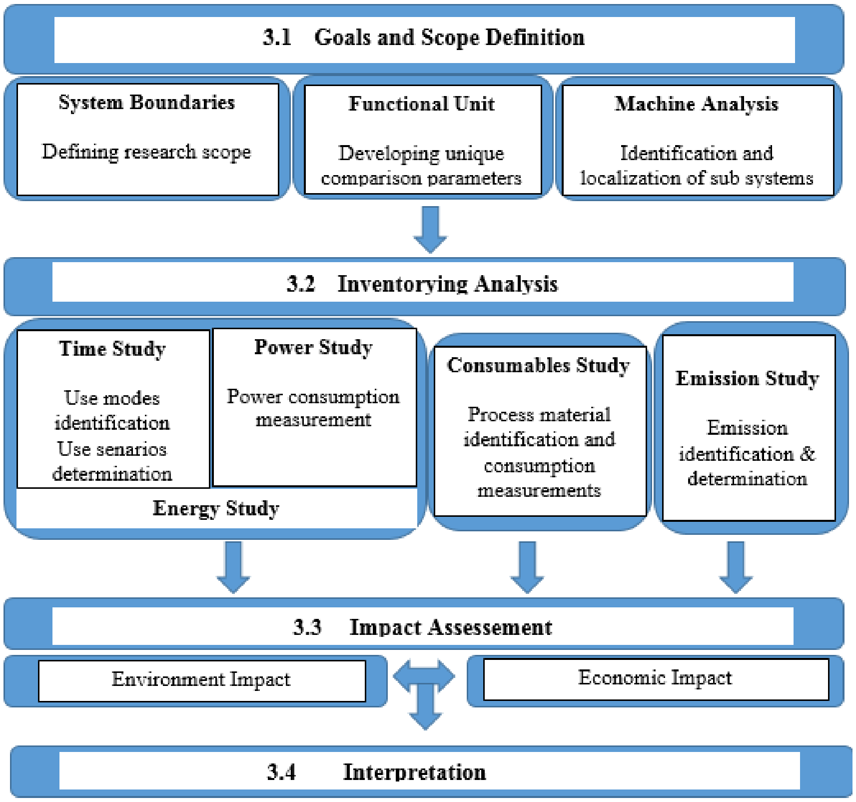


Figure 15. Overview of CO_2PE! Framework (Redrawn from Kellens et al., 2010a).

Figure 16 illustrates the framework of CO_2PE! UPLCI! Initiative with dashed line.

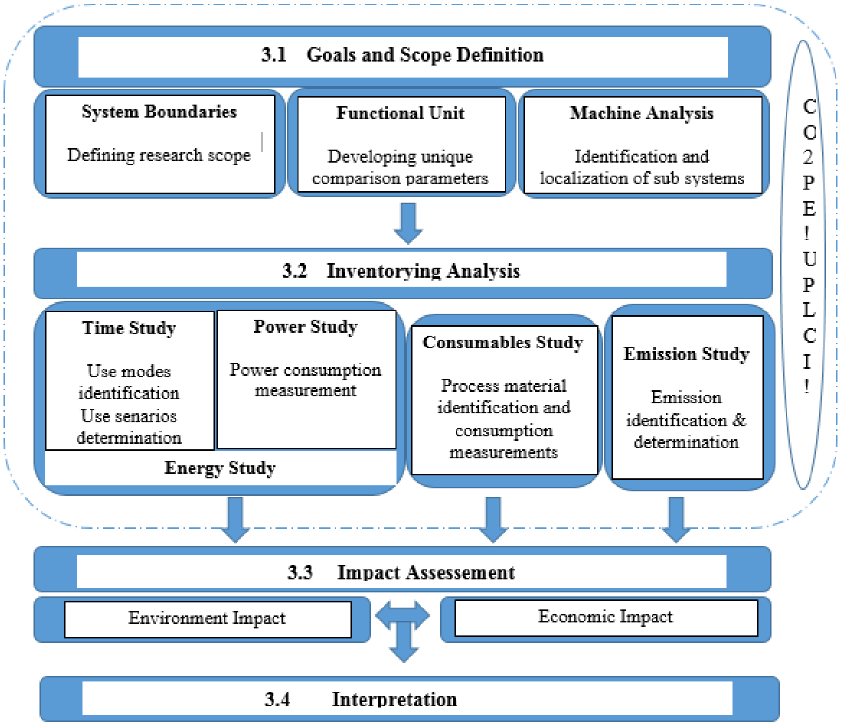


Figure 16. Overview of CO_2PE! UPLCI! main steps (Kellens et al., 2010a and 2012).

As shown in Figure 16 the impact assessment and interpretation are outside the scope of the proposed model thus only two steps of the CO_2PE! Initiative are included. Appendix II exhibits detailed frame work of this systematic methodology.

3.1.1 Goal and scope definition

The first step of the proposed LCA -like model must be defined clearly with consistency with intended unit process. The goal must result in an up-to-date data sets of LCI in the studied process. The system boundary and functional units are important parts of the scope definition according to Kellens et al. (2010a). A consideration of the machine tool architecture as well as all sub-processes and identification of their location within the machine tool is necessary.

System boundaries

The system boundaries define the unit process to be studied and which sub process of the unit process to be investigated individually. This may include all value chain of the process such as material processing, maintenance, production, and even disposal of the machine tool or just on the operating phase of a section or the whole unit process.

Functional unit

After defining the boundaries, the functional units must be defined both quantitatively and qualitatively and must be measurable (Kellens et al. 2010a). The functional unit serve as basis to which all other inputs and output materials relate. Other datasets define the various functional units based on material, process and geometry variations. The parameters or conditions of the input that govern LCI characteristics as well as the generated features in the output product are listed based on available process experience and literature. Energy, materials and process aids (e.g. lubricants or gases) are consumed, and emissions are emitted in the course of production. The influence of all identified environmental impact differ from each other. As some may have severe impact with others having only a minor impact to the environment. All identified impact categories may be vital regardless their degree of impact.

Parameter selection and machine analysis

A primary selection of parameter and investigation of the machine system is necessary prior to the analysis. These parameters may be ranked in an approximate manner based on their influence to created environmental impact from the largest to least effect.
During the machine tool analysing, the machine setups is considered in details as well as the energy and resource consuming units and their possible subsystems. (Kellens et al., 2012a).

3.1.2 Inventorying analysis

The inventory analysis comprises of all time, power, consumables and emissions. The inventorying can be based on measured, calculated, estimated values or a mixture of the three. Data collection may be based on either 1) screening approach to include power, materials and related emission or 2) on an in-depth approach where power, material, process emission as well as time studies are performed. The former is often faster than the latter due to the period used.as the latter can take up to several days. The screening approach results often result in an approximated inventorying (Kellens et al., 2012a).

The period of study, differentiate these two approaches though the in-depth approach may also include on a screening or not to provide a more accurate and complete inventory data that can be used for further improvement studies in manufacturing processes (Kellens et al., 2012a).

Energy study

The investigating of the energy can be done by studying the power and production time. These two aspects are necessary as they reflect the energy consumptions in any process.

Time study

The study time is necessary during the inventorying if the in-depth approach is used for data collection. This is done to identify the different modes of productions, machine tools and their shares in stipulated period. The modes of production may include the preheating of machine tools, exposure of beam, recoating of powder, material removal and cooling down of the system. The time study include the machine tool start-up and all intermediate phases until switching off machine systems.

Power study

The power study follows with measured power after the various productions modes are identified in the time study. Measuring electrical power for all identified modes is needed in order to determine energy consumptions. All machine tool as well as all related active energy consuming units (ECU's) for each of the selected levels is done. Table 2 shows some modes of the production in LAM according to Kellens et al. (2012b).

Table 2. Production modes overview. (Kellens et al., 2012b).

Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Production mode	Start-up mode	Full-power mode	Partial-power mode	Standby mode	Shutdown mode	OFF mode	Other mode(s)

As Table 2 shows the different modes identified in the time study are further divided to include sub modes. This will assist in identifying energy and other resource consuming unit.

Consumable study

Data inventory for the LCI analysis is done to also take into account all flows of material in the identified modes during the production process. The consumables include process aids such as lubricants, compressed air, gases (nitrogen, N_2 and oxygen, O_2) and even process equipment needed for production. The created amount of waste is process depending thus within the UPLCI, it is considered as part of consumable though the raw-material flow is not regarded as relevant for unit process study (Kellens et al. 2010a).

Emission study

A study of all emission is performed for each of the production modes to record all related waste emitted during production (Kellens et al. 2012a). These may include generated reusable, unusable and recyclable wastes as well as other intangible wastes like noise and heat.

3.1.3 Impact assessment

This stage includes studies to determine the pattern of energy and resource usage of the process based on data from the previous stages. During this stage of an LCA, all possible economic and environmental impacts are analysed. Kellen et al. (2010a) in their study have used eco-indicator 99 [10](H A) to calculate impacts of SLM and SLS based on ecoinvent[11] database. It is necessary to identify the sample batch for the LCA in order to identify the most contributing factor to the environmental impacts (Kellens et al. 2010a).

3.1.4 Interpretation

At this stage of the methodology, an interpretation of the results is done and reported in most informative way. An evaluation of all potential needs and opportunities to reduce any identified impact of products or processes on the environment are systematically analysed. This stage focuses on finding ways to deal with impact categories as will be identified in the impact assessment. For instance if energy is found to be the more severe impact, then a selective switching on and off could be utilised for the different modes if it will not disturb production. Time reduction could also be a tactic of improving energy consumption as it is dependent on how long the machine system run. Therefore, building time can be minimised by altering other variants to lessen the energy consumption. (Kellens et al. 2010a)

3.2 Levels studied in this thesis

The process phases and consumables of each of the manufacturing processes may be dissimilar and large. The difference lie on the different energy and material demands of separate processes like CNC machining and LAM at the various phases. As such it is necessary to identify the various stages of studied manufacturing process for easy comprehension and handling. The individual processing levels of the manufacturing process could be considered with respect to energy consumption (Wang et al., 2013) or be restricted as suggested by Duflou et al. (2012). According to Duflou et al. (2012) five levels of energy saving strategies can be identified in manufacturing system organisations:

1. “Device/ unit process,
2. Line/cell/multi-machine system,
3. Facility,
4. Multi-factory system,
5. Enterprise/global supply chain”.

---

[10] According to Earthshift Inc. (2014) eco-indicator 99 is method used for LCA that is based on damaged oriented approach.

[11] According to Ecoinvent Association (2015) ecoinvent “is an association that supply consistent and transparent life cycle inventory (LCI) data”.

This explains the fact that efficiency of the systems may be measured from various stages and not just the production stage as in the case of this thesis. Whichever level is chosen, the highlighting of system boundary and selected parameters of the experiment is essential in order to ensure the right selection of unit processes and steps to be studied.

EXPERINMENTAL PART

4 AIM OF EXPERINMENTAL PART

The aim of the experimental part of this thesis was to 1) carry out a life cycle inventory data collection of CNC machining and LAM and 2) investigate the effect of process variations on specific energy consumptions (SEC) in LAM process The purpose of the practical test was to identify and document the different machine units and phases of each of the manufacturing processes and to ascertain their potential impact to efficiency. The inventorying data of power, raw material, possible emissions and time taken for producing test pieces in each process were studied by measuring, calculating or estimating. Screening (without time study) and detailed approaches (including time study) were used to collect all needed data on production phase.

5 EXPERINMENTAL PROCEDURE

5.1 Limitation of research topic

System boundary

Figure 17 represents the system boundaries in experimental part of this thesis.

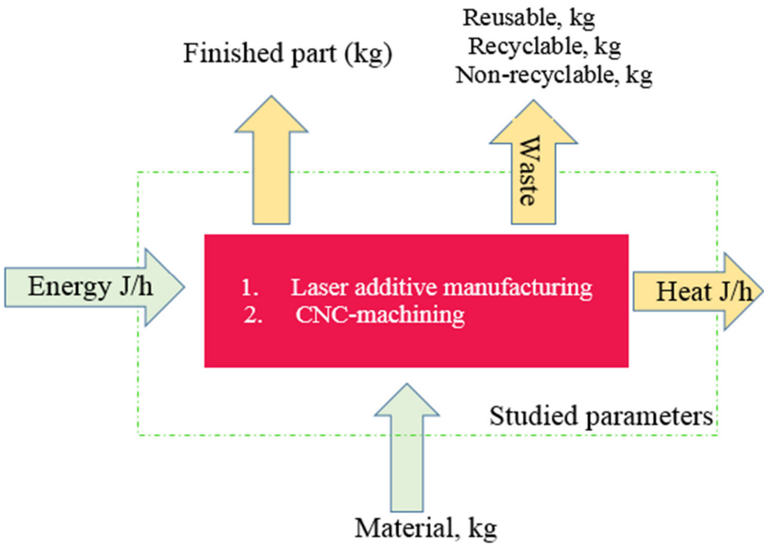


Figure 17. System boundaries used for experimental study of this thesis.

As it can be observed from Figure 17, input and output data are indicated with a green and yellow arrows respectively while the studied manufacturing processes are shown in the red shaded area. The system boundary of this thesis was limited to only the primary production and does not include any post processes like polishing or heat treatment. Data taken included power, time values, inputs and outputs materials in kilograms as well as auxiliary materials like cutting liquids used. Weight of input material, reusable waste, recyclable or non-recyclable were measure either prior or after production.

The CNC machining production inventorying was based on the screening approach as defined earlier. Six different machining processes were used in this thesis to make one part. These processes included:

1. Outside turning (M1),
2. Drilling, M2,

3. Inside turning (rough cut, M3 and finishing, M4),
4. Milling, M5 and
5. Cut-off, M6.

The LAM data collection was carried out based on the in-depth approach. The modes identified in the LAM production were:

1. Start up (initial stand by)
2. Heating,
3. Idling to create inert atmosphere (standby),
4. Process (e.g. exposure, recoating),
5. Cleaning and removing (stand by) and
6. Sawing of parts

Selected levels

The CNC machining comprised of levels as shown in Figure 18.

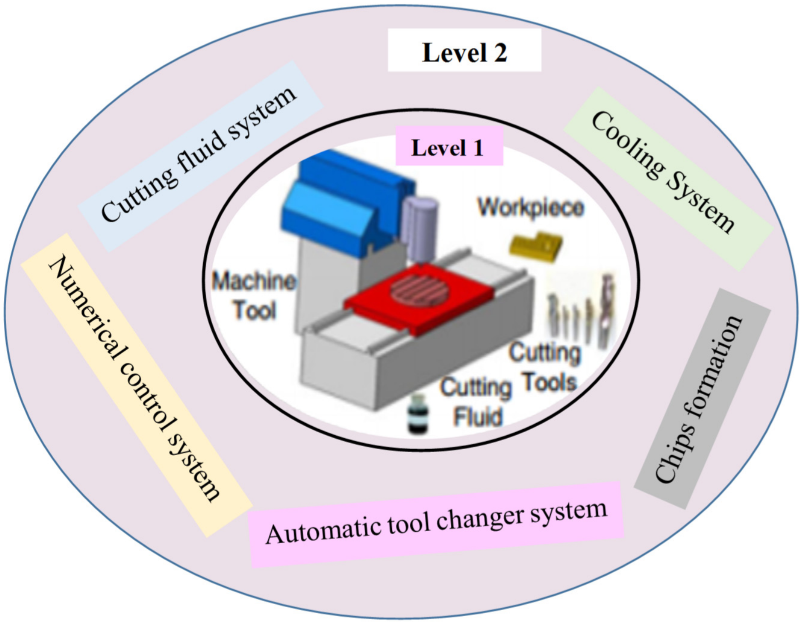


Figure 18. Stages of CNC machining tools studied in this thesis (modelled from Avram et al., 2011).

As it can be seen from Figure 18, the intended data inventorying was focused on the energy consuming units indicated on both levels of the CNC machining. The power values of automatic tool changer, spindle motors, rotating tools and cutting fluid motor were examined for energy analysis whereas the consumable and emissions studies were limited to input and output raw materials and cutting fluid.

The LAM production had dissimilar energy and resource consuming unit than in the CNC machining system. The levels to be studied within the LAM are as shown in Figure 19.

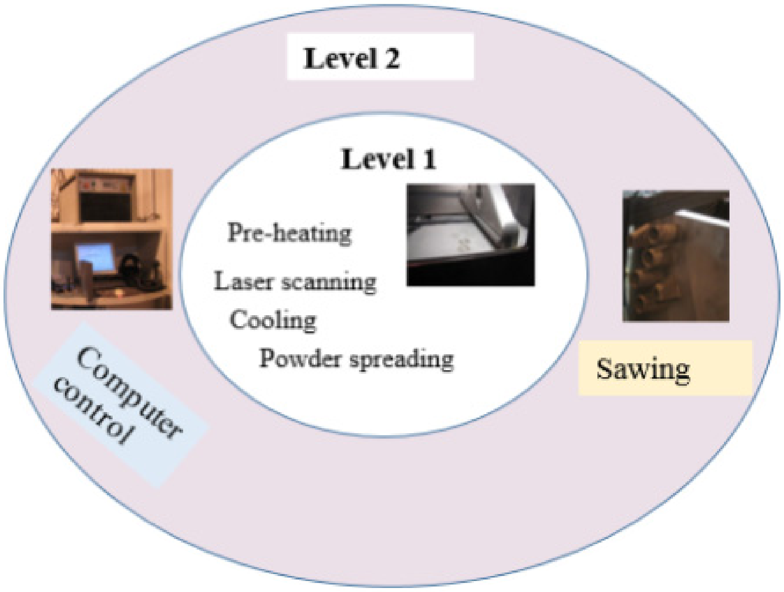


Figure 19. Stages of LAM machine tools studied in this thesis.

Material and energy flows into the various levels shown in Figure 19 were used as determinates energy consumption in LAM. The machine tools studied in the first level included heating units, laser and its cooling unit, servo, scanners, machine tool lighting, etc. The second level elements were studied as they complemented the finishing of production.

5.2 Experimental set-up

5.2.1 Material used in CNC machining

Material used for the CNC machining test pieces was AISI 316L (EN 1.4404) stainless steel bar. This steel has similar chemical composition as ASTM F138 ("Standard Specification for Wrought 18Cr-14Ni-2.5Mo Stainless steel Bar (ASM International, 2014). This steel type have density of 8000 kg/m^3 The Table 3 outlines the composition elements and weight percentages of 316L stainless steel used in this thesis.

Table 3. Alloying composition of stainless steel 316L bar.

Alloying element	Chromium	Molybdenum	Carbon	Nickel
Content of component, [%]	16.5-18.5	2 .25-2.5	0.03 (maximum)	10.0-13.0

As Table 3 shows this type of steel has high amount of molybdenum which increases the overall corrosion resistant properties. These grades keep an excellent toughness property cryogenic temperatures due to their austenitic structure. They are used in applications that require high strength, corrosion resistance sterilisability, and weldability. They are applicable in industries such as medicine, food, oil and gas. For instance they are suitable for clamping elements or heat exchangers in aviation industry.

In commercial productions, modified grades with lower carbon content are often used to reduce hardness of a material. This is often done in practical situations in order to lessen difficult of cutting that may cause rapid tool wear. The bar used in this thesis did not include such modifications however for corresponding material properties in both CNC machining and LAM materials.

5.2.2 Material used in LAM

The stainless steel used for the LAM parts was an optimised powder (EOS StainlessSteel 316L) for metallic LAM. This type of powder are possible to build layer thicknesses of 20 µm with minimum wall thickness of 400 µm (0.4 mm) under standard processing parameters. The building orientation for the parts determine the final ultimate tensile strength of this type of stainless steel ranging between 630 + 20 and595 ± 20 MPa. Parts made with this powder maintain their properties in vast temperature ranges and can effectively also be used at cryogenic temperatures. Table 4 illustrates chemical composition of 316L stainless steel powder.

Table 4. Alloying composition of EOS StainlessSteel 316L powder (3trpd, 2014).

Alloying elements	**Content of component, [%]**	**Alloying elements**	**Content of component, [%]**
Chromium	17.5 -18	Phosphorus	0.03 (maximum)
Molybdenum	2 .25 - 2.5	Cupper	0.50
Carbon	0.03 (maximum)	Manganese	2.00
Nickel	12.5 -13.0	Silicon	0.750 (maximum)
Sulphur	0.01(maximum)	Nitrogen	0.10

316L stainless steel powder can offer economic gains in production compared to competitive materials in medical application while strength per weight and corrosion resistance are minimal. These type of steels are particularly suited for medical application like surgical instruments and implants as well as fields that require high levels of corrosion resistance and ductility.

These type of power are also suitable for making useful models, and customised products or final goods, like watches and jewellery. Due to an added freedom of shaping and structural integrity the material afford parts such as watch cases are possible to make cost-efficiently and easily whiles resources are saved due to defined hollow spaces. Post-processing, like heat treatment and polishing, can be utilised to improve mechanical and surfaces quality of parts made from this type of powders. (3trpd, 2014; ASM International, 2014). However, no post process was performed within the boundary of this thesis.

5.2.3 Geometry of work pieces

Three test samples were designed as sample A, B and C for the experiments study. Samples A and C were designed to be manufactured with LAM whereas sample B was planned to be produced with both CNC machining and LAM. Dimensions of the work pieces were 20 x 40 x 35 mm and an internal hole with a diameter of 24 mm. The models A and C were used as one of the criteria to affirm complexity and flexibility in LAM while sample B offered a base to compare resource and energy consumption for both processes. The Figure 20 shows the designed geometries used for this thesis.

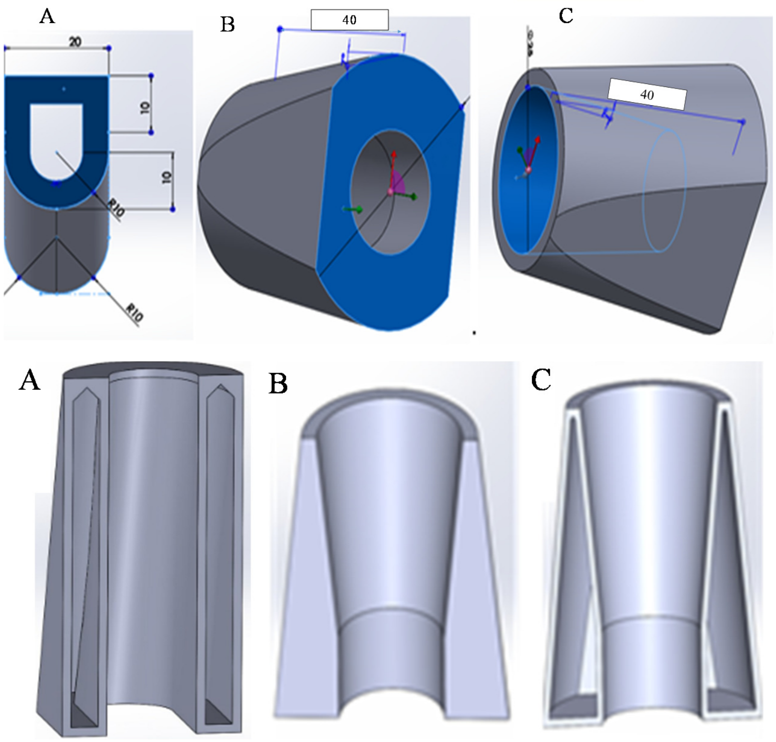


Figure 20. Solid and cross sectional views of samples A, B and C used in this study.

As it is shown in Figure 20, the models were designed to have solid and hollow walls. Parts of the samples were planned with LAM only as CNC machining could not be used to make them. It was not for instance feasible to produce models A with CNC machining the process could make the sharp edges the internal hollow wall in sample C. The internal geometry of sample A was designed to have sharp corners, hollow wall and a chamfered outside geometry. The internal shape of samples B and C were circular and symmetric. However, sample B was designed with solid wall whiles sample C had hollow wall.

Samples A and C were also designed with a 2 mm holes a passage to remove excess powder after building the process Figure 21 exhibits.

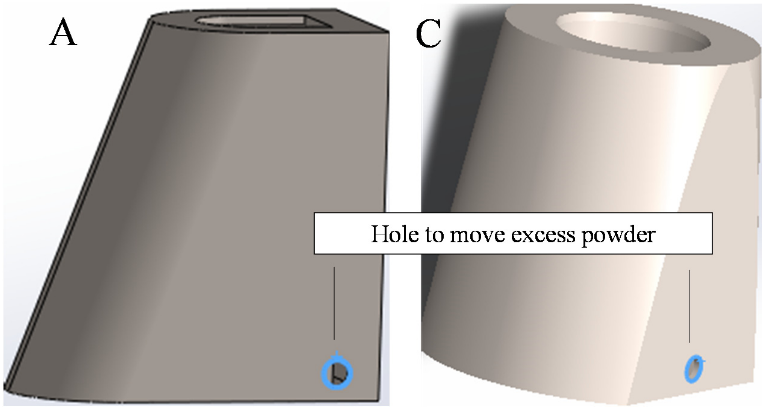


Figure 21. Illustration of holes for removal of excess powder.

As Figure 21 shows all surplus power that remained in samples were taken into account with the incorporation of the holes.

The height of samples were limited to 40 mm in order to minimise the built-up time of LAM. Using sample height higher than this value often increase the process time. As energy consumptions is related by time it was necessary to plan a production with minimised production duration.

A compromise of internal geometry of parts was also made in designing stage on sample B to carter for CNC machining underperformances. The sample were designed initially with curved edges, chamfered outer contour in asymmetric form. This was modified to have rounded edges after careful considerations as shown with sample B in Figure.

5.3 Equipment used

5.3.1 CNC machining equipment

The machining centre used for the CNC machining was PUMA 2500Y multi axis lathe with a Fanuc 18i –TB (turning and boring) controlling system. Figure 22 shows the CNC machine centre that was used in this thesis.

Figure 22. Illustration of the CNC-multi axis lathe machine used in thesis.

The machining centre had a working volume of 2918 x 1775 x 2060 mm (height x width x length) and a weight of 4800 kg. The specifications of PUMA 2500Y is attached as appendix III.

5.3.2 LAM equipment

A modified research machine representing EOS EOSINT M-series was used to produce the LAM test in this thesis. This machine has a laser source working with laser power of 200 W and wavelength of 1070 nm. The focal length used for the parts was 400 mm and the system was equipped with IPG YLS-200-SM-CW fiber laser and a Scanlab hurrySCAN 20 scanner.

Figure 23 illustrates the machine used in the experiments for LAM.

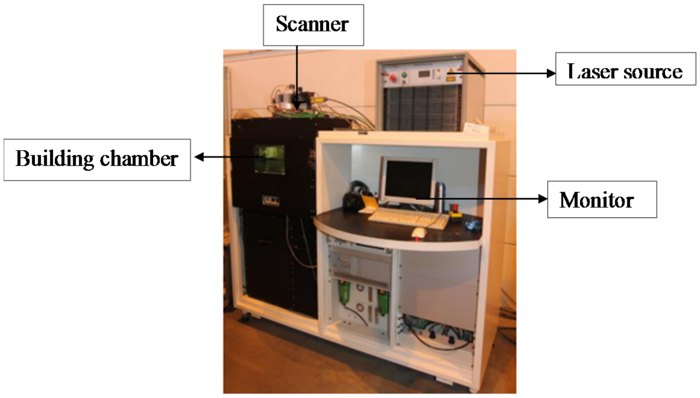
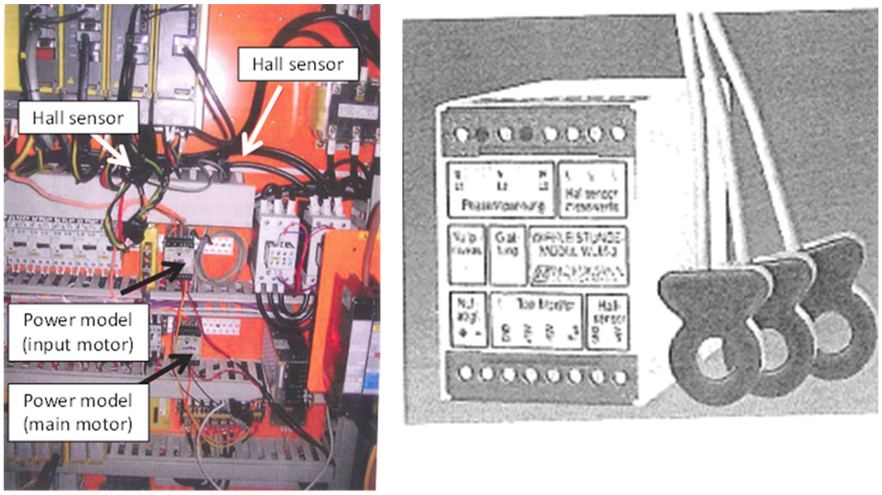


Figure 23. Representation experimental set up of LAM system.

5.3.3 Power measuring equipment for CNC machining

The device used to record current voltage for power analysis in CNC machining is as shown in Figure 24.



a. Arrangement b. Sensors

Figure 24. Representation power measuring setup in the CNC machining (Pirnes, 2006).

This device had radar that was attached to machining centre as Figure 24 demonstrates. The sensor recorded voltage within -10V and +10 V. The cables were connected to the lathe machine to measure current. Detail information of power measuring in the system was not available as the monitoring device was pre-assembled before the experiment. Obtaining data on the power measurement device used in CNC machining was not readily accessible due to lack of information as the personnel that had installed device was vacant. Thus any future studies done in this area must ensure new power measuring device connection in order avoid any lack of information.

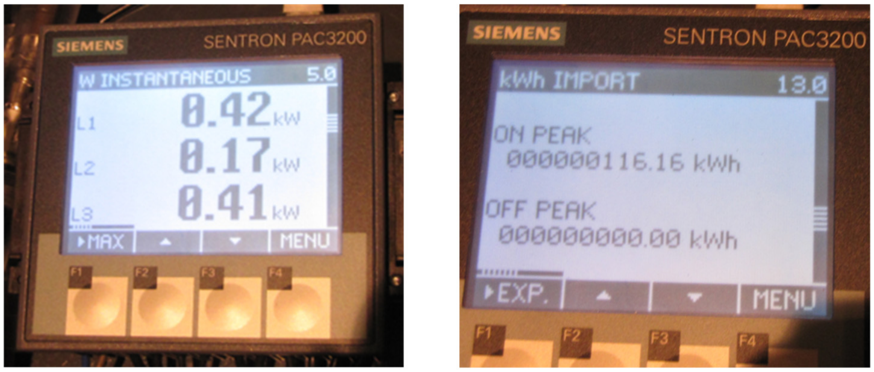
5.3.4 Power monitoring equipment for LAM

The measuring device used in LAM to record power and energy consumption values was Siemens Sentron PAC 3200. A LabView program was also used to monitor energy profile as the building process was made. The power measuring device offered a precise and reliable power values from all individual electrical consuming unit. It offered possibility to assess the state of systems and quality of power by providing important measured power values (Siemens AG, 2007).

Some features of the device are:

1. Visualisation of power values,
2. Central evaluation and documentation of all measured values,
3. Improvement of system with a continuous observing of power values,
4. Identification of savings potential through the transparency of power flows.

Figure 25 shows the power measuring device used to measure power and energy consumption in LAM.



Power reading Energy reading

Figure 25. Representation of power measuring device used in LAM.

6 DESCRIPTION OF EXPERIMENTS

The LCI methodology defined in the CO2PE! UPLCI! Initiative was somewhat followed to collect data in this thesis. The two methods described earlier for data collection were utilised for inventorying in this thesis. CNC machining inventorying was done according to the screening approach while the in-depth approach was used to collect data in LAM. The data collected in CNC machining included power, input-output materials (including wastes of metallic and cutting liquid) whereas data recorded in LAM consisted of time, power, input-output material (including metallic waste).

6.1 CNC machining processes

The machining experiment was carried out to collect and analyse the energy, power, input raw material and output material in the CNC machining. Four different pieces were manufactured on the CNC lathe machine. Numerical control code (G code) were created to specify the tooling paths for each of process. Figure 26 shows section of the NC coding during the machining process.

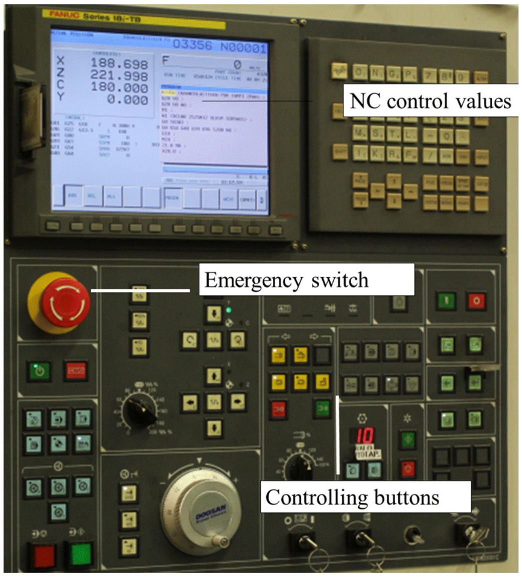


Figure 26. Representation of section of NC code and controlling keys in CNC machining.

As it can be seen from Figure 26, the CNC machining controlling unit included switches and buttons for controlling the cutting processes. All necessary changes required in programed G-code for example the cutting speed were changeable from this panel.

Manufacturing parameters were changed after manufacturing the first test piece to reduce or prevent risk of rapid tool wearing. The reference cut made according to the modified code was analysed in this thesis as the first reference was done prior to experimental data collection. However, test piece one represented in this thesis was made with the first version of G-codes.

A50 x 40 cm (diameter x height) round bar was used as input material. However, for each of the test pieces a 50 x 45 mm was used as starting stock as the final part length was 40 cm. Figure 27 shows the stock material used in this thesis.

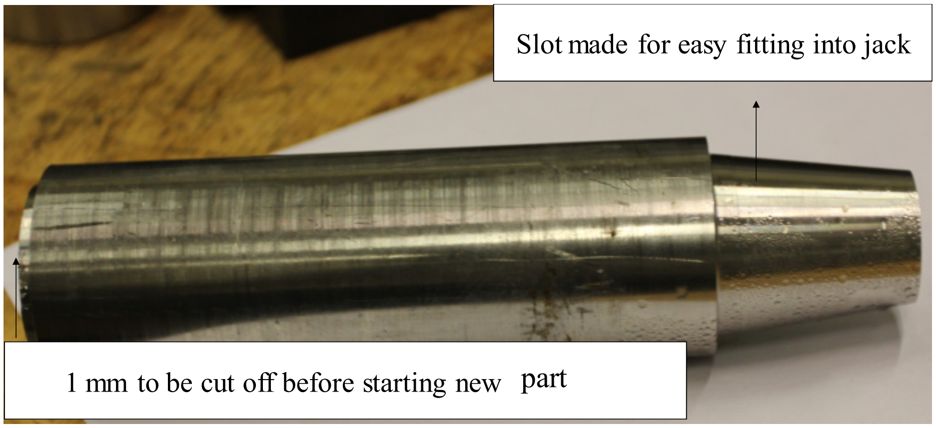


Figure 27. Representation of CNC machining start up bar.

As seen from Figure 27, the end of the stock material was machined to a specified shape to suit chunk holder groove. The dimension of starting bar used in this thesis was more (5 mm) than a size that would have been used in commercial production. Practically a 45 mm diameter bar would have as pointed by lab personnel.

A reference (air) cut run to test the machining code was performed on the CNC machining centre. The steel bar was positioned to the holder during this stage without tool and part touching each other. There was no cutting fluid delivered during this phase.

This phase was obligatory as a trial of machining toolpaths and to also warm up machining centre as well as activation of sub systems like the lubrication unit.
There were six machining operations performed with five different tools during the fabrication. Only five tools were used in this experiment even though the lathe machine had 8 tool holding capacity. There were five tool changes during each machining in the sequence of outside turning, drilling, inside turning and inside finishing, milling and cut-off. Figure 28 illustrate the CNC machining experimental arrangement.

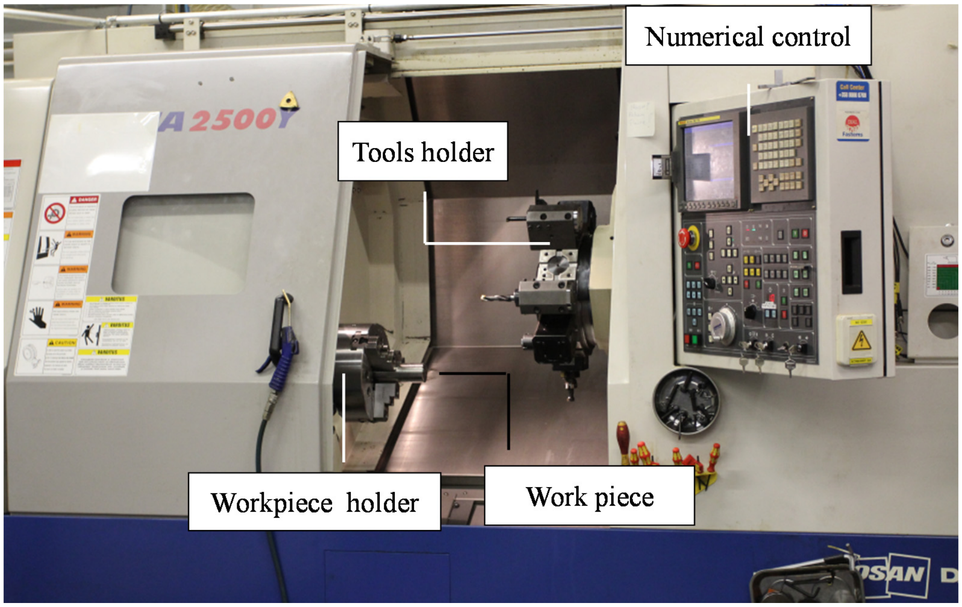


Figure 28. Representation of CNC machining set-up.

A turning, drilling, milling and cut-off operations were performed sequentially on the PUMA 2500Y CNC-lathe machining centre. The detailed description of each of the machining periods are described later in this section.

Temperature control and lubrication of tool tip of the system was achieved with reliable lube system for all carriages and spindle during the actual cutting (when tool touch work piece) to help prevent wear of sideway surfaces and smooth movement. A 150 l lubricant was used in a ratio 95 % to 5 % of water and oil (CIMStar 501-02 oil). The lubrication was activated during the actual cutting runs. The drilling operation was characterised with continuous supply of cooling lubricant through the internal channels of drill tool.

An outside turning with an end face mill was performed for the desired outside diameter. An initial 1 mm was turned from test piece to have a uniform bar surface prior to machining a new test piece. Figure 29 illustrates the actual part and cut off length.

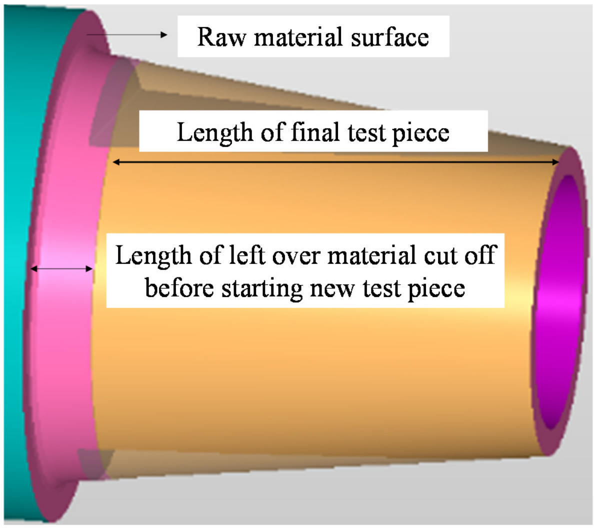


Figure 29. Representation of final part and excess length to be cut off.

As it can be noticed from Figure 29, the pink coloured area needed to be flattened before starting to machine a new part.

The first of the sequential machining operations, outside turning, was done with test piece rotating while tool was held static. Figure 30 shows the arrangement of the turning tool and machining process during the experiments.

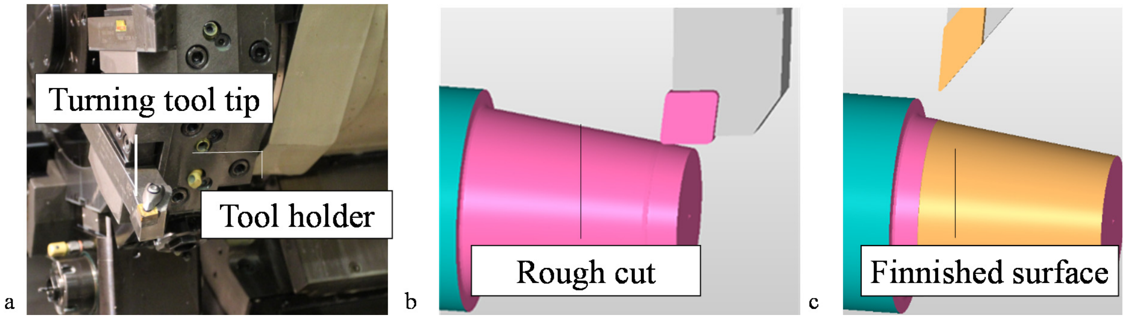


Figure 30. Illustration of outside turning (a) toolset-up (b) shaping of outside geometry (c) finishing of outside surface.

As it can be seen from Figure 30, the outside turning of test pieces included a rough and finishing cutting. These process were aided by continuous supply of cutting liquid.

A drilling operation with 16 hard metal drill tool was used to drill the internal geometry sequel to tool change. Figure 31 shows the arrangement of the drilling tool.

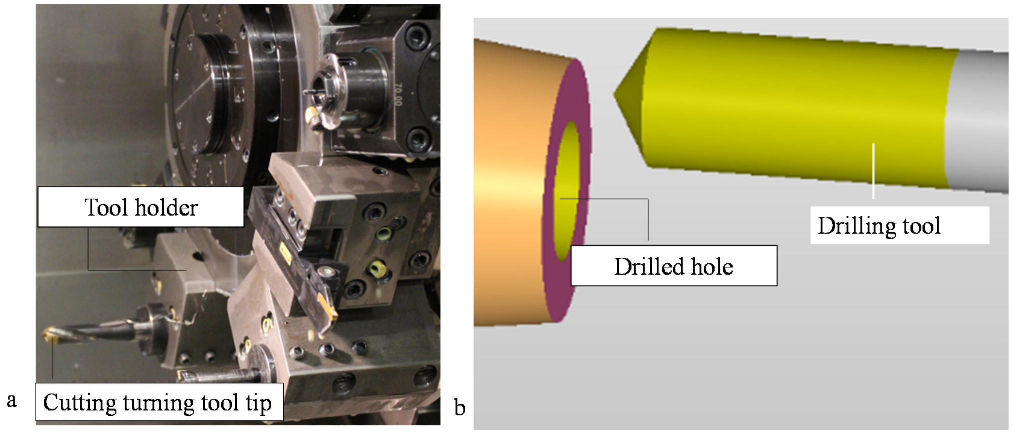


Figure 31. Illustration of (a) drill toolset-up (a) drilling process.

During this phase the work pieces rotated as the tool remained stationary. Majority of material removed during the CNC machining test was in this phase as about 18 mm hole was crated.

The third machining process, inside turning, was performed after the drilling. Drilling tool was replaced by turning tool automatically as it can be seen Figure 32. The rough and finish cuts were made with one tool but different cutting parameters.

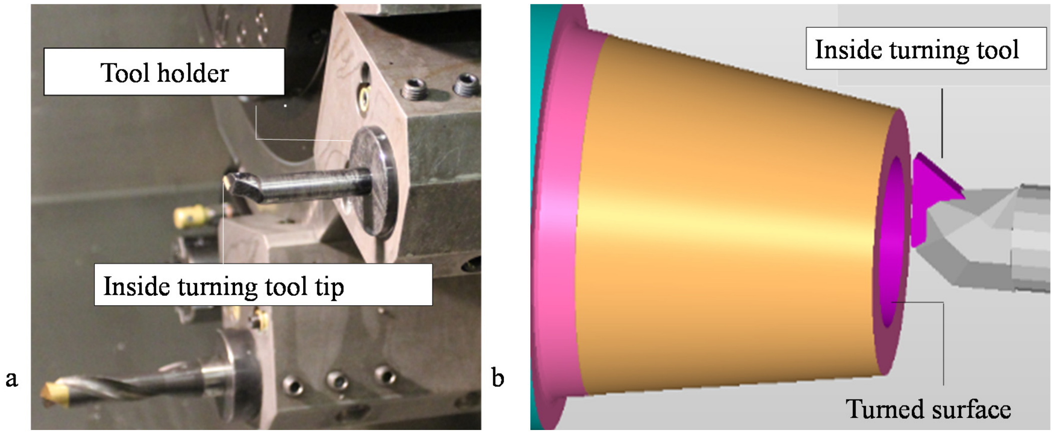


Figure 32. Illustration of inside turning (a) toolset-up (b) rough and finish cut.

The milling process was performed after the turning of the internal hole. The turning tool was changed to milling tool as shown in Figure 33.

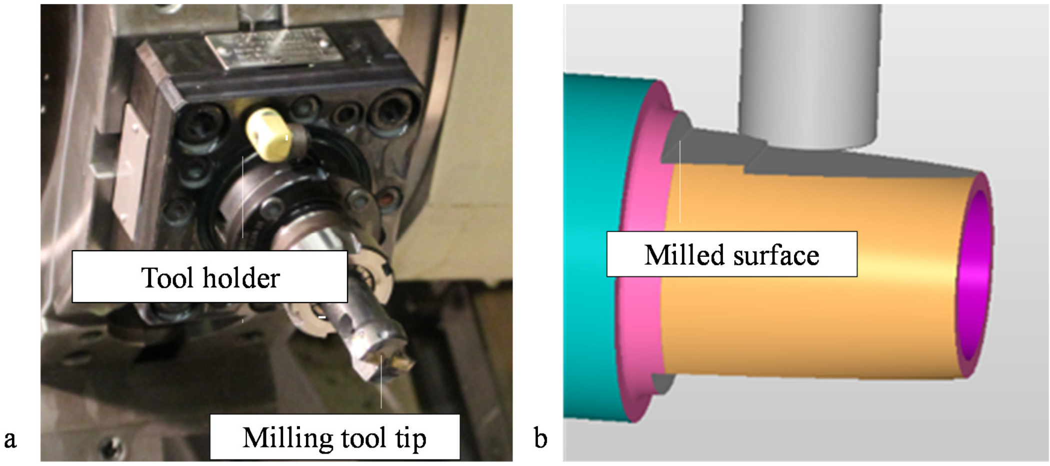


Figure 33. Illustration of a) milling toolset-up b) milling process.

Majority of manufacturing time were used during the milling process. The work pieces were stationary while the tool moved in this phase. However tool was held static for few seconds in order to mill other surface (in rotation of 180 °) of parts.

The last of the sequential processes separated the machined work piece from the chunk with turning tool. Tool was change from mill tool to turning tool as shown in Figure 34.

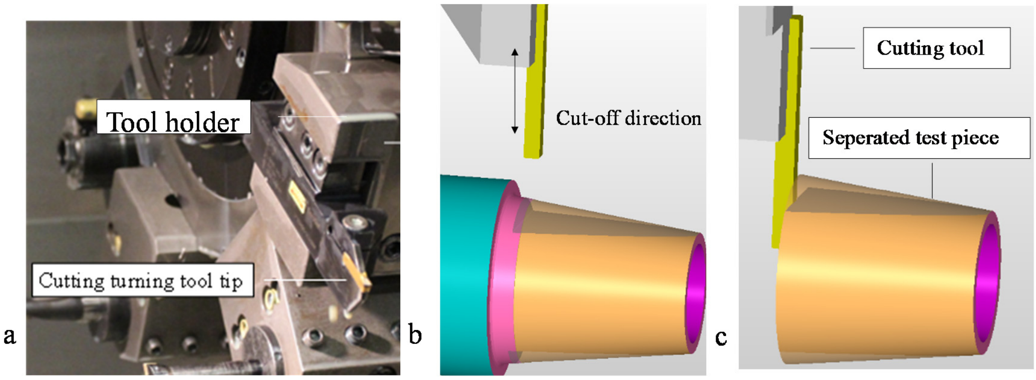


Figure 34. Illustration of cut-off (a) toolset-up (b) direction (c) part.

The turning tool was fed radially to parts surface to separate the final parts from the stock material. Two other test pieces made out to record different values to ensure reliability and validity of results.

Some of the main cutting parameters used to machine the sample B on the CNC machining centre are as shown in Table 5.

Table 5. Parameters used for CNC machining.

Process	Parameter	value
Outside turning	Spindle speed, *S*	180 [rpm]
	Feed rate, *f*	0.30 [mm/min]
Drilling	Spindle speed, *S*	200 [rpm]
	Feed rate, *f*	0.10 [mm/min]
Inside turning (rough and finishing)	Spindle speed, *S*	1000 [rpm]
		150 [rpm]
	Feed rate, *f*	0.10 [mm/min]
		0.20 [mm/min]
Milling	Spindle speed, *S*	200 [rpm]
	Feed rate, *f*	100 [mm/min] for X-axis 200 [mm/min] for Y-axis
Cutting	Spindle speed, *S*	150 [rpm]
	Feed rate, *f*	0.2 [mm/min]

6.2 LAM processes

Two pieces of samples A, B and C were built with the LAM process instead of initially planned amount of three pieces of each due to impact on the manufacturing time. Only about a quarter of building platform was utilised in the experiments of this thesis. The Figure 35 shows the placed test sample as per 1) two pieces 2) three pieces 3) six pieces (half) and 4) 12 pieces (full) of each sample per separate build.

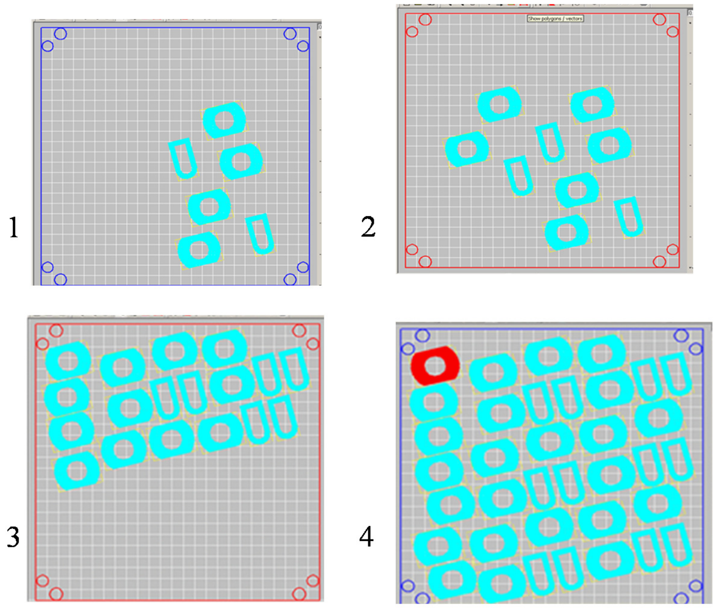
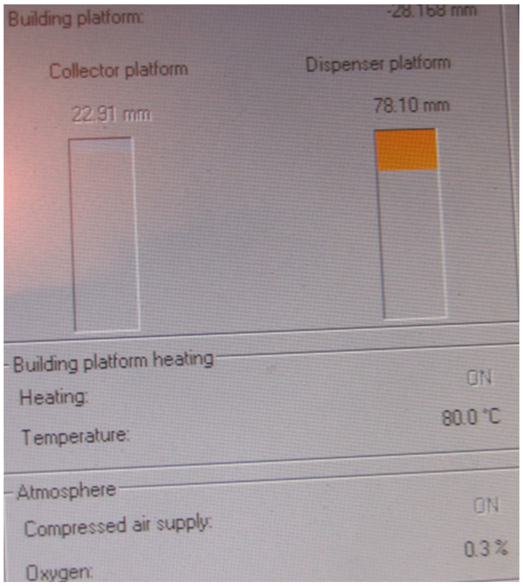


Figure 35. Representation of platform utilisation.

The Figure 35 (number two) demonstrates the platform utilisation as used in this thesis. The numbers one, three and four show other possible variants that may applied in a production. The total time required to make parts were estimated from the number of parts placed on the platform. For instance estimated time for building three pieces of each took approximately 130140 s (36.1 h) whereas building two pieces of each sample were completed in 102960 s (28.7 h).

The LAM process started by switching on the machine with power measuring system activated. Heating of the platform started after 420 s after which all necessary adjustments to level the platform into right position were done. Metallic powder was weighed and fed to the container and STL file was loaded to the computer.

The chamber was then closed again to heat the platform to the required temperature (80 °C). The suitable inert atmosphere necessary to support building process was generated at the same time. An automated controlling system purged oxygen out and as Nitrogen was fed into building chamber. Their levels were monitored on the computer screen as shown in Figure 36.



Building platform: -28.168 mm

Collector platform 22.91 mm

Dispenser platform 78.10 mm

Building platform heating

Heating: ON

Temperature: 80.0 °C

Atmosphere

Compressed air supply: ON

Oxygen: 0.3 %

Figure 36. Representation of temperature and oxygen measurement.

As shown in Figure 36 the prerequisite atmosphere required to assist smooth building process was attained and this was maintained throughout experiment. The building process began by spreading layers of metallic powder when platform was heated to about 80 °C and oxygen level was around 0.30 %. The sequence of building parts followed in order of returning of recoater, dispersion of new powder and scanning of the next layer. Figures 37 and 38 exhibit sections of LAM during the test.

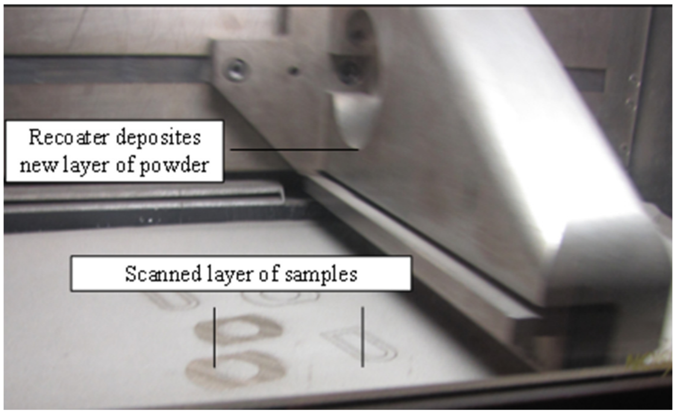


Figure 37. Representation of recoater movement.

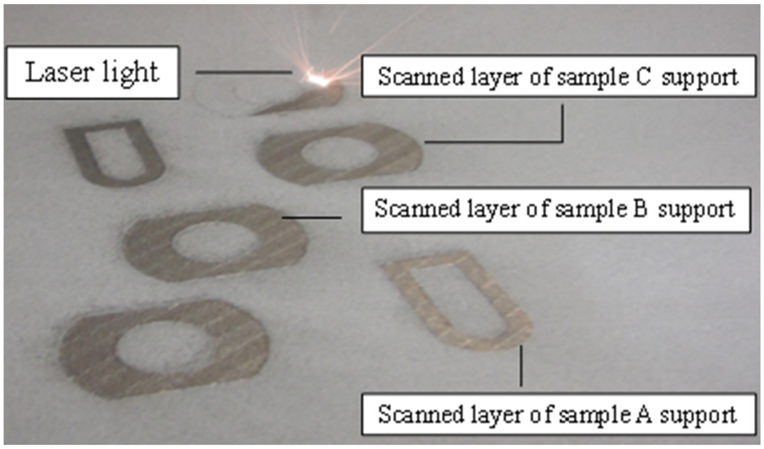


Figure 38. Representation of scanning process.

The process continued with scanning of supports structures after which main parts were also built. The building process stopped after about 100800 s (28 h) and chamber was opened to remove platform. The system was left on standby mode while all excess powder were collected from chamber. The powder in the hollow walls were also removed from the provided holes.

The LAM machine was shut off after which power measuring device was switched off. Figure 39 shows the platform with test pieces.

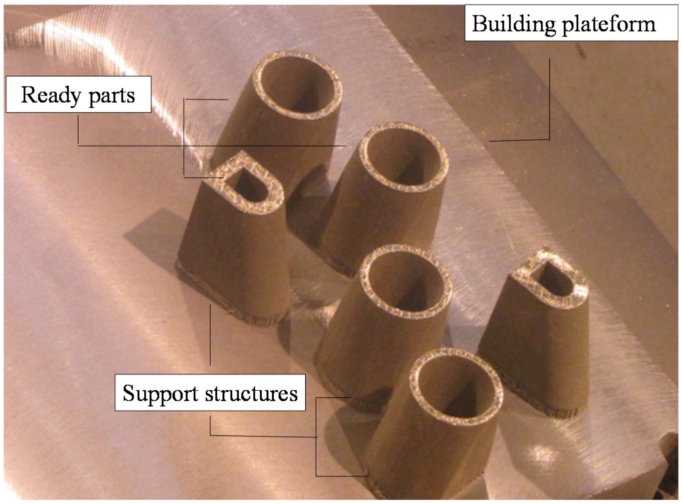


Figure 39. Representation of ready built parts attached to platform.

As it can be seen from Figure 39, the support structure appear dissimilar in construction from the actual parts, the supports are net-like.Additional process was needed to remove parts from the platform .The parts were removed from the platform with a mechanical sawing machine.

Figure 40 illustrates the sawing process set up.

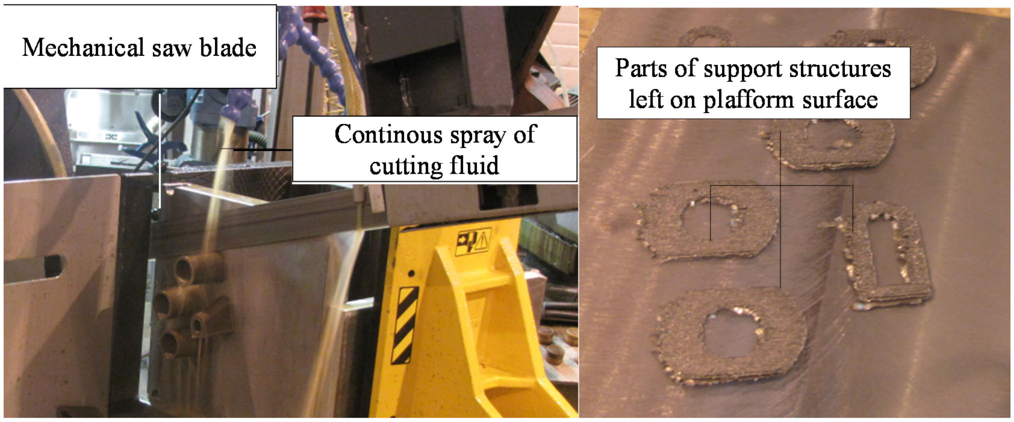


Figure 40. Illustration of sawing setup during part removal.

As it is demonstrated in Figure 40 the removing of the test pieces from the platform was aided by a continuous flow of cutting fluid. It can also be observed that, parts of the support structures remained on the surface of the building platform. Additional process will be needed to smoothen the surface before it can be used for another task. The energy required and material to be removed in levelling the platform were not included in this thesis as it was not within the scope of this thesis. However designing further studies to include this stage could give a full consideration of the entire energy and material consumption during the production stage.

A specially designed sieve was used to filter the powder to remove all particles higher than the required grain size by vibration. Figure 41 shows the device used to filter the leftover powder.

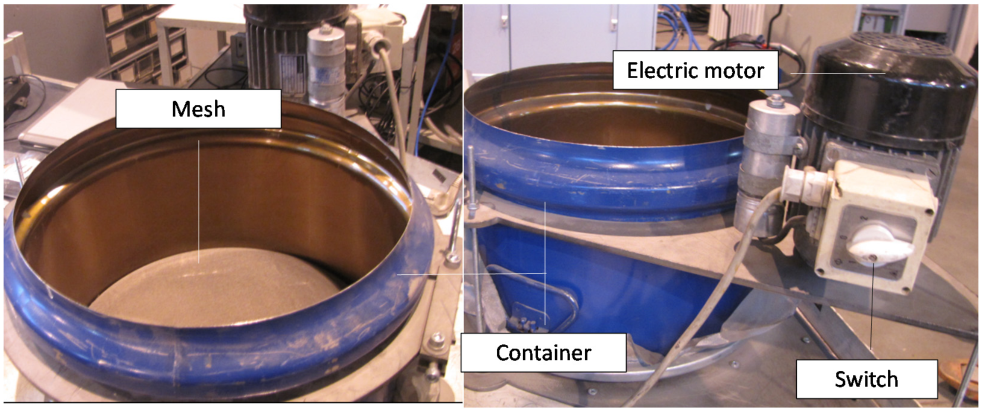


Figure 41. Representation of powder filtering set up.

As it can be seen from Figure 41, the sieve used to separate powder particles was connected to an electric motor. The filtering was achieved by means of vibration force aided by the electrical motor. Particle size up to the allowable grain size (63 µ) passed via the mesh into a flask while higher sizes remained in the container. The parameters used to build test pieces with the LAM are shown in Table 6.

Table 6. Process parameter used for the laser additive manufacturing.

Parameter	Laser power	Scan speed	Layer thickness	Wavelength	Focal length
Value	200 W	1000 mm/s	0.02 mm	1070 nm	400 mm

6.3 Power measurement in CNC machining

The power measurement in the machining was done by using the current sensor to measure the voltage in the machining centre. Spindle motor rotating tool and axes motors were main units taken considered. The measuring was done in every second and were written to device disc. During the machining phases, the monitoring device slept for about 1000 ms before next measuring this indicate some averaging of power measurement from the system. The current of the motors were measured through a Nordmann GmbH WLM active power metering module. The electrical power values by carriages axes during the machining and power for the tool change were measured. The power values for the main spindle (S1), rotary tool (S2) and carriage (X, Y, Z) servo motor were recorded with a wireless link module.

The power values were given in percentages from the measured voltage of the lathe. These were converted to watts by multiplying them by the maximum power values as given in machine manual. A maximum (22 kW) power for machining times up to 600 s (10 min) and minimum (15 kW) with working times beyond 420 s (7 min) stipulated for main spindle. Since machining lasted more than 600 s (10 min) the maximum machining power capacity (22 kW) was used.

6.4 Power measurement in LAM

The power measurement was achieved with the Siemens Sentron PAC 3200. The initial energy and final energy on the measuring scale were recorded before and after manufacturing. Power measurements were taken every 10 s during the LAM process due to the high number of data to be handled if measure every second. Power was recorded in two seconds interval during the sawing process. The electrical energy consumption views from both the LabView and power meter remained nearly constant during specific mode of the building process. The meter recorded highest power value during the laser scanning.

Figure 42 illustrates power measurement set-up and power profile as used and recorded in this thesis.

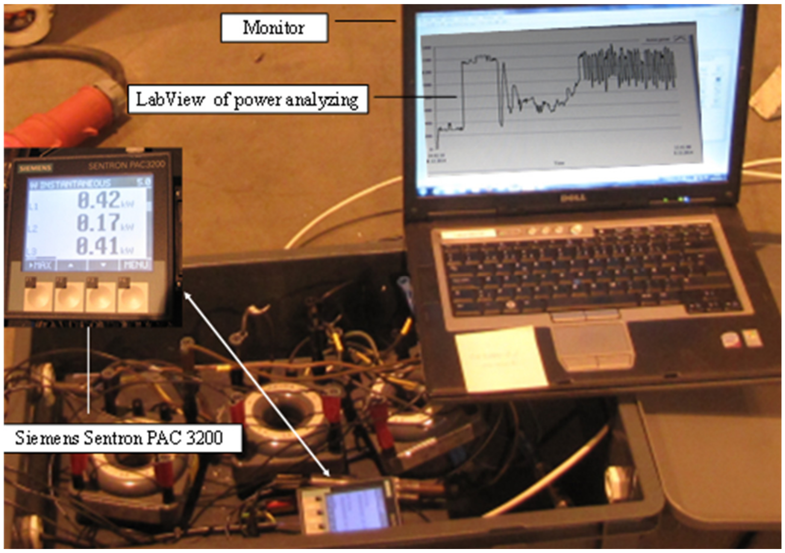


Figure 42. Exhibition of power monitoring set-up used during LAM.

Figure 42 shows a partial view of the power values in the LAM process. Power monitored from the various machine tools varied according to the different modes. For instance, during the heating, power values were higher than the preparation stage. This was as a result of activated heating units that required higher electrical power

6.5 Equations used

6.5.1 Power analysis

CNC machining

There were three electrical power driven units identified in CNC machining: namely $P_{spindle}$, P_{axes} and $P_{lubtication}$. The average of individual process power P_{CNC}, measured in each machined phase was determined by summing the average values from all the machining processes. These amount of power values of the spindles motors and carriage servos.

Since machining is aided by lubrication, power value for the lubricating motor $P_{lubrication}$ (400 W) as given in machine manual were considered during the actual cutting estimation. This was however excluded from reference cut power calculation as lubrication was not activated during the phase. Equation 1 was used to determine the power in kW for the motors.

$$P_{kw} = 0.126 \cdot e^{0.5648\,pv} \tag{1}$$

where	P_{kw}	power in kW,
	p_v	voltage.

The recorded voltage during the CNC machining were converted to power values as equation 1 shows (Ratava, 2014).

Equation 2 was used to define the combined power value in each phase.

$$P_{CNC} = P_{spindle} + P_{axes}(+)P_{lubrication} \tag{2}$$

where	P_{CNC}	power value during CNC machining,
	$P_{spindle}$	power to drive spindles, (S1 +S2),
	P_{axes}	power for moving X, Z, and Y axis,
	$P_{lubrication}$	power for lubrication motor.

Equation 3 combined the different machining processes for the determination of total average power, P_{avg} per part.

$$P_{avg} = AVG(\sum_{i=0}^{n} P_{outside} + \sum_{i=0}^{n} P_{drilling} + \sum_{i=0}^{n} P_{inside} + \sum_{i=0}^{n} P_{milling} + \sum_{i=0}^{n} P_{cutting} + \sum_{i=0}^{n} P_{tool} \tag{3}$$

where	P_{avg}	power average,
	$P_{outside}$	power during the outside turning process,
	$P_{drilling}$	power during the drilling process,
	P_{inside}	power during the internal turning process,
	$P_{milling}$	power during the milling process,
	$P_{cutting}$	power during to cut ready part off stock,
	P_{tool}	tool change power (power measured during tool change).

LAM

The four modes identified were 1) standby, 2) heating, 3) process during the LAM process; and one ancillary mode 4) sawing. The total electrical power consumed in LAM, P_{LAM} was determined using equation 4.

$$P_{LAM} = P_{standby} + P_{heating} + P_{processing} + P_{sawing} \tag{4}$$

where	P_{LAM}	total of average power in LAM,
	$P_{standby}$	average of power for activities such as cleaning and removing,
	$P_{heating}$	average of power to heat LAM chamber,
	$P_{processing}$	average of power values during recoating, laser scanning, platform travels, etc,
	P_{sawing}	average of power values to saw work pieces from platform.

6.5.2 Energy analysis

The energy used in each of the modes of production were determined for both manufacturing processes. The power of each process mode was multiplied by time to get the energy, E_{method}, consumed in producing each part according to equation 5. The subscript, method is replaced with the manufacturing process accordingly in both processes. Average values of recorded power were used.

$$E_{method} = P_{process} \cdot t_{process} \tag{5}$$

where	E_{method}	energy consumed in each manufacturing method,
	$P_{process}$	average power in each method,
	$t_{process}$	time taken to perform each manufacturing phase.

CNC machining

Two approaches were used to calculate the total energy in CNC machining to ensure reliability of energy calculations. The energy consumption values were determined using summation of electrical energy consumption. Equation 5 was also used to find energy by multiplying averages of power values in each phase with time taken to complete machining task.

The total energy used in CNC machining was calculated as shown in equation 6.

$$E_{CNC} = \sum_{i=0}^{n} E_{outside} + \sum_{i=0}^{n} E_{drilling} + \sum_{i=0}^{n} E_{inside} + \sum_{i=0}^{n} E_{milling} + \sum_{i=0}^{n} E_{cutting} + \sum_{i=0}^{n} E_{tool} \tag{6}$$

where	E_{CNC}	Total energy used to machine one test piece,
	$E_{outside}$	energy consumed during the outside turning,
	$E_{drilling}$	energy consumed for drilling,
	E_{inside}	energy consumed for inside turning,
	$E_{milling}$	energy consumed during milling,
	$E_{cutting}$	energy consumed to cut-off test piece,
	E_{tool}	energy consumed for tools change.

LAM

The energy consumption during the LAM process (E_{LAM} or E_{total}) was estimated by combining the energy used in all modes as equation 7 shows.

$$E_{LAM} = E_{stanby} + E_{heating} + E_{processing} + E_{sawing} \tag{7}$$

Where	E_{LAM}	total energy consumption in LAM,
	$E_{standby}$	energy used for activities such as preparation, cleaning, cooling,
	$E_{heating}$	energy used to heat and create inert atmosphere,
	$E_{processing}$	energy used for recoating, scanning, platform travels, etc.,
	E_{sawing}	energy used to saw work pieces from platform.

An evaluation of the energy consumption per each of the test pieces were calculated using equation 8.

$$E_{con} = \frac{vi}{v_{TOT}} \cdot E_{LAM} \tag{8}$$

where	E_{con}	estimated energy consumed as per part,
	E_{LAM}	total energy consumed to make all test pieces,

vi	volume of per part,
V_{TOT}	total volume of all test pieces.

Appendices IV and V represent the results of energy calculation in CNC machining and LAM respectively.

6.5.3 Mass loss calculations

CNC machining

The material that were lost during the CNC machining were the stainless steel material and cutting fluid used for cooling and lubrication. The volume of removed material (chip) from the stock material were determined as equation 9 shows.

$$V_{removed} = V_{input} - V_{part} \tag{9}$$

where		
	$V_{removed}$	volume of removed material,
	V_{input}	volume of starting material,
	V_{part}	volume of final part.

The mass loss due to raw material, m_r, was estimated using amount of removed volume of material per part ($V_{removal}$, [cm^3]) multiplied by the density of material (ϱ, [kg/cm^3]). Volume of starting bar were estimated using solid works. The equation 10 was used to determine amount of removed mass. Appendix IV represents results of removed mass and volume of material.

$$m_r = V_{removed} \cdot \varrho_{316L} \tag{10}$$

Where		
	m_r	removed mass,
	$V_{removed}$	volume of removed material,
	V_{input}	volume of starting material,
	V_{part}	volume of final part,
	ϱ_{316L}	density of stainless steel 316L.

6.5.4 Specific energy consumption

In order to determine the SEC for producing each of the test pieces, it was necessary to determine the amount of mass and volume deposited. The deposited mass were determined using SolidWorks software, LAM system and measuring scale. The SEC for producing the sample pieces were estimated using equation 11.

$$SEC = \frac{E_{LAM}}{m_d} \tag{11}$$

where	SEC	specific energy consumption,
	E_{LAM}	energy used to deposited or remove amount of material,
	M_d	deposited mass.

Appendix IV shows the amount of removed mass and volume in CNC machining and the amount of deposited mass and volume in LAM parts are shown in appendix V.

The SEC in CNC machining was not included in this studies however its inclusion into further studies may offer a more appreciative energy consumption comparison.

7 RESULTS AND DISCUSSION

An analysis of test piece appearance, power, time, energy and materials consumptions in each of the manufacturing processes from the different manufacturing processes are presented in this section. The power and energy analysis were determined based on individual test piece in CNC machining while in the LAM results were evaluated based on combined build and assumed variants of production.

7.1 Experimental results of CNC machining

7.1.1 Visual evaluation of quality of test pieces

There were four test pieces produced with CNC machining. However, data for energy analysis were based on only three parts as the first was machined as a trial of the designed code. The parts produced with CNC machining are illustrated in Figure 43.

Figure 43. Representation of test pieces produced with CNC machining.

The three similar parts produced with CNC machining are demonstrated indifferent views as shown in Figure 43. These parts were made after making changing in the G-code to the feeding direction of milling tool was changed from axial to radial movement. This resulted in a smother surface quality as shown in Figure 43. Figure shows the quality of test piece made with milling tool fed radially.

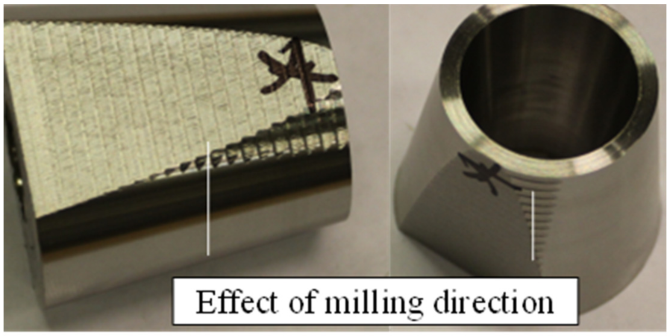


Figure 44. .Representation of machined tried part.

As seen from Figure 44, the quality milled surface on part was poor compared to the test pieces shown in Figure 43.

7.1.2 Material consumption

Raw material (316L stainless steel bar)

The Table 7 is an analysis of input and output materials in the CNC machining.

Table 7. Input-output analysis in CNC machining.

Input in mass, m [kg]	Final part mass, m[kg]	Removed mass, m[kg]	Percentage of lost material, [%]
0.71/one part	0.18/one part	0.52/one part	~ 74.1
2.12/three parts	0.55/three parts	1.57/three pieces	

As Table 7 indicates the total mass removed from one test piece was found to be 0.52 kg/part indicating about 74.1 % loss of stock material and 25.9 % efficacy. This utilisation analysis was based on the starting bar dimensions (50 x 45 cm) used for this thesis.

Nevertheless, if the exact stock of material (45 x 45 cm) as would have been used in industrial production was utilised, only about 68 % (0.39 kg) of material would be wasted and 32.0% (0.18 kg) used as final part. This shows that there was about 0.14 kg per one piece or 0.42 kg per three pieces excess material removed as waste in this thesis.

Cutting fluid

The material loss due to lubrication is estimated by applying an approach by Kalla et al. (2010). In their study, it was assumed that a 208 l/machine was reusable in machining centre until disposal after specified weeks (2 weeks as used).

It was estimated that about 150 l/machine was used in the machining centre used for this thesis (Selesvuo, 2014).

Assuming cutting fluid is used 204 h/8 weeks, then the cutting fluid loss is 150 l/ (204*60) per minute, which is 0.012 l/min or about 12 g/min. Since the coolant is 95 % water, the oil loss is 5 % or 0.6 g cutting oil/min or 0.01 g/s.

As the cooling oil was only delivered during the machining phases without the tool change The total machining time is estimated by subtracting the tool change times Kalla et al. (2010).

The machining time 1 part t_m = 691.s
Mass loss of the coolant = kg cutting oil / s* ts
=0.001 kg / s*691 s = 6.91 kg cutting oil/part
=6.91 kg cutting oil/part. 3 =20.7 kg

This means that approximately 21 kg of cooling liquid is lost during the CNC machining process (not including the trail test). This value is based on assumption made from literature and the information available to this thesis. For instance the machining centre in this thesis changes lubrication twice in a year dependant on the usage (Selesvuo, 2014). Occasional top up with 80 to 90 l of the cutting fluid is added at intervals when level fall below required amount however, this was not considered in the estimation.

The amount of lubricant used during the machining and the exact amount of generated waste could not be measured as some chips were mixed with coolants. Using the mass of final parts weighed and the weight of initial stock, amount of removed raw material were determined theoretically.

7.1.3 Energy consumption profiles

The individual rate of energy consumption per motor during CNC machining for both reference and actual cutting cases are analysed in this section.

Figure 45 shows the power profile during the reference cutting (air cut).

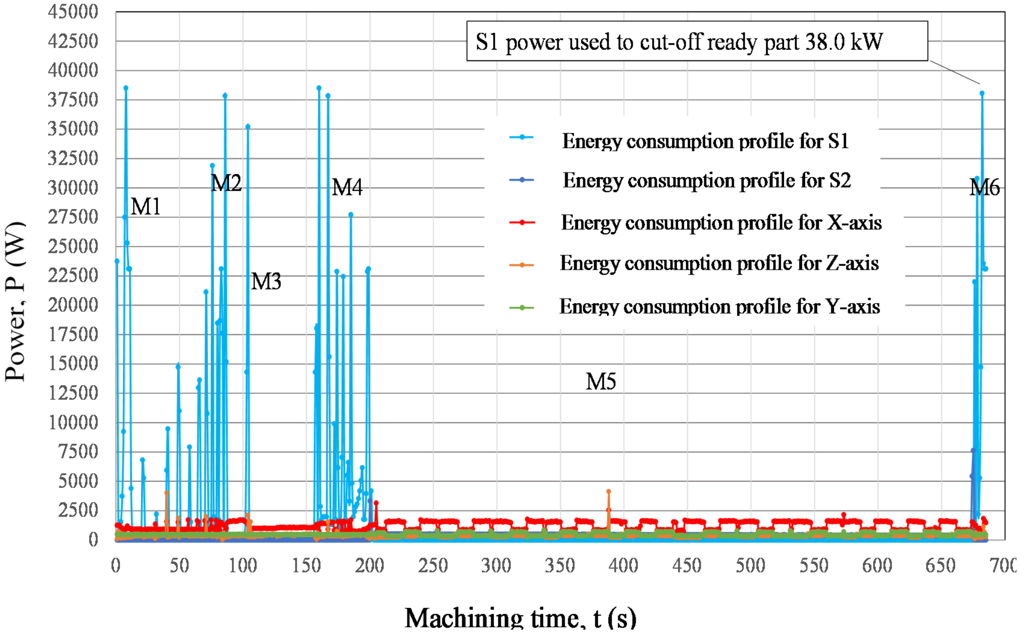


Figure 45. Power vs. machining time in CNC machining reference cut in CNC machining.

As it can be seen from Figure 45, the energy consumption profile for the various machining processes are indicated as M1, M2, M3, M4, M5 and M6. The profile of energy consumptions for the five different motors are shown .The reference cut was completed in 685 s (11.4 min). As shown in Figure 45 power values for spindle motor reached as high as 38.0 MW during the turning and cut-off operations.

Figure 46 illustrates reference cutting with energy consumption in every one second.

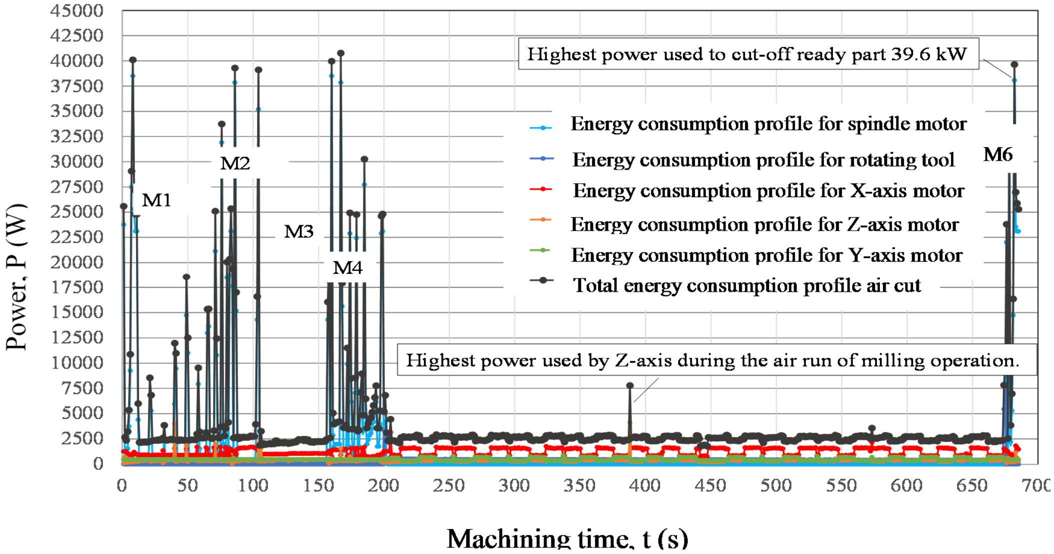


Figure 46. Power vs. machining time in CNC machining reference cut in CNC machining.

The profile of the combined energy consumption per motor are presented in Figure 46. The black shows combined energy profiles. It can be established from Figure 46 that even though no cutting was done in the reference cut rate of energy consumption were high with high power peaks.

Figure 47 represents the rate of energy consumption during the actual cutting.

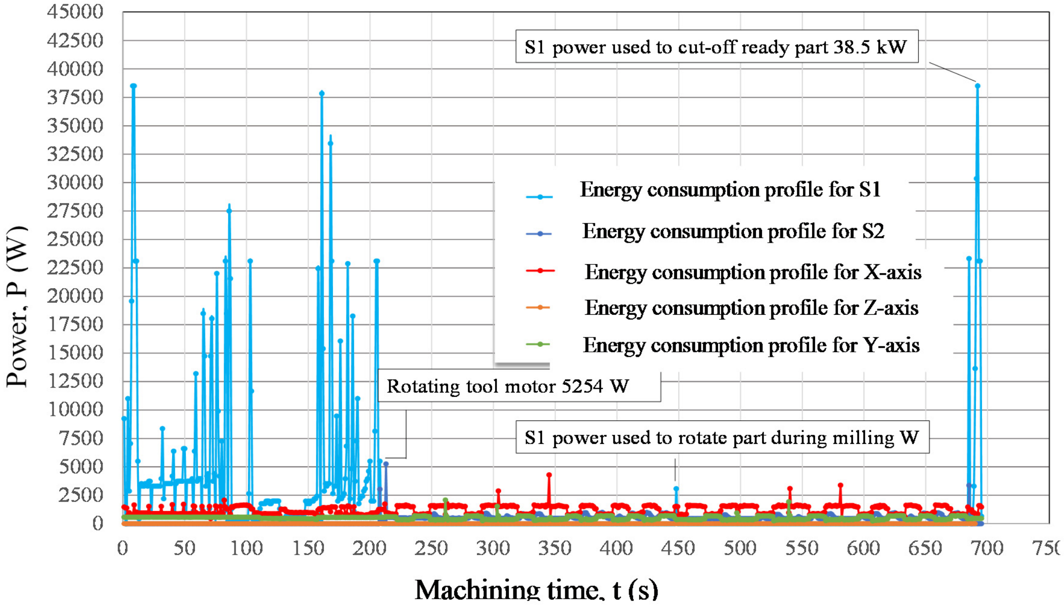


Figure 47. Power vs. machining time in CNC machining actual cut in CNC machining.

Figure 47 shows that the highest power (38.5 kW) value was recorded with the final cut off of the finished test piece. The profile of energy consumption during air cut did not show much variance from the actual cut. For instance as the energy profile during reference cut (Figure 45) indicated maximum power) value of 7.66 kW for the rotating tool, the actual cutting indicated only a 5.24 kW maximum power value for rotating tool. As it can be observed from Figure 47, the power peaks for Z and Y axes servo motor remained nearly constant with Y- axis servo showing a slightly higher power values than Z- axis.

Figure 48 illustrates the profile of energy consumption of all motor.

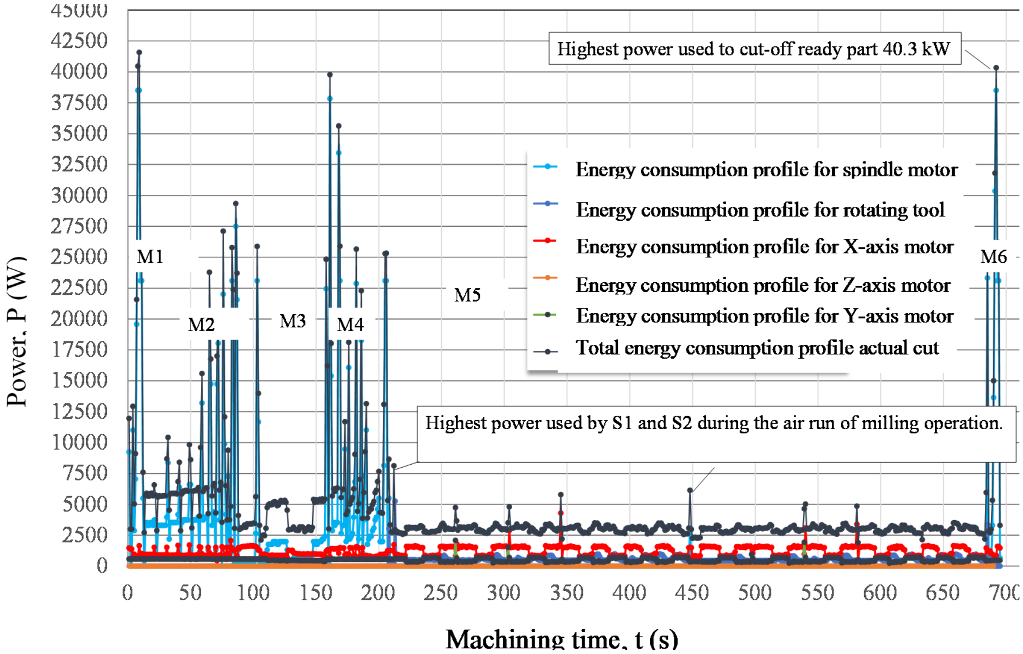


Figure 48. Power vs. machining time in CNC machining actual cut in CNC machining.

The energy consumption during the milling operation (1.45 MJ) was higher compared to the other machining processes. For instance only about a 0.71 and 0.13 MJ were utilised during the outside turning and drilling respectively from the excel analysis. The variance in energy consumption during the different machining processes was as a result of length of machining time. During the milling phase an average power of 3050 W was used, and energy consumption was high due to time.

An analysis of individual motors also indicated difference in energy consumption in the various units. The spindle motors exhibited maximum power values during the actual and reference cutting as shown in Figures 45 and 47.

The difference in energy consumption during the air-cut and actual cut revelled minimal differences. For instance the energy consumption and time values during the reference cut (2.77 MJ, 685 s) and the actual cut (3.25 MJ, 695 s) indicate that additional energy of 0.48 MJ was required to perform actual work. Also the maximum power values during the part cut-off as indicated in Figure 46 and 48 indicate approximately only about700 W differences. The amount of energy consumption during the reference cut for the Z and Y axes motors were least (0.27 and 0.35 MJ respectively) compared amount consumed by the main spindle motor (1.26 MJ) and X-axis (0.84 MJ). The average power values for Z and Y axes were constant with only about 392 and 910 W respectively.

The amount of energy used during the tool change was higher than amount used in air cutting even though machining time remained almost same. This could be attributed to the high retraction force required to disengage tools from work piece. The average of the energy consumptions during the tool change for machining the three test pieces was 0.10 MJ. This value is almost the equivalent to the amount (0.13 MJ) used in the drilling process. (See appendix IV).

The same parameters used for the reference test were used to machine test 2 and 3. The initial feed and rotation speed used to make the test piece 1 were modified in order to decrease the machining time. The difference in total energy consumption in test piece one, two and three was as a result of change in machining time. (See appendix IV). During the experiment, $P_{spindle}$ and P_{axes} were approximately 1.53 MJ and 1.44 MJ respectively.

The time taken to machine one test piece was approximately 685 s (11.4 min) with an average power value of 588-1200 W depending on the process. About 90 kJ energy was used for all tool changes in machining one test piece. Table 8 illustrates energy consumption for both reference and actual cut.

Table 8. Power, time and energy consumption values in CNC machining.

Mode of test	Power, P (kW)	Time, t(s)	Energy, E(MJ)
Actual cut	4.73	689	3.36
Air cutting	4.04	685	2.77

The values in Table 8 show the averages for power and time values during the machining of the three different parts and for the reference cut. The difference of consumed energy for the actual machining was determined by comparing the energy consumption during the “air” cut (2.77 MJ) and actual cutting (average 3.52 MJ) processes. The amount of energy consumed in the reference cut was about 580 kJ lesser than the required values for the actual cuts. The analysing was based on an average of the values from the three parts.

An analysis based on the different machining processes was made. The power value during the milling operation was constant with about 3.05 kW however accounted for highest energy used as milling time was about half of total machining time. The power profile for during the various CNC machining processes are presented in Figures 49-53 in a sequential order.

Outside turning

The starting phase of the machining was the outside turning. Figure 49 illustrates the energy profile during outside turning operation by the different motors.

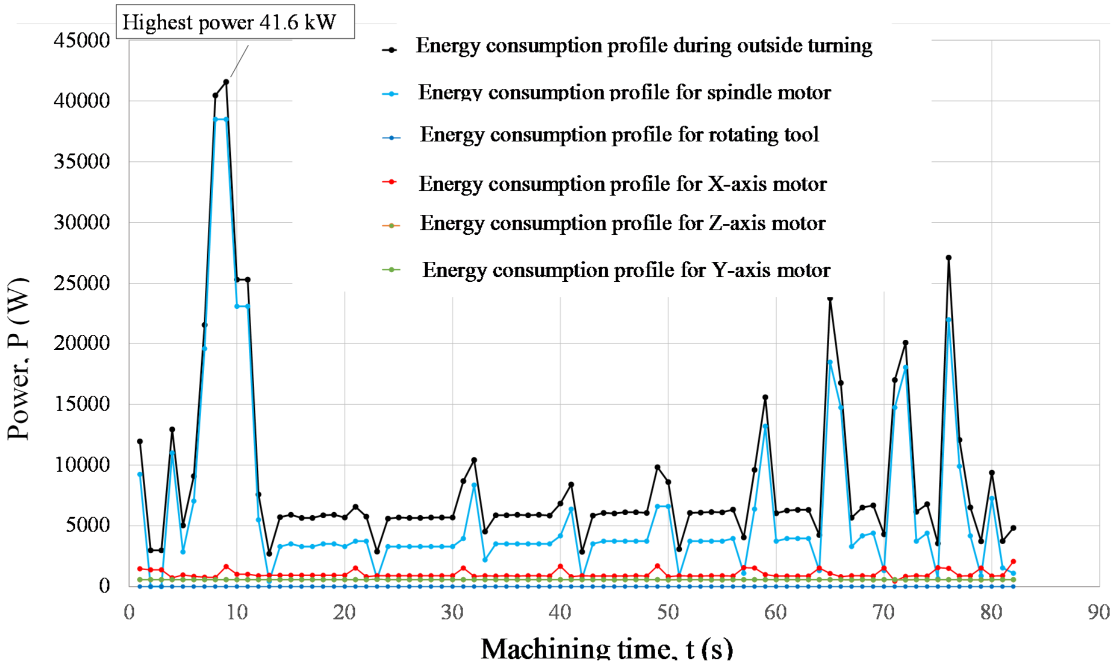


Figure 49. Power vs. machining time during outside turning in CNC machining.

Figure 49 shows the total time and power peaks during this phase. The time used for turning the outer surface of part was 82 s and the total energy consumption for turning each of the parts was about 713 kJ. As it can be noticed from Figure 49, majority of the total energy (713 kJ) was used during the outside turning S1 (508 kJ) and the carriage motors (172 kJ) whiles the rotating tool motor recorded no power values. This show that about 72 % of total energy were used by spindle motor and 27 % by the X, Z and Y axial servo motors. The rotating tool showed zero power values during the outside turning phase as the tool was held in fixed. An indication that about 33 kJ of electrical energy was used to operate the lubrication motor during the outside turning as well as other losses.

The power values in the various motors were uneven during this process. For instance the spindle motor shows a highest power value of 38.5 kW to a low value of 440 W. During this phase average power value for Z and Y axes remained constant with about 510 and 574 W respectively. Relating these values to the lubrication motor power (400 W) indicated only about 110 W additional power values to drive a carriage motor.

Drilling

The second phase of the machining process was the drilling operation (see Figure 50).

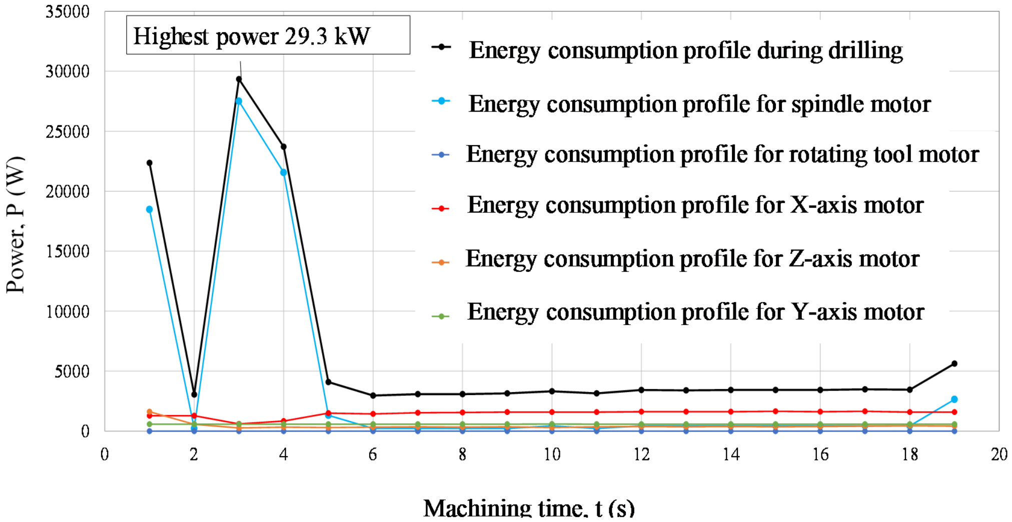


Figure 50. Power vs. machining time during drilling in CNC machining.

As it can be seen from Figure 50, the total time for drilling the internal diameter hole was 19 sand the total energy consumption was 130 kJ. The spindle and carriage motors consumed 76.3 and 47.0 kJ. The maximum power peaks values (23.7-295 kW) were recorded at the initial stage mostly due to the spindle motor (21.5-27.5 kW). The electrical energy consumed per X, Y and Z axes were 27.9, 10.9 and 8.31 kJ respectively. The spindle motor energy (76.3 kJ) contributed the highest portion to total energy (130 kJ) during the drilling phase. The power values during the drilling process was rather even and small compared to the turning process. As it can be noticed from the Figure 50, the power values by axes motors remain constant with an average power values of about 1462; 437; 577 W for X, Z and Y axes motors respectively.

Inside turning

The turning of the internal hole was performed after the drilling process. Figure 51 exhibits the power profile during this turning of the internal surface.

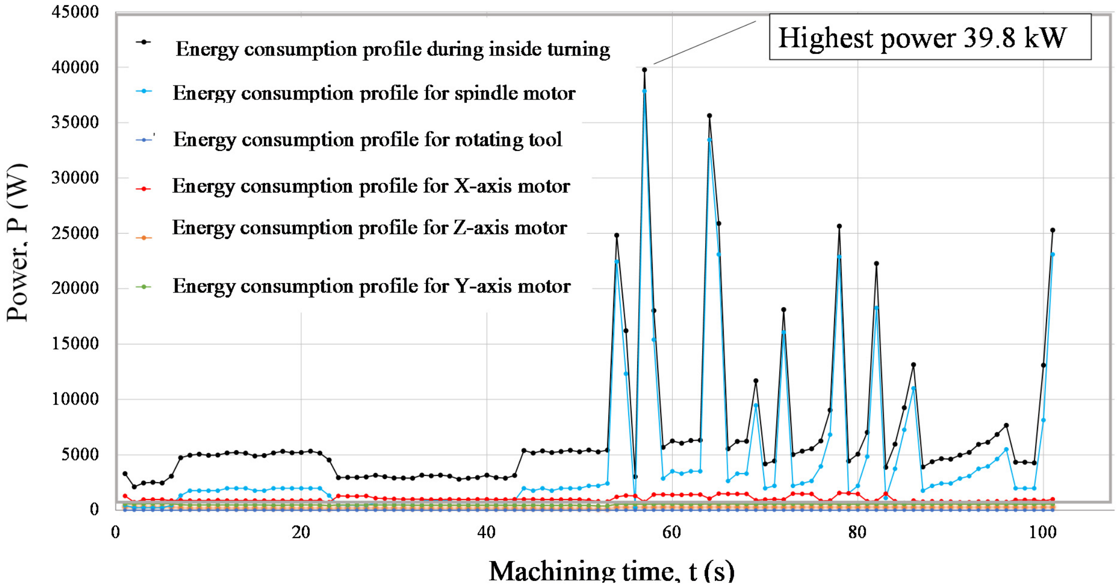


Figure 51. Power vs. machining time during inside turning in CNC machining.

This phase was performed within 96 s as illustrated in Figure 51. The total energy consumption was 699 kJ. The spindle motors consumed 61 % of the total energy with 427 kJ whiles the remaining were consumed by the carriage and lubrication motors.

Milling

The Figure52 illustrates the milling phase of the CNC machining experiment.

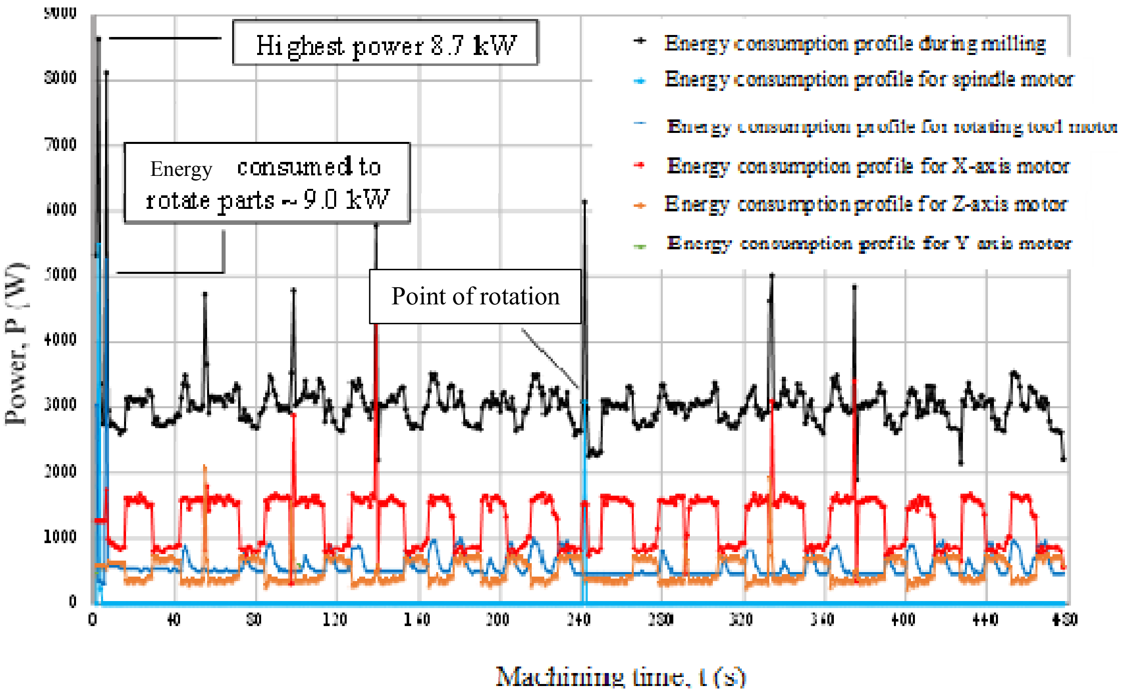


Figure 52. Power vs. machining time during milling in CNC machining.

As it can be noticed from the Figure 52, most of the power values were below 2000 W compared to the other processes analysed earlier. The few high peaks recorded were only about 4730 to 6100 W. And these were mostly at the start of milling each of the surface. Averagely power values for all motors were low. Rotating tool motor (700 W), Z and Y axes motor (500 W) and Z axis (1500 W). The spindle indicated no power values after the 6 s, however it recorded about 3040 W for three seconds (242-245 s) and returned to static position. The highest power value of the spindle motor was as a result of part rotation from zero point to 180^0. Even though milling was completed with low average power values (200-600 W), the time taken (477 s) was vast compared to other manufacturing stages. This increased the total energy consumption during milling. The energy consumed during this process was 1.45 MJ which accounts for about half of the total energy (3.25 MJ) used for machining one part.

Cut-off

The final process was done to separate the machined geometry from stock material. The Figure 53 shows the energy consumption profile during this phase.

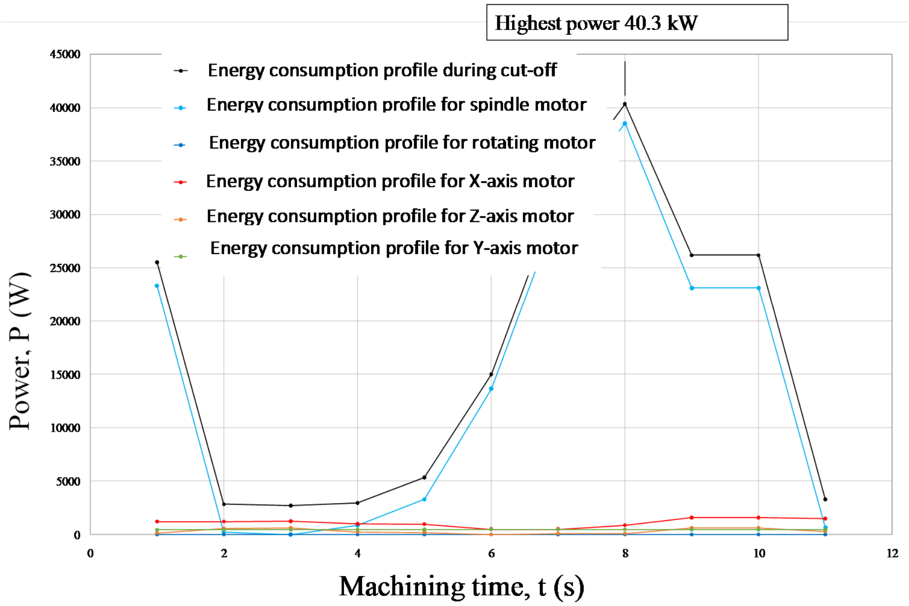


Figure 53. Power vs. machining time during cut-off in CNC machining.

As Figure 53 shows, the power values during the final cut off were high (average 14.5; peaks 38.5 kW) for the spindle motor as other motors recorded relatively lower power values (322 -1094 W). The rotating tool remained stationary in this process thus recorded no power values. Time taken to complete the cut-off was 11 s and the total energy was 0.18 MJ.

The power profile and time taken for the CNC machining processes were very uneven. Whiles majority of the energy were consumed by the spindle motor, the X axis was the only carriage motor characterised with higher energy consumption.

7.2 Experinmental results of LAM

7.2.1 Visual evaluation of quality of test pieces

Figure 54 shows work pieces manufactured with LAM.

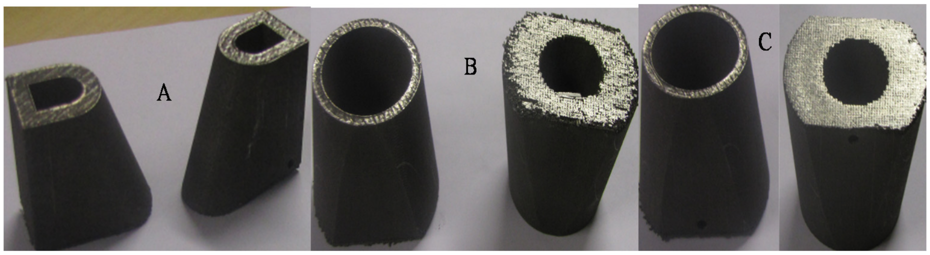


Figure 54. Representation of sample A, sample B and sample C built with LAM.

The surface quality of the LAM built sample were not as smooth as the CNC machined parts. The surface finish of LAM parts appeared course and this may be one of the shortfalls of LAM in terms of appearance if surface evenness is required in application. Additional post processes may be used to smoothen the parts made with LAM which may require extra energy and time consumption.

7.2.2 Material consumption

Raw material (316L stainless steel powder)

The material usage in LAM manufacturing are as presented in Table 9.

Table 9. Input–output material in LAM.

Input,[m [kg]	**Output, m [kg]**	**Reusable mass, m [kg]**	**Disposed mass, m [kg]**	**% mass lost**
25.5/build (6 parts)	0.56/six parts	24.7	0.24	0.92 (~ 1.00)

As it can be seen from the Table 9, the material flow of LAM was more efficient compared to the CNC machining as Table 7 shows. The mass of disposed material includes the estimated weight of support structure, powder mixed with cutting liquid in the sawing process as well as all unaccounted mass. A higher efficacy was realised in LAM as material lost was only about 1.00 %. The waste estimation included only the stainless steel and did not consider waste like cutting fluid used during the sawing process.

7.2.3 Energy Consumption profiles

The energy consumption profile during the different modes of the LAM are presented below. Figure 55 presents the energy consumption during the start-up of the process to when the heating of the system began.

Standby

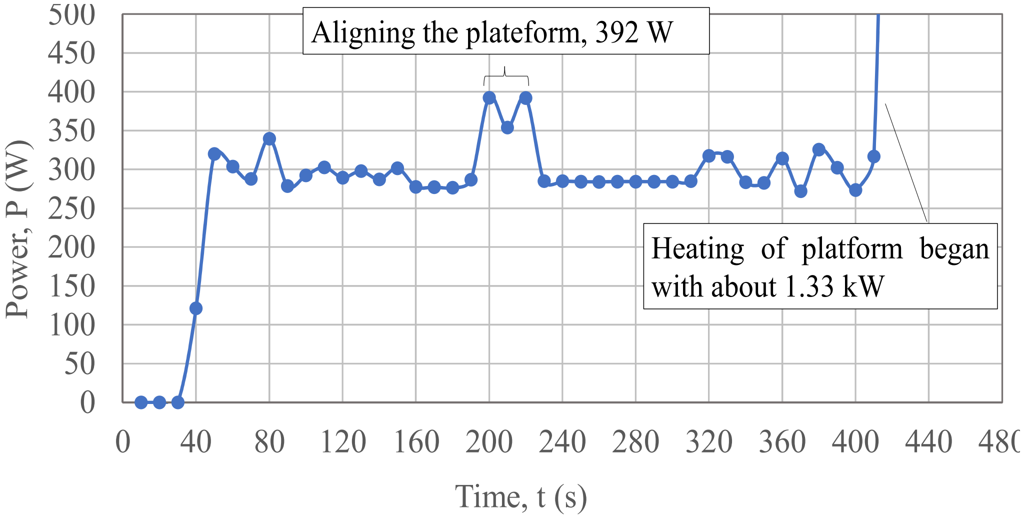


Figure 55. Power vs. time during start-up and preparation in LAM.

As it can be seen from Figure 55, power values during this standby phase was constant at about 300 W. The power values increased during the movement of the platform and recoater.

Heating and inert creation

The duration between the initial standby, first 480 s (8 min) and the process time consisted of the heating and waiting time to create the desired inert atmosphere in building chamber. Figure 56 shows energy profile during the heating phase.

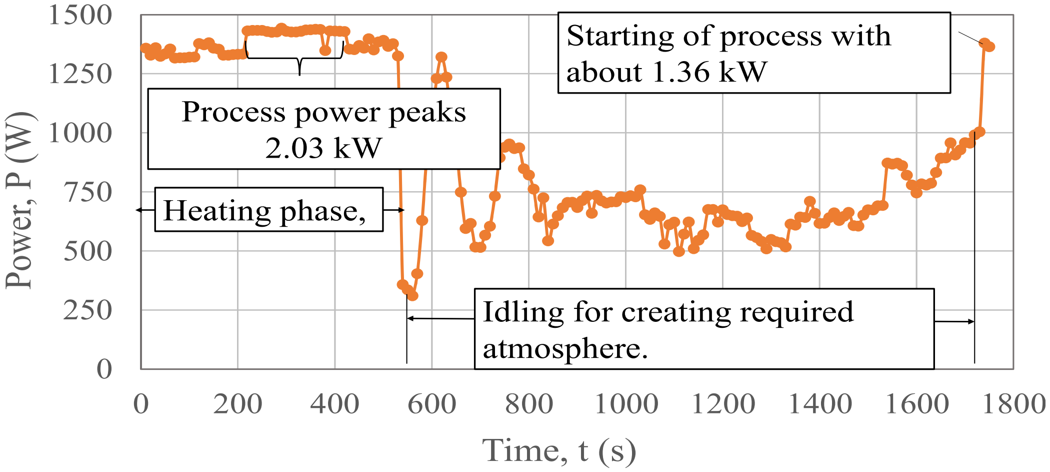


Figure 56. Power vs. time during platform heating in LAM.

Figure 56 shows a sharp rise in power value after which it stabilizes to 750 W. The highest part of the energy were used to heat the platform. The remaining energy were consumed in creating the right atmosphere for process to begin. Low energy consumption were maintained in the LAM process due to the constant temperature (80^{o}C) of platform during the building phase.

Process (layering and scanning)

The Figure 57 is an illustration of energy consumption profile during the supports and main part building.

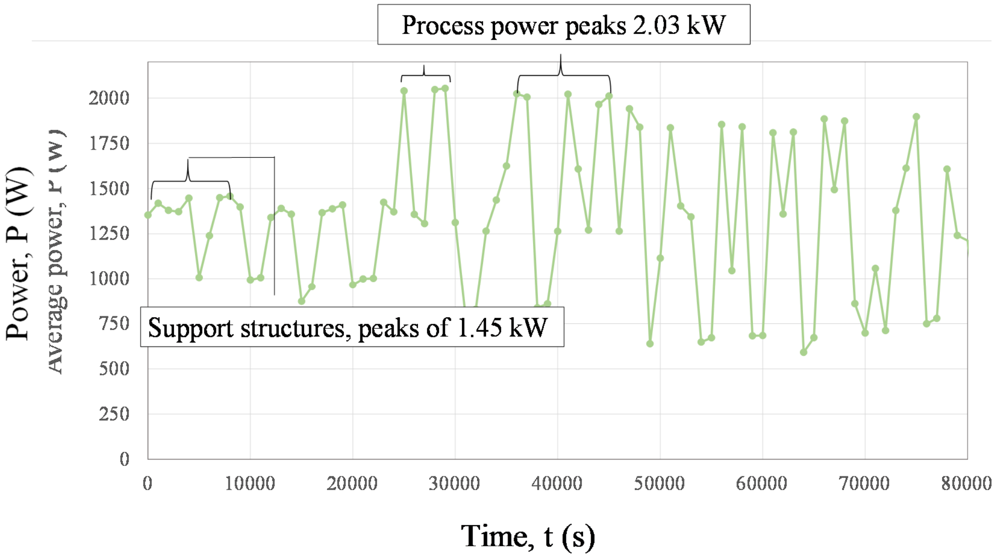


Figure 57. Power vs. time during process (supports and main parts) in LAM.

As it can be seen from the Figure 57, power values were almost constant during the different phases of the building process. The peaks (1800-2030 W) correspond to scanning time while the low power (510-700 W) range relate to recoater, platform and powder container movements.

Energy consumption during part building were observe to have slight difference for the supports and actual parts. While the support building phase had an average power value of 1.32 kW at scanning, the actual parts showed 2.03 kW. The variance in power usage was a result of dissimilar design of supports from main parts as Figure 39.

Sawing

The Figure 58 is an illustration of energy consumption during the sawing process.

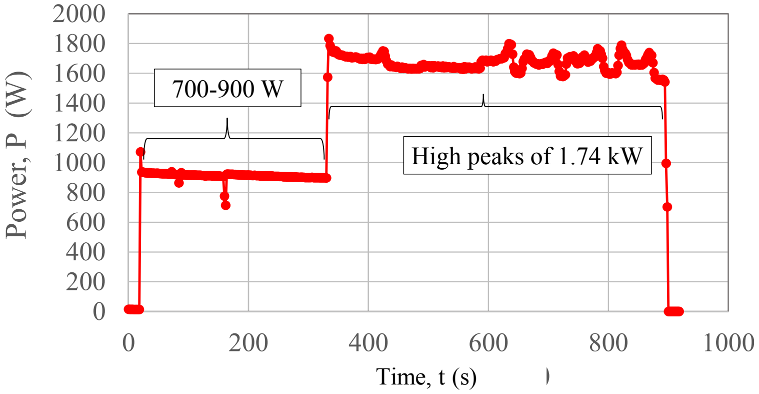


Figure 58. Power vs. cutting time during sawing in LAM.

As Figure 58 illustrates, the power values in removing parts from the platform were uniform for all the samples. This shows energy usage is not dependant on the geometry of parts build with LAM. The initial stage of the cutting showed low power values (700-907 W) after which it increased and remained to high value (1790 W). The increment could be as a result of activated cutting fluid system and part-tool interaction.

The total energy consumption in LAM experiment was 12 MJ including sawing. An average of 1225 W in 103210 s (28.7 h) was used to manufacture the parts during the LAM process. The total time and average power for making the six parts in LAM were 103200 s (28, 67 hr) and 1225 W respectively. The total time and energy used to heat the platform were 530 s (8.88 min) and 0.73 MJ respectively with an average power value of 1.38 kW. The combined standby time and energy in fabricating the parts were 28.3 min and 0.95 MJ respectively. The individual time and average power during the various standby modes are presented in appendix V. The total energy consumed in processing mode, $E_{processing}$ was 125 MJ. Out of this total energy value 16.4 MJ (4.55 kWh) was used to build the supports structures at an average power of 1.86 kW in 8 820 s (2.45 h). After the building process ended the sawing of parts from the platform followed with an average power value of 1337 W. Time and energy used during all the identified modes in LAM are presented in Figure 59.

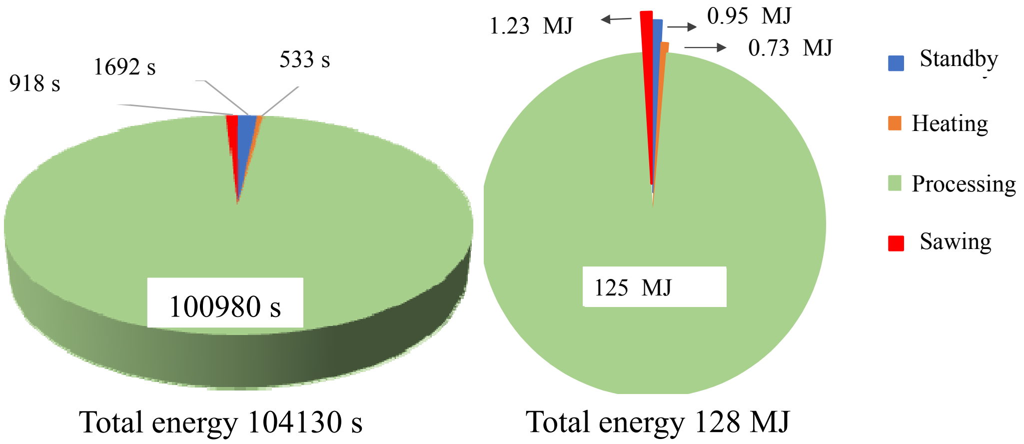


Figure 59. Total a) time [s], and b) energy, [MJ] of LAM respectively.

As it can is seen from the Figure 59 processing mode during LAM production consumed majority of time and energy. The processing mode (supports and main parts) accounted 125 MJ. The sawing mode had lower share of processing time (917 s) compared to the standby modes (1698 s), however, the average power value (1910 kW) during sawing was higher than values from the three standby modes (274, 685,492 W). As energy is resultant of time and power, E_{sawing} (1.23 MJ) was higher than the energy (0.98 MJ) from the three standby modes $E_{standby}$.

The four modes identified in LAM indicated different energy consumptions either as a result of time or power variance. The energy values analysed include consumption during standby, heating, processing and sawing modes. Table 10 illustrates the calculated average power, time and total energy consumptions of the different modes.

Table 10. Energy consumption in LAM.

Mode	Average power, P [W]	Time, t [s]	Energy, E [MJ]
Standby	562	1698	0.95
Heating	1380	530	0.73
Process	1237	100980	125
Sawing	1337	918	1.23

The energy consumptions in LAM were calculated using equation 7. Averages of the power values during each of the modes were used to determine the total energy usage. The energy used to saw the parts from the platform (1.23 MJ) was almost twice the combined energy used in heating the platform and for the three standby modes.

A theoretical estimation of individual energy consumptions were evaluated to approximately illustrate effects of combined build to individual builds.

The share of energy of the different test pieces as estimated in LAM are shown in Table 11.

Table 11. Energy consumption per number of part.

Sample number	**A**	**B**	**C**
Share of energy,[%]	18.0	61.3	20.7
Energy used /twice sample,[MW]	23.3	79.3	26.7
Energy used/one part,[MW]	11.6	39.7	13.4

The values in Table 11 were determined based on the estimated time and mass of parts using equation 8. Appendix V shows details of power, energy and time used in each of the modes in LAM.

7.3 Evaluation of energy and resource consumption

7.3.1 Evaluation of production time in CNC machining and LAM

An estimation of total manufacturing time in CNC machining shows that the number of parts produced directly determine total manufacturing time as parts are made separately with same energy and material consumptions. Table 12 represents approximated result of manufacturing time in CNC machining on assumption of each parts produced in same time.

Table 12. Estimated time of CNC machine based on batch size.

Number of parts	**Time taken / one part, [s]**	**Total time taken/ parts, [s]**
One	685	685
Two	685	1 370
Three	685	2 055
Six	685	4 110
Twelve	685	8 220

As it can be seen from Table 12, the total production time in CNC machining is dependent on the number of parts produced. The values in Table 12 are only predicted based on the actual cuts and do not include reference and trail cuts. It must be notified however that additional manufacturing time as result of either running reference cut or trail test could increase estimated time.

The time taken to build parts in LAM is not directly dependant on the number of parts produced. The ability to use one activities for several part (e.g. recoater movement to spread powder for all parts) reduces time usage in the production phase. Dispersing of powder was not dependent on the amount of parts build though time taken to scan parts was increased as more parts were built. Thus time increment could be as a result of the scanning of the different geometries. Table 13 illustrates the various estimated manufacturing time based on batch size in LAM.

Table 13. Estimated time of LAM based on batch size.

Number of parts	Building time, t [s]	Estimated time/part, t [s]
Twice sample A	44 400	22 200
Twice sample B	58 260	29 130
Twice sample C	46 500	23 250
Twice of each sample A, B and C	103104	17 184
Thrice each of sample A, B and C	130 140	14 460
Six pieces of each sample (half build)	233 580	12 976
12 pieces of each sample (full build)	444 960	12 360

From the experimental values (2 times of each sample), time taken (103104 s) to produces all six pieces indicated some difference as would have per sample. Time share was about 9540 s (2.65 h); 16452 s (4.57h) and 8064 s (2.24 h) lesser than estimated time if built individually for sample A, B and C respectively.

7.3.2 Comparison of CNC machining and LAM material flow chart

This comparison is based on the estimated and calculated values relating to material loss in both manufacturing processes. For instance in estimating the cutting fluid loss, only the amount of cutting oil was considered which necessarily does not include water usage. Also the exact amount of cutting fluid used during the sawing in LAM were only based on estimation and not measured This caution that not all mass losses in both processes were analysed in this thesis work.

CNC machining

The material inventorying in the CNC machining included raw material input and final part output. The cutting fluid used to aid cooling of spindle and sub spindle unit and for the smooth movement carriage axes of machine parts were also taken into account. The Figure 60 shows the resource and material flow chart in the CNC machining as measured in this thesis.

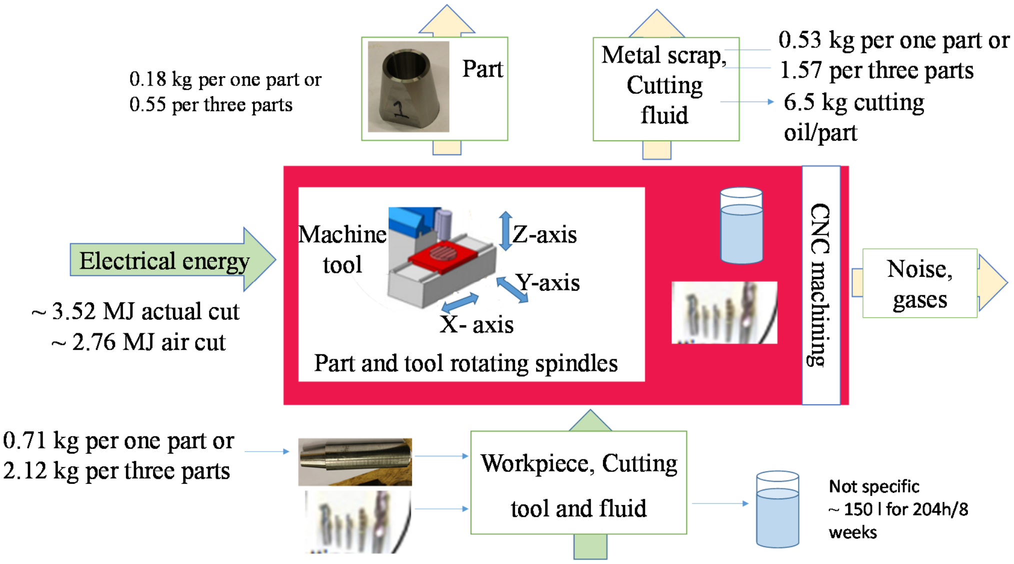


Figure 60. Representation of CNC machining material flow chart.

As it can be seen from the Figure 60, the energy and materials used in the CNC machining are summarized. The various machine tools (X, Y, Z, spindle motor and rotating tool) motors were responsible for about 3.52 MJ energy consumption. About 6.5 kg cutting oil/part was estimated for machining all three piece which means 1 part required 2.16 kg. The CNC machining was found to also generate substantial amount of unmeasured emissions like noise.

LAM

The material flow analysis of LAM considers all input and output powder and parts. The inventorying included final parts, supports structures, reusable powder, non-reusable and unaccounted powder that were mixed with cutting fluid. Figure 61 represents the material flow of LAM as recorded in this thesis.

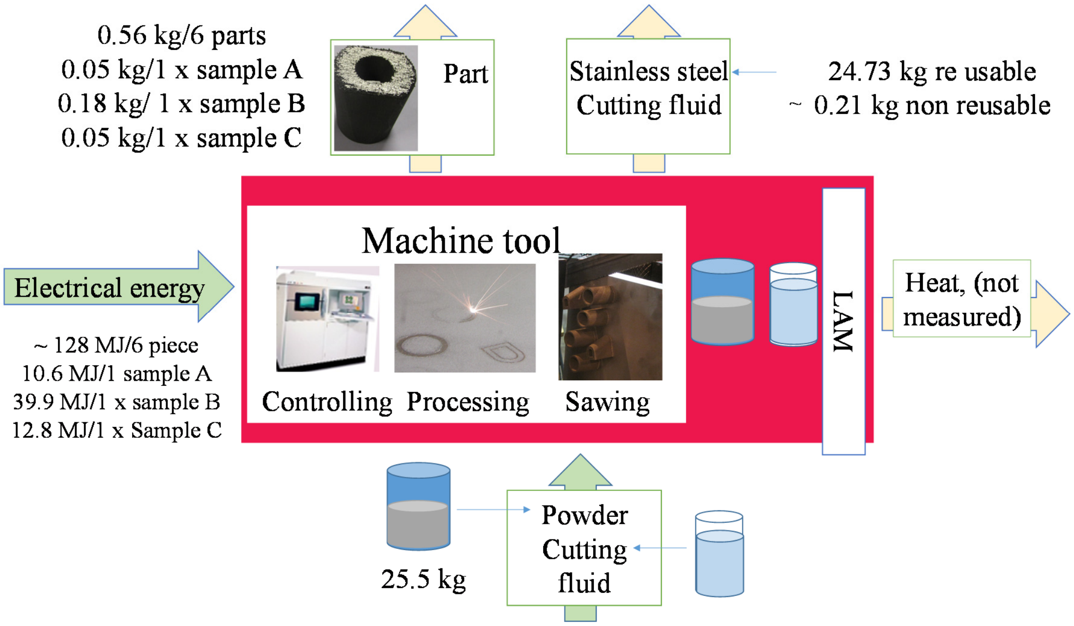


Figure 61. Representation of material flow chart in LAM.

As it can be seen from Figure 60 and 61 the energy consumptions (39.7 MJ/sample B) are high compared to energy consumptions (3.52 MJ/sample C) in CNC machining (see Figure 60). However, it can also be noticed from Figure 60 that, about 74.1 % of material input to CNC machining were lost with only 25.9 % used for final part. LAM highlights a higher material utilisation with only about 1.00 % waste of input material (see Figure 61). The material flow chart of LAM also indicates about 97 % reusability of powder which does not require any processing. The reduction of the weight of sample C (55 g) compared to the sample B (183 g) indicates raw material efficiency benefit as three-thirds of weight was eliminated. This issue is however limited to this thesis where weight of part did not play a role on functionality of parts.

7.3.3 Evaluation of SEC and energy consumption

SEC in LAM

The SEC was determined based on experimental values with mass of parts and energy consumptions in LAM (six parts). Also the SEC for the overall build set was determined based on values from the estimated platform utilisation results. Table 14 is an evaluation of SEC for LAM.

Table 14. Summary of SEC in LAM based on results of the empirical results.

Number of parts	**Six parts**	**Six parts**	**Six parts**	**Six parts**
SEC	60.1 [kWh/kg]	0.46 [kWh/cm^3]	216 [MJ/kg]	1.69 [MJ/cm^3]

The specific energy consumption during the combined built was 60.1 kWh/kg (216 MJ/kg) in LAM. This value fall within the SEC (201-241 MJ/kg) recorded by Baumers et al., 2012 and Mognol et al., 2006 (see table 1).

The SEC as estimated based on 1) quarter 2) half 3) full utilisation of the building platform in LAM analysed in Table 15. There was equal number of each sample placed on the platform during the planning stages. This was done so that SEC could be comparable as well as ease the tabulating of right amount of masses and volume placed. Table 15 shows the estimated SEC and the number of parts practicable in each variant.

Table 15. Representation of SEC in LAM based on estimated values (not empirically tested).

Planned platform utilisation	**SEC**	
Quarter (3 piece of each sample; 9 parts)	50.68 [kWh/kg]	0.40 [kWh/cm^3]
	184 [MJ/kg]	1.47 [MJ/cm^3]
Half (6 pieces of each sample; 18 parts)	45.3[kWh/kg]	0.36[kWh/cm^3]
	165[MJ/kg]	1.31[MJ/cm^3]
Full (12 pieces of each sample; 36 parts)	43.3[kWh/kg]	0.34[kWh/cm^3]
	156[MJ/kg]	1.25[MJ/cm^3]
Twice sample A only	161 [kWh/kg]	1.21[kWh/cm^3]
	579 [MJ/kg]	4.34[MJ/cm^3]
Twice sample B only	58.5[kWh/kg]	0.45 [kWh/cm^3]
	211[MJ/kg]	1.65 [MJ/cm^3]
Twice sample C only	140 [kWh/kg]	1.10 [kWh/cm^3]
	504 [MJ/kg]	3.95 [MJ/cm^3]

As Table 15 shows, SEC reduces as the number of parts increase in LAM. The equation 11 was used to determine the estimated values. The energy consumption is determined per number of parts placed on the platform as illustrated in Figures 35. This conforms to the study by (Baumers et al., 2011) which advised that energy consumption in AM processes were unique according to specific production and thus a generalisation of energy consumption must be resisted. However SEC in Tables 14 and15 (empirical value 216 MJ/kg and most of the estimated SEC values 156-579 MJ/kg) agree with SEC recorded in literature (see Table 1).

The SEC for the combined building reduces as number of parts built were increased as shown Figure 62.

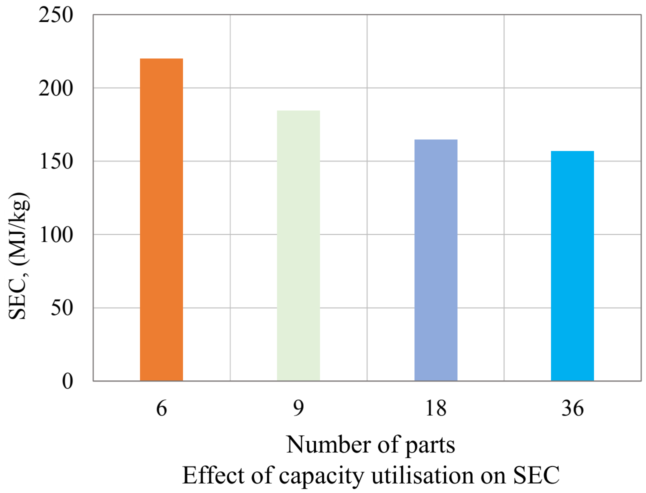


Figure 62. Effect of batch number on SEC in LAM.

As it can be noticed from Figure 62, the amount of parts in a build affect the specific energy consumption in LAM. This shows that an effective use of platform can result in lesser energy usage to deposit kilograms of material in LAM.

Rate of energy consumption in CNC machining and LAM

Evaluations of the effect of number of size on energy consumption in CNC machining and LAM are as shown Figure 63.

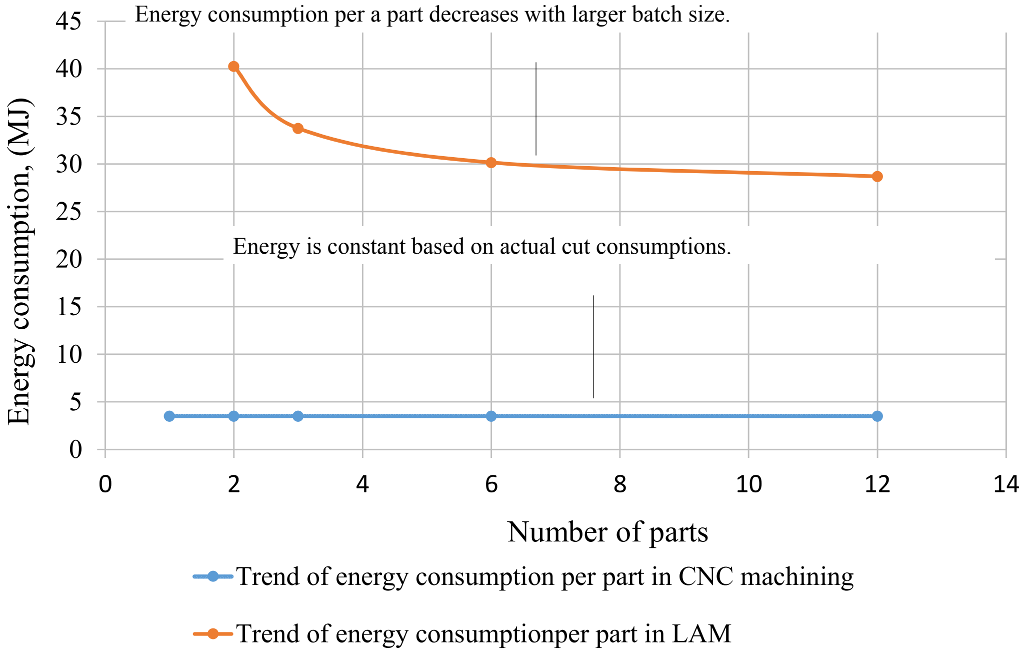


Figure 63. Energy consumption vs. batch size in CNC machining and LAM.

The comparison shown in Figure 63 is based on an assumption of producing only sample B with both processes. The energy consumption reduces in LAM per part as number of size is increased (orange line) whereas it remains constant with increased number of parts in CNC machining (blue line). The energy consumption of LAM correspond to energy required to build one part. However, the number of parts shows number of each sample in the build in CNC machining.

The energy consumption to produce one part was higher in LAM (39 MJ) than the consumption in CNC machining (3.52) for the comparable sample (B). However, this energy efficiency of CNC machining alone cannot compete effectively with LAM for energy efficiency advantage. This is because CNC machining had higher temporarily higher energy consumption values than LAM. As such complex and sophisticated electrical capacitors or electrical parts will be required to support the power peaks at the different processes during production. The cost of production could be assumed to be high in CNC machining in comparison to LAM as a result. The high power peaks entice high electricity bills and may also increase higher energy consumptions (Salminen, 2015; Kellens et al., 2013).). This issue however needs a further study.

With maximal capacity usage in LAM the energy consumption and SEC could be reduced as multiple parts are possible to build at a time (see Table 15). This affirms the results presented by Baumers et al. (2011). Also the possibility to manufacture hollow and net structure with LAM offer new opportunities to manufacturing freedom.

The difference in power values were also relatively smaller than the variance in power during the CNC machining. For instance, the power range in LAM was about 300 W to 2000 W while CNC machining ranged between 46.0 W and about 38000 W.

As it was required to make the empty and trial cut in the CNC machining experiment, the LAM did not include any such phase. There might be risk of unsuccessful parts in LAM as no trail test are done however seldom happen .As much the energy used for reference cut was used for the actual cut this confirms to the study by Diaz et al. (2011).

7.3.4 Analysis of CNC machining and LAM systems

An evaluation to compare systems of both CNC machining and LAM were made as presented in Table 16.

Table 16. System analysis of CNC machining and LAM.

Method	**CNC machining**	**LAM**
Form of raw material	Bar	Powder
% mass lost	74.1	1.00
Energy source	Electric powered (mechanical energy)	High power laser (thermal energy)
Process residues	Material chips, tools scrap cutting liquid	Material chips, heat, cutting liquid
Disposal of residue	Recycling, landfill	Reuse, recycling, landfill.

As it can be seen from Table 16 it can be argued that material utilisation [12]in LAM is about 79.0 % and 21.0 % in CNC machining. This shows approximately four times higher material utilisation in LAM compared to CNC machining. One dispute that may be raised with LAM is the initial amount of stainless powder used as input. This is because only about 2.65 % of

---

[12] Is a term used to express the difference between the weight of raw material used to produce a part and the weight of the finished part

the input material was used to build the final parts and support structures. As such it is necessary clarify that this was as the result of the size of the powder container in LAM system used in this thesis. There are variance in commercial LAM systems and powder containers differ. Thus start up powder may differ from system to system.

8 CONCLUSIONS AND SUMMARY

The aim of this thesis was to 1) Find the impact of LAM on environmental and economic aspects and 2) Conduct LCI analysis of LAM in comparison with CNC machining. The efficiency and effectiveness of both manufacturing process were assessed based on the amount of energy, input-output material as well as related emissions (solid and liquid) released into the atmosphere.

The literature review of this thesis introduced sustainable development and the factors that affect sustainability in manufacturing companies. During the literature review similar LCI studies were found to be based on a systematic methodology, UPLCI! CO2PE! Initiative, developed by Kellens et al. (2010). This tool gives a systematic guide to conduct LCI on discrete manufacturing in accordance with ISO 14044 and ISO 14040. The framework of this method was followed partially to conduct the inventorying in this thesis. This is because the needed data base for the collection and analysis of the unit process inventory was not applied in this thesis.

The review of the influence of both processes to the environment and economy were deliberated. The SEC in LAM as recorded by several comparative studies were analysed and some of the results were compared to outcome of this thesis. From the literature reviews studied it was identified that SEC of LAM of metals ranged between 107 and307 MJ/kg depending on the methodology and LAM system used.

Also as majority of the literature preferred CNC machining in terms of energy efficiencies. LAM was recommended for raw material effectiveness, manufacturing flexibility and agility. CNC machining was identified to consume as much energy however in air cutting as that required to perform actual cutting. Since the air cutting was mandatory in CNC machining, one may argue that large amount of energy are wasted in performing a reference cut in CNC machining.

Experinment tests were made using a 5 axis lathe (PUMA 2500Y) machining center to produce CNC- machined parts and a modified research version of EOS EOSINT M280 for LAM parts. The system boundary used for the experimental study in this thesis is as presented in Figure 64.

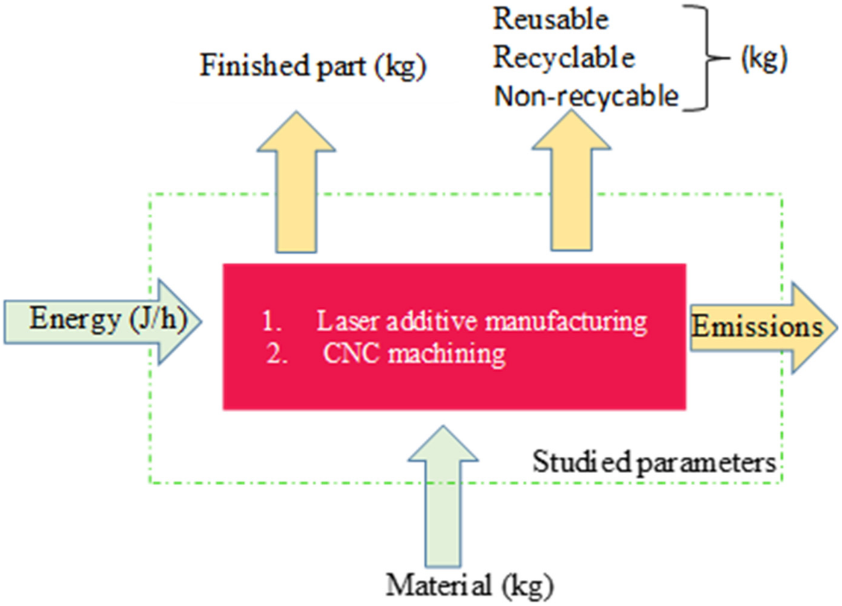


Figure 64. Representation of system boundary used for experimental study.

As it is can be seen from Figure 64 this thesis did not include any post process nor pre-processes for both manufacturing processes. Thus it did not consider any input or output to or from the techno sphere. Energy and material lost in removing parts from platform in LAM were however considered in the data inventorying.

Figure 65 illustrates the machine tools and levels of production considered for the LCI analysis as used in this thesis.

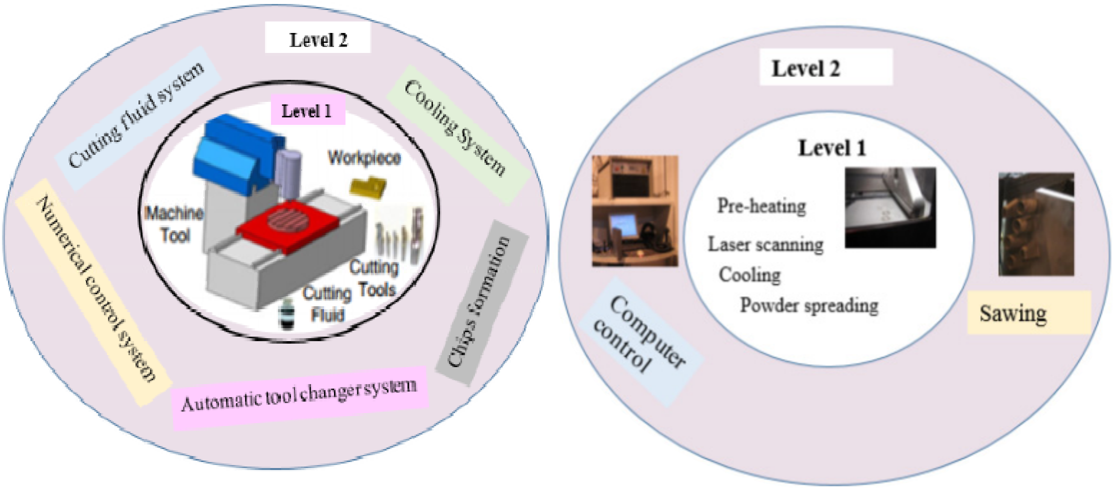


Figure 65. Representation of studied units in both machine tools.

As it can be seen from Figure 65, the different units studied in the machine tools of both CNC machining and LAM are illustrated. Data collection were planned for both primary (stage 1) and secondary (stage 2) levels in production phase. The machine tools studied in CNC machining was spindle motors and carriage (X, Y, and Z) axes motors whereas power monitoring in LAM consisted virtually of all machine tools during production phase. Machine tools considered in LAM were laser source, computer, heating unit, building chamber, scanners etc. The goal of the experiment was to measure the input-output material, energy and waste in CNC machining and LAM processes as well as highlight the most energy consuming units.

Three sample parts were designed to be manufactured with both processes. Figure 66 illustrates the designs of the sample used in this thesis.

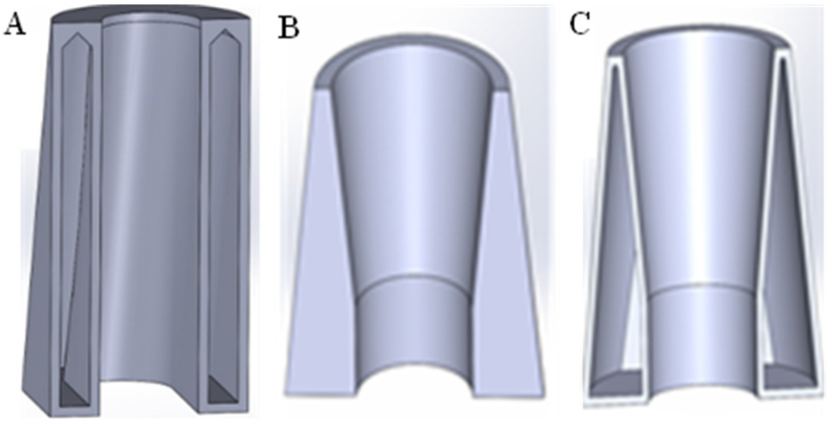


Figure 66. Presentation of samples used in thesis.

As it can be seen from Figure 66, samples were designed to have hollow and solid walls with varying shape of internal hole geometry. Only the sample with solid wall and circular internal shape (sample B) was planned to be made with CNC machining. This was due to limitation of CNC machining to complexity. All three sample built using LAM. The material used for the experimental study was 316L stainless steel (bar for CNC machining and powder for LAM).

After analyzing the inventory data, it was noticed that about 74.1 % of material input to CNC machining were lost with only 25.9 % used for the final parts. A higher material utilisation however was seen in LAM as generated waste was only about 1.00 %. This indicated a potential higher economic benefit of LAM in terms of cost of raw material as material utilisation was more efficient. This result confirmed the study by Fraunhofer ILT. (2013) and Dehoff et al. (2013).

The results of this thesis indicated that energy usage in LAM was increased by part complexity nor batch size. Energy used in LAM could not be assumed as sum of energy per part as total energy consumed per part with higher batch was lesser than energy per part with lower batch. The results of this thesis confirms the fact that a higher production size decreases energy consumption in LAM as several parts were possible with a combined build. CNC machining on the other hand required same amount of energy to produce each part separately even though the required energy were smaller than amount required in LAM to produce comparable part.

The energy required to produce one part of sample B with LAM processes was approximately about 10 times higher than the consumed quantity used in CNC machining. As about 3.52 MJ was used to machine one test piece with CNC machining LAM consumed about 39.9 MJ energy to make similar part. As such it may be energy inefficient to make sample B with LAM. Theoretical estimation of SEC in LAM (36 parts) was about 43.3 kWh/kg which was reduced in comparison to the recorded value for making six parts (60.1 kWh/kg). This value was only based on theoretical estimation however the reality may be vary as different production parameters and assumptions could apply. This issue needs further studies though as it is based on estimated value and may not reflect true consumption from LAM.

In terms of input-output material analysis CNC machining had higher waste output compared to the LAM. Raw material input to useful output ratio were low in CNC machining. As only about 183 g out of 707 g 316L stainless steel bar input was left as final part with about 524 g removed as waste. There were more waste related to CNC machining like cutting fluid and chips as well as other unmeasured emissions like noise.. In LAM, more than about 97.0 % (24.7 kg) of the unused material were reusable without any recycling or processing. This correlated to the study by Aliakbari (2012) which revealed that about 98 % of raw material were reusable in LAM. This highlight sustainability benefit in LAM as amount of SEC required to atomise powder may be reduced (Soukka, 2015). Potentially, raw material cost reduction are possible with LAM than CNC machining on production level when weight of parts are of importance. However, cost relating to raw material for production startup may favor CNC machining as extensive amount was required to begin LAM production in this thesis.

Another comparative assertion of both process is the ability to produce parts of reduced weight. The sample B weighed 183 g whereas the same geometry with hollow wall (sample C) weighed approximately 60.0 g, only about 24.7 % of their combined weights. Thus ability to reduce weight of parts using LAM can effect high energy saving during the use phase when used for dynamic application similar to case study of EOS (2014).

This thesis has demonstrated that both processes can offer effectiveness in manufacturing companies. The impact of the two processes studied were geared toward material, energy and possible emissions relating to selected levels on production.

LCI data on discrete manufacturing processes can be applied to achieve profitable selection of process that may highlight energy and raw material efficiency as well as efficacies of the manufacturing processes itself. This can affect positively to environmental and economic decision making processes. For instance even though the LAM showed only about 1.00 % of material waste, the manufacturing time (28.7 h) used for production was enormous hence a higher energy consumption. In this regards parts that are possible to be produced with CNC machining like sample B may offer a higher productivity with CNC machining than with LAM on production phase.

The main conclusions of this thesis is that LAM may offer four main advantages over CNC machining in manufacturing industry. The use of LAM may support:

1. Building of geometrically complex components,
2. Reduction of resource consumption,
3. Offer swift production,
4. Reduce production cost due to efficient use of raw material.

The adoption of LAM to build discrete parts may lead to reduction of resource consumption as well as elimination of emissions (eg noise, liquids) and operating cost (e.g. cutting tools) compared to CNC machining. Regardless these advantages of LAM higher energy consumption were identified with its usage compared to CNC machining on the production phase as shown in this thesis. However the results of this thesis does not reflect a full environmental benefit as couple of metrics: energy, time and raw material were studied within very narrow boundaries.

Main findings indicate that LAM might offer a higher efficiency in terms of raw material based on efficient material utilisation as shown in this thesis. Also LAM was found to be more flexible than CNC machining as almost any shape is possible to be built with it.

There was also much control of energy consumptions in LAM than could be effected in CNC machining as batch size could be increased to decrease energy consumption per part in LAM. As a result the SEC reduced in LAM as batch were estimated with higher numbers.

9 FURTHER RESEARCH

In this thesis a preliminary study of the energy and raw material consumption of the different machine tools in both manufacturing processes were investigated. The outcome of this thesis has shown the consumption rates of energy and raw material in CNC machining and LAM. However, selected energy consuming unit and levels within the production phases were studied. Thus taking further studies to include more border scope for LCI on in similar methodology may offer a better evaluation of energy and material consumptions. Advance studies can be done:

1. To investigate more subsystems of both processes in order to identify all energy consuming units,
    - Include smoothening of platform or post processing like heating or polishing,
    - Include all energy consuming unit in CNC machining e.g controlling computer.
2. To determine how and when to use LAM for maximum material and resource efficiency,
3. To include raw material production (bar and powder) phases,
4. To comprise production cost such as energy and raw material costs.

Also, because test samples were not designed with any functionality there was no consideration of practical issues that might be needed for comparison in relation to specific use. For instance parts designed for high pressure or forces application might require additional material or energy to include ribs that will improve strengths of hollow walled parts. This can be designed as part of future studies that will include practical use cases of parts.

Also from the results of the thesis, generated metal scrap generated from CNC machining can be used to improve circular economy as pure steel bar removed can be reprocessed and used for other AM processes like DED which does not require specific grain size of powder. These metal waste can be crashed into powder form without re-melting and recasting phases after removing cutting oil with water and alcohol. As such the amount of energy and bulk metal needed to produce powder by atomisation could be minimised.

REFERENCES

1. Bechmann, F., 2014. Head of Development, Concept Laser. 19.12.2014 2014. Interviewer 3DPI. [Web document]. [Accessed 18.11.2014]. Available at http://3dprintingindustry.com/2014/03/19/interview-dr-florian-bechmann-concept-laser/

2. 3trpd, 2014. Material Specification 316L Stainless Steel. [3trpd webpage]. [Accessed 18. 11. 2014] Available at http://www.3trpd.co.uk/wp-content/uploads/2013/03/316l-stainless-steel-2012.pdf

3. Aliakbari, M., 2012. Additive Manufacturing: State-of-the-art, Capabilities, and Sample Applications with Cost Analysis," Master's thesis, Royal Institute of Technology School of Industrial Engineering and Management.

4. Anon., 2011. CIMdata. [Web document]. [Accessed 5. 9. 2014]. Available at http://www.product-lifecycle-management.info/

5. ASM International, 2014. EOS expands 3D printing materials with Ti64ELI and Stainlesssteel 316L for medical devices. [ASM webpage]. [Accessed 18.11.2014]. Available at http://www.asminternational.org/web/hts/news/newswire/-/journal_content/56/10180/17897864/NEWS;jsessionid=3BEDB6B214D4918972580B15348790A0?p_p_id=webcontentresults_WAR_webcontentsearchportlet_INSTANCE_Dp9EatmyGsZu&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column-2&p_p_col_pos=2&p_p_col_count=3

6. Avram, O., Stroud, I. and Xirouchakis, P., 2011. A multi-criteria decision method for sustainability assessment of the use phase of machine tool systems. International Journal of Advanced Manufacturing Technology, 53:5-8. Pp. 811-828.

7. Batterham, R. J., 2003. Ten Years of Sustainability: Where do we go from here? Institution of Chemical Engineers, 58. Pp. 2167 – 2179.

8. Baumers, M., Tuck, C., Wildman, R., Ashcroft, I. and Hague, R., 2011, Energy inputs to additive manufacturing does capacity utilisation matter, Proceedings of the 23rd Solid Freeform Fabrication (SFF) Symposium, August 2011, Texas, USA, pp. 30-40.

9. Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Rosamond, E., Hague, R., 2012. Combined Build–Time, Energy Consumption and Cost Estimation for Direct Metal Laser Sintering, Proceedings of the Solid Freeform Fabrication (SFF) Symposium. The University of Texas at Austin.

10. Bourhis, L.F., Kerbrat, O., Hascoet, J.-Y., and Mognol, P., 2013, Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing, International Journal of Advance Manufacturing Technology, 69. Pp. 1927–1939.

11. Chopra, S. and Meindl, P., 2010. Supply Chain Management: Strategy, Planning and Operation, 4th Edition, Pearson, Boston.

12. Cohen, D., Sargeant, M., and Somers, K., 2014. 3-D printing takes shape. [McKinsey & Company webpage]. [Accessed 15.09.2014] Available at http://www.mckinsey.com/insights/manufacturing/3-d_printing_takes_shape

13. Conserve Energy Future, 2015. Current Environmental Issues. [Web document]. [Accessed 19.2.2015]. Available at http://www.conserve-energy-future.com/current-environmental-issues.php

14. Diaz, N., Redelsheimer, E., and Dornfeld, D., 2011. Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Hesselbach, J. and Herrmann, C., (Ed.), Springer. Pp. 263-267.

15. Dahmus, J. B., and Gutowski, T.G., 2004. An environmental analysis of machining, Proceedings of IMECE, Anaheim, California, USA.

16. Dehoff, R, 2013. Materials for aerospace. Advanced Materials and Processes, 171: 3. Pp. 15-27.

17. Deloitte Development LLC, 2010. Sustainability in business today: A cross-industry view. [Web document]. [Accessed 12. 11. 2014] Available at http://www.deloitte.com/assets/Dcom-Korea/Local%20Assets/Documents/Green/2011/kr_Green_Sustainability_in_business_today_20110121.pdf

18. Drizo, A., and Pegna, J., 2006. Environmental impacts of rapid prototyping: an overview of research to date. Rapid prototyping journal, 12:12. Pp. 64-71.

19. Duflou, J. R., Kellens, K. and Dewulf, W., 2011. Unit process impact assessment for discrete part manufacturing: A state of art. CIRP Journal of Manufacturing Science and Technology, 4:2. Pp. 129-135.

20. Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann,C., Jeswiet, J., Kara, S., Hauschild, M., and Kellens, K., 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals. Manufacturing Technology, 61:2. Pp. 587- 609.

21. Eaton, 2014. [Web document]. [Accessed 25. 09. 2014] Available at http://energy.gov/sites/prod/files/2014/03/f12/webinarslides_additive_manufacturing_021114.pdf

22. EC, 2010. [European Commission website]. [Accessed 9. 10. 2014]. Available at http://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Final_energy_consumption,_EU-

27,_2007_(1)_(%25_of_total,_based_on_tonnes_of_oil_equivalent).PNG&oldid=25774

23. EC, 2011. [European Commission website]. [Accessed 9. 10. 2014]. Available at http://ec.europa.eu/energy/observatory/countries/doc/key_figures.pdf

24. EC, 2014a. [European Commission web site]. Updated October 7, 2014. [Accessed 25. 09. 2014] Available at http://ec.europa.eu/eurostat/statistics-explained/index.php/Russia-EU_-_basic_statistical_indicators

25. EC, 2014b. European Commission. Climate action. [EC website]. [Accessed 9. 10. 2014]. Available at http://ec.europa.eu/clima/policies/ets/index_en.htm

26. EOS, 2014. [EOS webpage]. [Accessed 7. 10. 2014] Available at http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study

27. EPA, 2015. Risk Management Sustainable Technology, Life Cycle Assessment. [United States Environmental Agency website]. Updated May 8, 2014. [Accessed 19.2.2015]. Available at http://www.epa.gov/nrmrl/std/lca/lca.html

28. European Union, 2014. EU energy in figures. ISBN 978-92-79-29317-7.

29. FEDCO, 2014. [FEDCO webpage]. [Accessed 17. 03. 2015] Available at http://fedco-usa.com/?q=seclcc

30. Fraunhofer ILT, 2013. Digital Photonic Production, Fraunhofer Institute of Laser Technology ILT [Web document] [Accessed 22. 10. 2014] Available at http://www.ilt.fraunhofer.de/content/dam/ilt/en/documents/product_and_services/Brochure_Digital_Photonic_Production. Pdf

31. Gasser, A., Backes, G., Kelbassa, I., Weisheit, A. and Wissenbach, K., 2010. Laser Additive Manufacturing: Laser Metal Deposition (LMD) and Selective Laser Melting (SLM) in Turbo-Engine Applications. Laser Technik Journal, 7:2. Pp. 58-63.

32. Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N. and Noble, I., 2013. Sustainable development goals for people and planet. NATURE, Macmillan Publishers Limited, 495. Pp. 305-307.

33. Guinee, J. B., 2002. Handbook on life cycle assessment - operational guide to the ISO standards. The International Journal of Life Cycle Assessment, 6:5. Pp. 311-313.

34. Gunasekaran, A. and Spalanzani, A., 2012. Sustainability of manufacturing and services: Investigations for research and applications. Internal Journal of production Economics, 140:1 Pp. 35-47.

35. Gutowski, T., Dahmus, J. and Thiriez, A., 2006. Electrical Energy Requirements for Manufacturing Processes. Proceedings of 13th CIRP International Conference on Life Cycle Engineering, 3.05-2.06.2006. Leuven, Belgium.

36. Huang S.-H., Liu, P., Mokasdar, A. and Hou, L., 2012. Additive manufacturing and its societal impact: A literature review. Int Journal of Advance Manufacturing Technology, 6:5-8. Pp. 1191-1203.

37. IGBP, 2013, Sustainable development goals for people and planet. [IGBP webpage]. [Accessed 17. 11. 2014] Available at http://www.igbp.net/news/news/news/sustainabledevelopmentgoalsforpeopleandplanet.5.561163a13d60576e12c4.html

38. Iogen Corporation, 2014.The world needs better soultions. [Iogen webpage]. [Accessed 11. 03. 2015] Available at http://www.iogen.ca/energy-future/index.html

39. Kalla, D., Twomey, J. and Overcash, M., 2010. MR 1 Drilling Process-Unit Process Life Cycle Inventory. [Web document]. [Accessed 19. 12. 2014] Available at http://link.springer.com/content/esm/art:10.1007/s11367-011-0352-0/file/MediaObjects/11367_2011_352_MOESM2_ESM.pdf

40. Kellens, K., Dewulf, W., Deprez, W., Yasa, E., and Duflou, J., 2010a. Environmental analysis of SLM and SLS manufacturing processes. Proceedings of LCE2010 Conference. Hefei, China, 19 - 21.05.2010, pp. 423-428.

41. Kellens, K., Yasa, E., Dewulf, W., Duflou, J., 2010b. Environmental Assessment of Selective Laser Melting and Selective Laser Sintering. Going Green CARE INNOVATION 2010. Vienna, Austria, 8.11.11.2010.

42. Kellens, K., Dewulf, W., Overcash, M., Hauchild, Z M., and Duflou, J. R., 2012a. Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI)-CO_2PE! Initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. International Journal Life Cycle Assessment, 17:1.Pp. 69–78.

43. Kellens, K., Dewulf, W., Overcash, M., Hauchild, Z M., and Duflou, J. R., 2012b. Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) - CO_2PE! Initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies. International Journal of Life Cycle Assessment, 17:2. Pp. 242–251.

44. Kellens, K., Dewulf, W., Lauwers,B., Kruth, J-P., and Duflou, J.R., 2013. Environmental Impact Reduction in Discrete Manufacturing: Examples for Non-Conventional Processes. Procedia CIRP, 6. Pp.27-34

45. Kim, K., Song, I., Kim, J., Jeong, B., 2006. Supply planning model for remanufacturing system in reverse logistics environment. Computers and Industrial Engineering, 51:2, 279–287.

46. Klocke, F., Klink, A., Veselovac, D., Aspinwall, D. K, Soo, S. L, Schmidt, M., Schilp, J., Levy, G. and Kruth, J-P.2014.Turbomachinery component manufacture by application of application of electrochemical, electro-physical and photonic processes. CIRP Annals - Manufacturing Technology, 63:2. Pp. 703-726.

47. Lee, M., 2011. Servitisation and the Future of Manufacturing: The power to help you succeed. [Barclays Corporate webpage]. [Accessed 5.09.2014] Available at http://www.cambridgeservicealliance.org/uploads/downloadfiles/2011-Neely-ServitizationAndTheFutureOfManufacturing.pdf

48. Lindemann, C., Jahnke, U., Moi, M. and Koch, R., 2013. Impact and Influence Factors of Additive Manufacturing on Product Lifecycle Costs. Direct Manufacturing Research Center (DMRC) and Chair of Computer Application, Paderborn, Germany, pp. 998-1008.

49. Luo, Y., Ji, Z., Leu, M. C., and Caudill, R., 1999. Environmental Performance Analysis of Solid Freedom Fabrication Processes, Proc. of the IEEE International Symposium on Electronics and the Environment, pp. 1-6.

50. Manyika, J., Sinclair, J., Dobbs, R., Strube, G., Rassey, L., Mischke, J., Remes, J., Roxburgh, C., George, K., O'Halloran, D. and, Ramaswamy, S., 2012. Manufacturing the future: the next era of global growth and innovation. [McKinsey & Company webpage]. [Accessed 15.09.2014] Available at http://www.mckinsey.com/insights/manufacturing/the_future_of_manufacturing

51. Jancovici, M-J., 2013. How do greenhouse gas emissions presently evolved? [Web document]. [Accessed 12.03.2015] Available at http://www.manicore.com/anglais/documentation_a/greenhouse/evolution.html

52. Mentzer, J., DeWitt, W., Keebler, J., Min, S., Nix, N., Smith, C. and Zacharia, Z., 2001. Defining supply chain management, Journal of Business Logistics, 22:2. Pp. 1-24.

53. Mognol, P., Lepicart, D., and Perry, N, 2006. Rapid prototyping: energy and environment in the spotlight. Rapid Prototyping Journal, 12:1. Pp. 26–34.

54. Morgan, J., 2013. Amaze project aims to take 3D printing 'into metal age' [BBC news webpage].[Accessed 15.09.2014] Available at http://www.bbc.com/news/science-environment-24528306

55. Morrow, W. R., Qi, H., Kim, I., Mazumder, J.and Skerlos, S.J 2007. Environmental Aspects of Laser-Based and Conventional Tool and Die Manufacturing. Journal of Cleaner Production, 15:10, pp. 932-943.

56. Neely, A., 2008. Exploring the financial consequences of the servitisation of manufacturing, Operations Management Research, 1:2. Pp.103-118.

57. Nyrhilä, O., Directing manager, EOS Finland. [Interview] (23.04. 2014).

58. Nyman, H. J. & Sarlin, P., 2013, 'From Bits to Atoms: 3D Printing in the Context of Supply Chain Strategies' CoRR abs/1306.4512.

59. Ogaldez, J., Barker, A., Zhao, F. and Sutherland, J.-W., 2012. Water Footprint Quantification of Machining Processes. Leveraging Technology for a Sustainable World. Proceedings of the 19th CIRP Conference on Life Cycle Engineering, 23.-25.05.2012. Berkeley, USA, Springer-Verlag Berlin Heidelberg, pp. 461-466.

60. Olakunle, A. 2010, Impact of Manufacturing Capacity Utilization on the Economy of Nigeria, an Empirical Analysis. [Web document]. [Accessed 27.10.2014]. Undergraduate thesis. 6 p. + appendixes 2 p. Available at http://www.academia.edu/1762422/The_Impact_of_Manufacturing_Capacity_Utilization_on_the_Economy_of_Nigeria_An_Empirical_Analysis
61. Perumal, H., 2006. Improving the supply Chain in your Company. International Institute of Management.

62. Piili, H., Widmaier, T., Happonen, A., Juhanko, J., Salminen, A., Kuosmanen, P., and Nyrhilä, O., 2013. Digital design process and additive manufacturing of a configurable product, Advanced Science Letters, 19:3. American Scientific Publishers.

63. Pirnes, J., 2006, Automaatiseen mittaus-ja säätöjärjestelmään liityvän laiteympäriston rakentaminen NC-sorville, Master Thesis, Lapeenranta University of Technology, Mechanial Department.

64. Ratava, J., 2014. CNC machining power equation. [Discussion]. (19.12.2014).

65. Reeves, P., 2014. Additive manufacturing a supply chain wide response to economic uncertainty and environmental sustainability.

66. Rickenbacher, L., Spierings, A., Wegener, K., 2013. An integrated cost-model for selective laser melting (SLM). Rapid Prototyping Journal, 19:3. Pp.208-214.

67. Ruffo, M. and Hague, J.R.M., 2007. Cost estimation for rapid manufacturing – simultaneous production of mixed components using laser sintering, Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture, 221:11. Pp. 1585-1591.

68. Salminen, A., 2015. Cost of energy in production [Interview] (20.01. 2015).

69. Salminen, A., 2014. Material consumption in Laser additive manufacturing [Interview] (05.05. 2014).

70. Siemens AG, 2007. Power meter SENTRON PAC3200 manual [web document]. [Accessed 27.1.2015]. Available at http://w3.usa.siemens.com/us/internet-dms/btlv/access/access/Docs/SENTRON_pac3200_manual_ul_PSC_en.pdf

71. Selesvuo, J., 2014. Life time cutting fluid in CNC machining cnter. [Email]. [19.12.2014]. Jari.Selesvuo@lut.fi 19 December, 2014

72. Sikdar, K. S., 2003. Sustainability Development and Sustainability Metrics, AIChE Journal, 49:8, pp. 1928-1932

73. Soukka, R., 2015. SEC in metal atomisation. [Discussion]. (28.01. 2015).

74. Sreenivasan, R. and Bourell, D. L., 2009. Sustainability Study in Selective Laser Sintering-an energy perspective, Proceedings of the 20th International Solid FreeForm Fabrication (SFF) Symposium, August 2009. Texas, USA, pp. 257-265.

75. Statistics Finland, 2008. Statistics Finland. [Web document]. [Accessed 2.10. 2014]. Available at http://www.stat.fi/til/ekul/2007/ekul_2007_2008-12-12_kuv_009_en.html

76. Earthshift Inc., 2014. Eco-indicator 99. [Webpage document]. [Accessed 16. 03. 2015]. Available at http://www.earthshift.com/software/simapro/eco99

77. UN, 2014. Secretary-General welcomes joint announcement by China and US on action on climate change. [UN webpage]. [Accessed 20. 10. 2014]. Available at http://www.un.org/climatechange/blog/2014/11/secretary-general-welcomes-joint-announcement-china-us-action-climate-change/

78. UNEP, 2011. Resource Efficiency: Economics and Outlook for Asia and the Pacific. [UNEP webpage]. [Accessed 12. 11. 2014]. Available at http://www.unep.org/dewa/Portals/67/pdf/Resource_Efficiency_EOAP_web.pdf

79. U.S. Department of Energy, 2014. Energy efficiency and renewable energy. [Web document]. [Accessed 20. 10. 2014]. Available at http:// http://energy.gov/sites/prod/files/2014/03/f12/webinarslides_additive_manufacturing_021114.pdf

80. WCED. (Ed.). 1987. Our common future: World Commission on Environment and Development. Oxford, UK: Oxford University Press, 1987, p. 47.

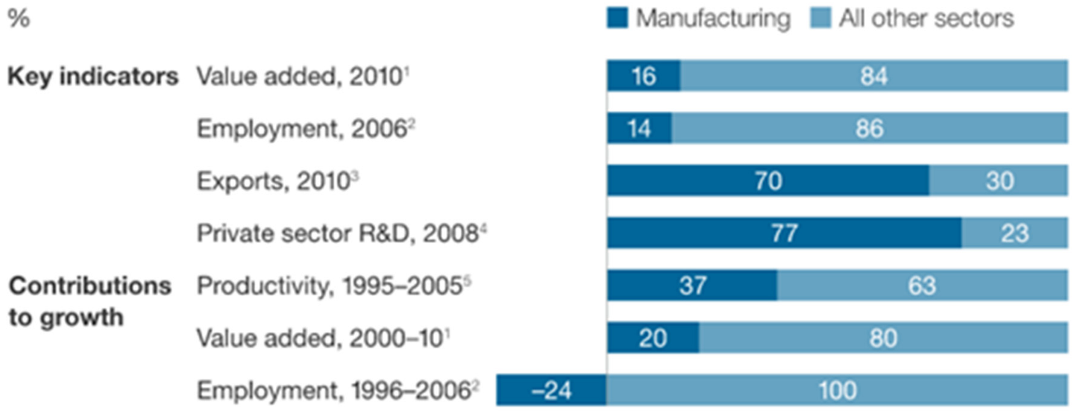
81. Yoon, H-S. Lee, J-Y., Kim, H-S., Kim, M-S., Kim, E-S., Shin, Y-J., Chu, W-S., and Ahn, S-H., 2014. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. International Journal of Precision Engineering and Manufacturing-Green Technology, 1:3. Pp. 261-279.

APPENDICES

Appendix I	Representation of Contribution of manufacturing on GDP.
Appendix II	Representation of UPLCI! CO2PE! Initiative frame work and system boundary unit identification.
Appendix III	Representation of PUMA 2500Y specifications.
Appendix IV	Power, time, energy, mass and volume of material results in CNC machining.
Appendix V	Power, time, energy, mass and volume of material results in LAM.

Represntation of Contribution of manufacturing on GDP

anufacturing contributes disproportionately to exports, innovation, and productivity growth.



[1] Based on manufacturing GDP as share of global GDP.

[2] 2006 data for advanced economies based on sample of United States, Japan, and EU-15; employment-growth contribution calculated for 1996–2006 period.

[3] Sample of 28 advanced economies (EU-15 plus Australia, Canada, Czech Republic, Hong Kong, Israel, Japan, Norway, Singapore, Slovakia, South Korea, Switzerland, Taiwan, and United States) and 8 developing ones (Brazil, China, India, Indonesia, Mexico, Russia, Thailand, and Turkey).

[4] 2008 average of manufacturing share of business R&D spending in Germany and South Korea (89%), Japan and China (87%), Mexico (69%), and United States (67%).

[5] Manufacturing share of productivity growth in EU-15 for 1995–2005 period.

Source: Analytical Business Enterprise Research and Development Database (ANBERD) and Structural Analysis Database (STAN), Organisation for Economic Co-operation and Development (OECD); EU KLEMS; Eurostat; IHS Global Insight; World Bank; McKinsey Global Institute analysis

Figure 1. Illustration of manufacturing sector contribution in the GDP of nations (Manyika et al., 2012)

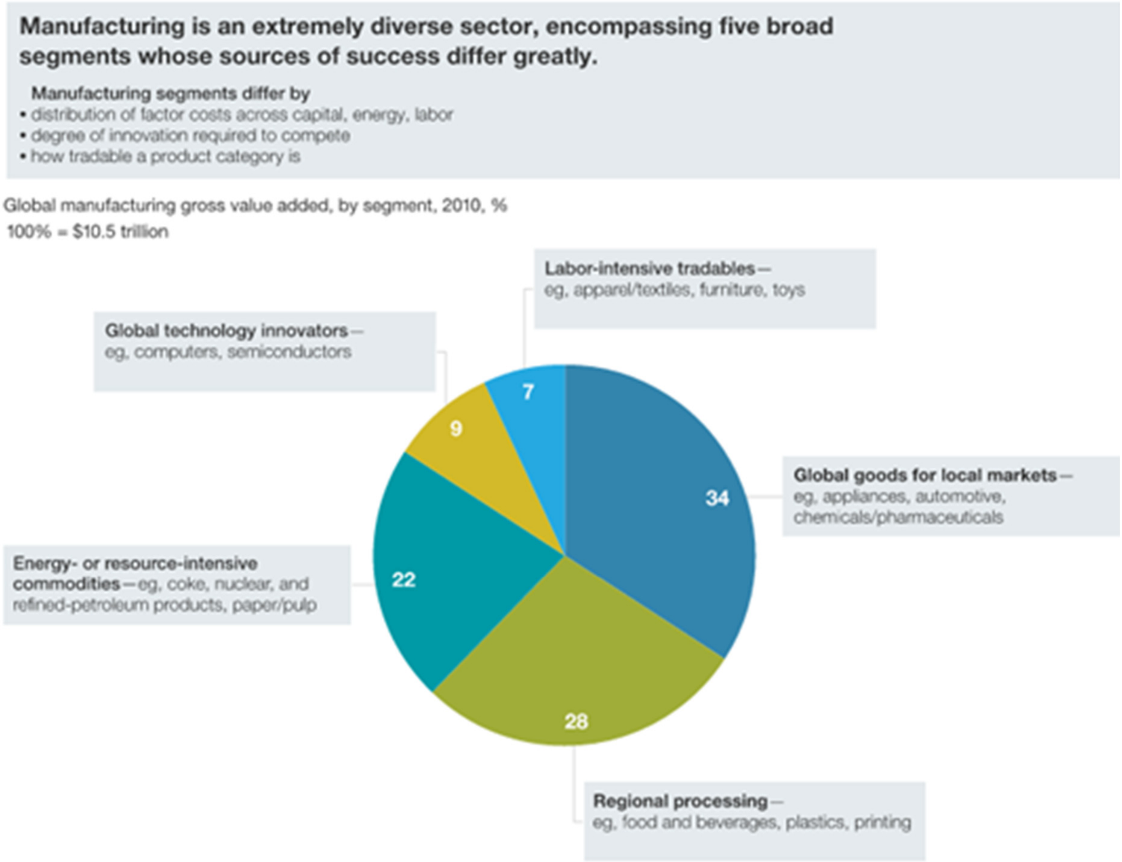


Figure 2. Representation of different sectors of manufactory industry.

Represntation of UPLCI! CO2PE! Inititaitive frame work and system boundary unit identification.

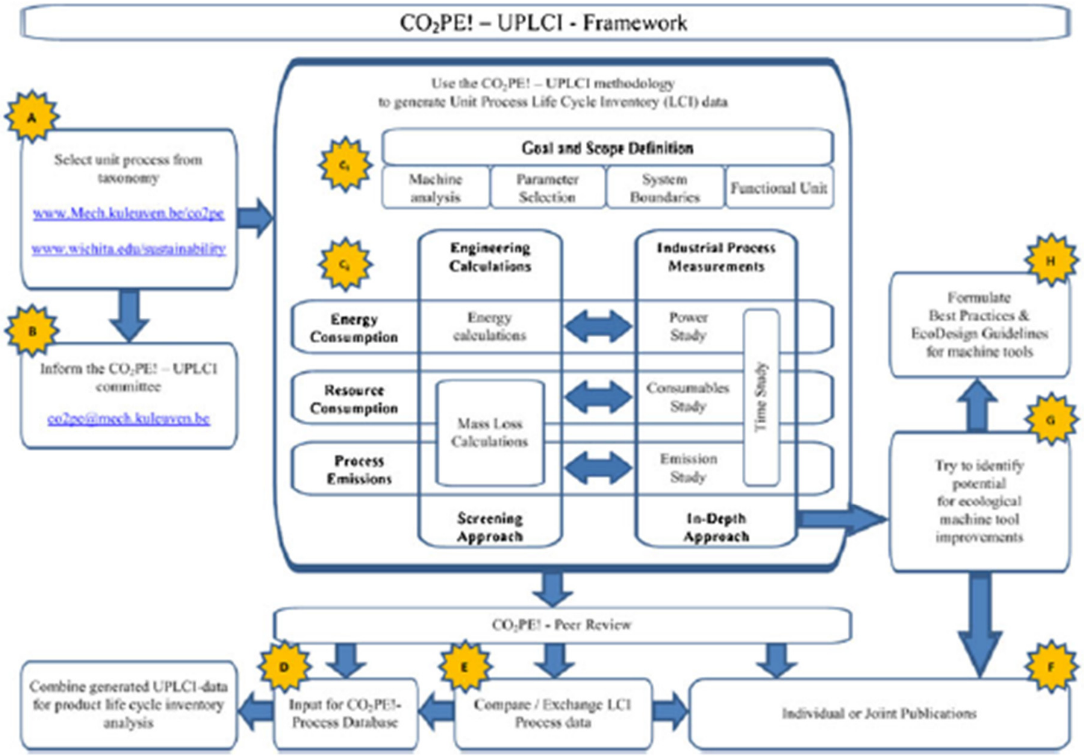


Figure 1. Overview of CO$_2$PE! UPLCI! Main steps (Kellens et al., 2012a).

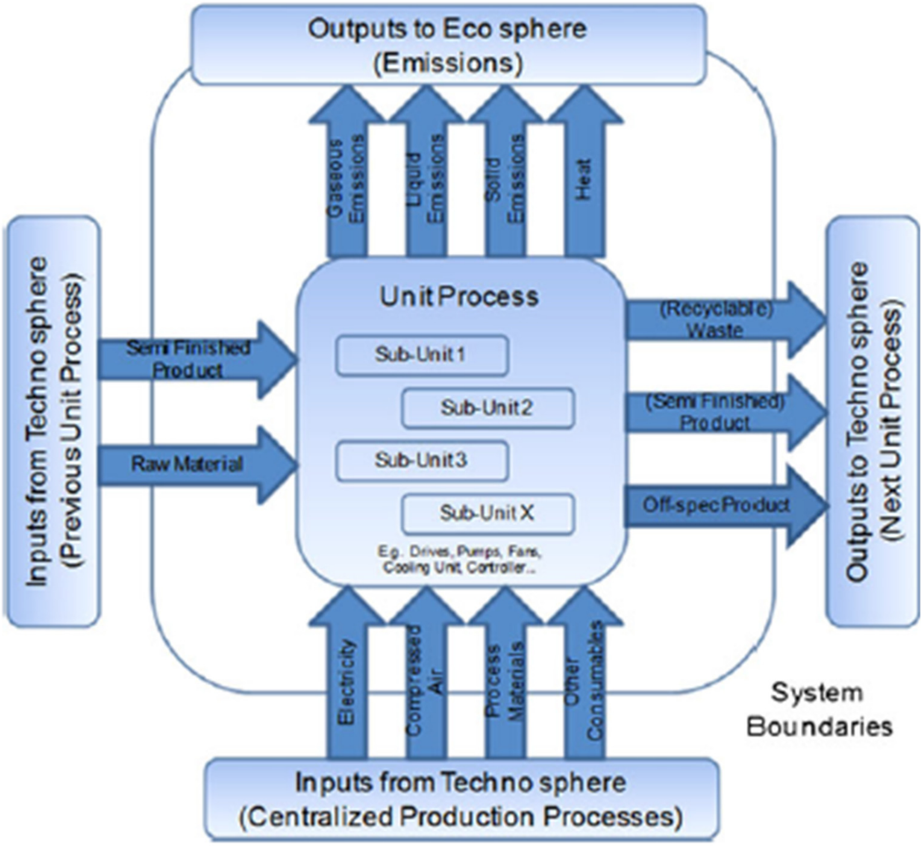


Figure 2. Overview of unit process selection (Kellens et al., 2010a and 2012a).

Represntation of PUMA 2500Y specifications.

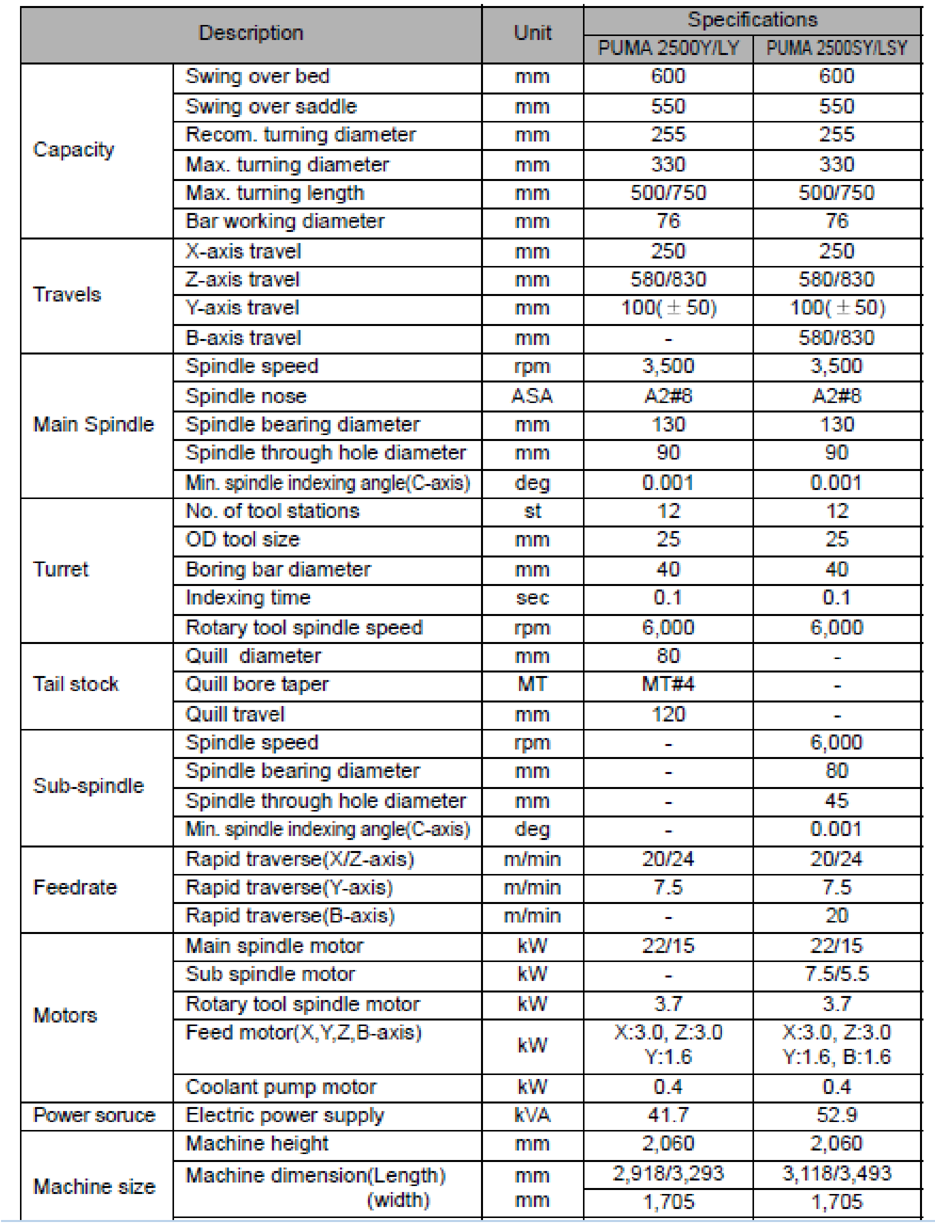
DAEWOO PUMA 2500Y
CNC-Lathe

Machine specificatios:

- Main spindle motor: 15/22 kW
- Integrated spindle: 50-3500 rpm
- Max. Torque: 433 Nm
- Tool revolver: 12 tools
- Rotary tools:
  - Power: 7.5 kW
- Max. turning length : 500 mm
- Max. turning diameter: 330mm
- Y-axis travel: +- 50 mm
- C-axis
- Programmable tail stock
- Control: Fanuc 18iTB

- Automatic tool measurement system
- Devices for robot connection

Figure 1. Representation of PUMA 2500Y lathe machine with main specifications.



Description		Unit	Specifications	
			PUMA 2500Y/LY	PUMA 2500SY/LSY
Capacity	Swing over bed	mm	600	600
	Swing over saddle	mm	550	550
	Recom. turning diameter	mm	255	255
	Max. turning diameter	mm	330	330
	Max. turning length	mm	500/750	500/750
	Bar working diameter	mm	76	76
Travels	X-axis travel	mm	250	250
	Z-axis travel	mm	580/830	580/830
	Y-axis travel	mm	100(±50)	100(±50)
	B-axis travel	mm	-	580/830
Main Spindle	Spindle speed	rpm	3,500	3,500
	Spindle nose	ASA	A2#8	A2#8
	Spindle bearing diameter	mm	130	130
	Spindle through hole diameter	mm	90	90
	Min. spindle indexing angle(C-axis)	deg	0.001	0.001
Turret	No. of tool stations	st	12	12
	OD tool size	mm	25	25
	Boring bar diameter	mm	40	40
	Indexing time	sec	0.1	0.1
	Rotary tool spindle speed	rpm	6,000	6,000
Tail stock	Quill diameter	mm	80	-
	Quill bore taper	MT	MT#4	-
	Quill travel	mm	120	-
Sub-spindle	Spindle speed	rpm	-	6,000
	Spindle bearing diameter	mm	-	80
	Spindle through hole diameter	mm	-	45
	Min. spindle indexing angle(C-axis)	deg	-	0.001
Feedrate	Rapid traverse(X/Z-axis)	m/min	20/24	20/24
	Rapid traverse(Y-axis)	m/min	7.5	7.5
	Rapid traverse(B-axis)	m/min	-	20
Motors	Main spindle motor	kW	22/15	22/15
	Sub spindle motor	kW	-	7.5/5.5
	Rotary tool spindle motor	kW	3.7	3.7
	Feed motor(X,Y,Z,B-axis)	kW	X:3.0, Z:3.0 Y:1.6	X:3.0, Z:3.0 Y:1.6, B:1.6
	Coolant pump motor	kW	0.4	0.4
Power soruce	Electric power supply	kVA	41.7	52.9
Machine size	Machine height	mm	2,060	2,060
	Machine dimension(Length)	mm	2,918/3,293	3,118/3,493
	(width)	mm	1,705	1,705

Figure 2. Representation of machining specification of PUMA 2500Y lathe machine.

Power, time, energy, mass and volume results in CNC machining.

Power, time and energy results of CNC machining. The average power in each process was multiplied by time taken to get total energy using equation 6.

The values of total power were calculated by the method from each process. The first step was to determine the various power consumptions during the reference cut (CNC machining):

Table 1. Results of energy calculations in CNC machining based on reference cut.

Process	Average power, P_{avg} [kW]	Time, $t_{process}$ [s]	Energy, E [MJ]
Outside turning	6.93	82	0.57
Drilling	6.31	11	0.12
Inside turning	5.64	104	0.57
Milling	2.58	467	1.20
Cutting	19.39	11	0.21
Tool change	18.5	5	0.09
Total		680	2.76

After that the values for all test piece numbers (1, 2, and 3) obtained were used to calculate energy. The lubrication system motor power was included to these energy as cooling and lubrication were activated. These values were calculated with help of Excel and they are represented in Table 2, 3 and 4.

Table 2. Results of energy calculations based on test piece number one.

Process	Average power, P_{avg} [kW]	Time, $t_{process}$ [s]	Energy, E [MJ]
Outside turning	8.70	82.0	0.71
Drilling	6.89	19.0	0.13
Inside turning	6.92	101	0.70
Milling	3.05	477	1.45
Cutting	16.6	11.0	0.18
Tool change	14.7	5.00	0.07
Total	56.86	695	3.24

Table 3. **Results of energy calculations based on test piece number two**

Process	Average power, P_{avg} [kW]	Time, $t_{process}$ [s]	Energy, E [MJ]
Outside turning	8.52	82.0	0.71
Drilling	6.61	19.0	0.13
Inside turning	7.08	95.0	0.68
Milling	3.04	477	1.45
Cutting	16.6	11.0	0.18
Tool change	21.4	5.00	0.12
Total		690	3.27

Table 4. **Results of energy calculations based on test piece number three.**

Process	Average power, P_{avg} [kW]	Time, $t_{process}$ [s]	Energy, E [MJ]
Outside turning	8.51	82.0	0.71
Drilling	6.64	19.0	0.13
Inside turning	7.11	95.0	0.70
Milling	3.13	476	1.45
Cutting	16.8	11.0	0.18
Tool change	21.4	5.00	0.12
Total		688	3.29

Equations 9 and 10 were used to calculate the volume and mass of removed material. These values were also verified with CAD model in SolidWorks. The density of the 316L stainless steel is 0.008 kg/cm^3. The energy estimation is only based on summation of actual cut and does not include energy usage during the reference cut.

Table 5. Results of mass and volume calculations.

Number of parts	One	Two	Three
Input volume, v_{input} [cm^3]	88.4	177	265
Input mass, m_{input}[kg]	0.71	1.41	2.12
mass removed, $m_{removed}$ [kg]	0.52	1.05	1.57
Energy, E [MJ]	3.52	7.04	10.6

Power, time, energy, mass and volume results in LAM.

The standby power represent activities as preparation before starting processing, idling time to create right atmosphere as well as other work done after scanning ended like removing and cleaning. The processing mode includes (Laser, recoater, and platform movements). Averages of recorded power were estimated and multiplied by each mode time to get the energy (E_{LAM}) values with the help of excel using equation 7.

Table 1. Results of energy calculations based on the different modes.

Mode	Avg. Power, P [W]	Time, t [s]	Energy, E [MJ]
Standby (starting the process)	274	400	0.11
Standby (idling inert atmosphere	685	1030	0.71
Standby (removing and cleaning)	492	260	0.13
Heating	1380	530	0.73
Process	1237	100980	194
Sawing	1910	918	1.23

The mass of the estimated platform utilisation were also determined as per number of parts placed on the platform. The deposited mass were estimated based on the volume assumption as given by LAM system. These values were multiplied by the density of 316L stainless steel (0.008 kg/cm^3) to get the mass deposited (m_d).

Table 2. Results of mass and volume calculations.

Number of parts	Volume, $v_{deposited}$ [cm^3]	Mass deposited, m_d [kg]	Estimated energy, E [MJ]	Estimated energy, E [kWh]
2X sample A,B,C	111	74.0	252	70. 1
3X sample A,B,C	0.86	0.53	289	80.2
6X sample A,B,C	222	1.76	290	153
12X sample A,B,C	444	3.53	553	80.1

The md and E_{LAM} were used to determine the SEC using equation 11.