A comparative cost analysis of conventional wrought steel and powder metallurgy (PM) gear manufacturing technologies

Kianian, Babak

2019

Document Version:
Publisher's PDF, also known as Version of record

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BABAK KIANIAN
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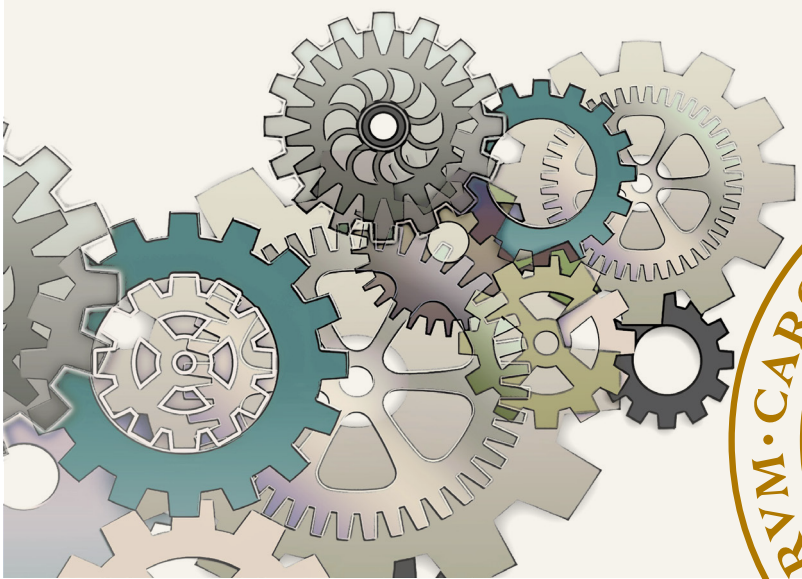

Abstract

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The industrial case studies, investigated in this licentiate, have gear manufacturing as the focus. The gear and transmission component manufacturing industry is an important sector as it provides one of the basic mechanical parts to industrial segments where motion and power transfer are needed. Two gear manufacturing techniques namely conventional wrought steel and powder metallurgy (PM) are compared from a cost perspective. Given the required performance and quality for automotive transmission application, the gear manufacturing processing routes and their production steps and cost drivers are analysed and compared through the utilization of the selected cost model, called performance part costing (PPC).

The industrial applicability of PPC model is compared with the commonly used standard costing, its use and its modified variations among practitioners through the case studies. The pros and cons of each approach are discussed. Given the assumptions made and reported in this licentiate for two different scenarios, the gear manufacturing cost of the analysed P/S processing route were 12% to 38% cheaper compared to the conventional wrought steel processing route. However, the acquisition cost for the analysed P/S processing route were almost three times higher than that of the conventional wrought steel gear.

Babak Kianian is a mechanical engineer (M.Sc.) with seven years' experience in product development and sustainable product-service system (PSS) design, specialising in Additive Manufacturing (AM) technologies e.g. 3D Printing in Swedish industries.

His speciality as a PhD candidate at Lund University in Sweden, since September 2016, is in developing manufacturing cost modelling and benefit analyses, and also their alignment with sustainability assessment of emerging technologies within the manufacturing industry. His PhD study focus is on Powder Metallurgy (PM) components and particularly press and sintering (P/S) processes with an automotive application e.g. transmission gears. Babak lives with his wife and two children in Nättraby, Sweden.

Printed by Media-Tryck, Lund 2019 NORDIC SWAN ECOLABEL 3041 0903

LUND UNIVERSITY

Department of Mechanical Engineering
Faculty of Engineering
Lund University

ISBN 978-91-7895-340-0

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LUND
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LICENTIATE THESIS

By due permission of the Faculty of Engineering, Lund University, Sweden.
To be presented on Friday, November 29th, 2019 at 13:00 at lecture hall M:A, M-building, Faculty of Engineering, Lund University, Ole Römers väg 1, 22100 Lund

Discussion leader

Associate Professor Peter Almström, Dept. of Technology Management and Economics, Chalmers University of Technology, Göteborg, Sweden

Organization Division of Production and Materials Engineering, Faculty of Engineering LUND UNIVERSITY	**Document name** Licentiate Thesis
	Date of issue November 2019
Author(s) Babak Kianian	Sponsoring organisation: Swedish Foundation for Strategic Research (SSF)

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Key words Gear manufacturing, Manufacturing cost analysis, Powder metallurgy (PM), Press and sintering (P/S), Wrought steel conventional gear manufacturing, Decision support system (DSS), Sustainability, Sustainable production (SP), Automotive Industry

Classification system and/or index terms (if any)

Supplementary bibliographical information	**Language English**
ISSN and key title	**ISBN** 978-91-7895-340-0 (print) **ISBN** 978-91-7895-341-7 (pdf)

Recipient's notes	**Number of pages** 156	Price
	Security classification	

Signature  Date 2019-10-01

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LICENTIATE THESIS

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Front and back cover images by Gerd Altmann, from Pixabay

Faculty of Engineering, Department of Mechanical Engineering

ISBN 978-91-7895-340-0 (print)
ISBN 978-91-7895-341-7 (pdf)

Printed in Sweden by Media-Tryck, Lund University
Lund 2019

Media-Tryck is an environmentally certified and ISO 14001:2015 certified provider of printed material. Read more about our environmental work at www.mediatryck.lu.se

MADE IN SWEDEN

To my family near and far

Acknowledgements

This journey has been intense, bumpy and sometimes confusing but ultimately rewarding and deeply meaningful.

I would like to thank my supervisors, Professors Carin Andersson and Pål Börjesson for their patience and kind support. I hope I have grown in your eyes and in this thesis and that, you can see the fruits of our hard work.

My academic career in Sweden has started in early 2013 with Professor Tobias Larsson believing in me and giving me a chance to start to take my first steps as an author, researcher and seeker of truth. Without his belief in me, I would not be here today and not have the life I now live today. I am deeply grateful for his ongoing friendship. Thank you.

Professors Göran Broman and Henric Johnson and assistant professor, Mats Walter have also been my supporters in my early academic journey and I still count on them as key mentors and friends. All three have given me so much and I hope that this work also reflects their faith in me and continued support.

The MSLS team for their friendship and very meaningful conversations, which stretched my brain and my heart to see more of the complexity of life and the interconnected nature of sustainability and the times we are living in. I hope that I can continue to learn with you all and count on your friendship in the years to come.

Assistant professor, Sam Tavassoli, who is one of my great friends, sport pal, and colleague. You have thought me how to write scientific articles and enjoy the dissemination of knowledge. Our early papers together helped to ground me in research and taught me so much. Your dedication to your work and the field inspire me. You are and will always be a very great friend to me. Thank you.

Christina Windmark, PhD, my office mate, friend and colleague. You have brightened so many of my days, we have shared the good and the bad together. I am so deeply grateful for all of your support and friendship. Thank you for the amazing welcome to Lund and opening your heart and family to me and my family.

There are so many previous colleagues at Blekinge Institute of Technology (BTH) and Lund University, who is hard to mention all here. Thank you all for your supports and contributions, especially my current colleagues at the division of production and materials engineering at M-Huset, LTH, Lund University. I would

like to thank and show my gratitude especially to, Jakob Johansson, for his support with preparation and presentation of my CIRP LCE 2019 paper.

I would like to appreciate my current research project partner companies, and say thank you to all the personal, who support me along the way so far. I cannot name them here due to the nature of this research concerning sensitive technical and financial data and NDA agreements. I hope the output of this research so far reported in this licentiate have both direct and indirect positive benefits in your line of work.

I would like to appreciate the financial support from the Swedish Foundation for Strategic Research (SSF) through the 'Nanotechnology Enhanced Sintered Steel Processing' project (grant no. GMT14-0045). I also would like to say thank you to all the colleagues involved in the overarching research project from Chalmers, KTH and Uppsala.

To my son, Oliver James, and my daughter, Lily Rose, who I love more than myself. You are the colours and meanings of my life. Thank you for being you. I hope someday you too will write your own stories and know that I will be there cheering you on all the way.

To my wife and best friend, Elaine Mary, who has been steering this ship all the way along during my academic career. This simply could not be done without you and your continuous support to hold our family strong. You are the one; I turn to in joy and in pain. Thank you for your lightness and perseverance. You have kept me strong when I felt weak and lightened my load when it got too heavy. I love you, thank you sweetheart.

To my family in Iran; especially my parents, Esmaeil Kianian and Maryam Amanpour, and my sister, Behnaz, who I'm living apart from for a very long time, thank you for believing in me. Mum and dad, the life values you thought me, along all these years supported me to be a better world-citizen, husband and father, and these will always stay with me. This licentiate thesis is for you. All of the late nights when I was a baby, all of the worry as I took my first steps into the world, all of your support as I packed my bags to fly to a far off land. I owe you my deepest gratitude. Your love fuels me from the inside. I hope this is in some way shows you both the fruit of your full-hearted work raising me. I love you all.

Babak Kianian

October 1st, 2019 – Lund, Sweden

Abstract

The transportation industry landscape is going through a massive transformation due to trends such as autonomous and electrified vehicles. The electrification trend has already started to display its ample influence on the automotive industry. New modern power and drivetrains need to be designed and manufactured based on the raising automakers' requirements e.g. higher performance, better noise vibration harshness (NVH) behaviour. Meanwhile, cost must be minimized in order to obtain or secure market competitiveness.

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Populärvetenskaplig sammanfattning

Transportindustrins landskap genomgår en massiv omvandling på grund av trender som autonoma och elektrifierade fordon. Elektrifieringstrenden har redan börjat visa sitt stora inflytande på bilindustrin. Nya moderna kraft- och drivlinor måste utformas och tillverkas baserat på att höja bilproducenternas krav, t.ex. högre prestanda, förbättrade brusvibrationshårdhetsegenskasper (NVH). Samtidigt måste kostnaderna minimeras för att uppnå eller säkra konkurrenskraft på marknaden.

I tillverkningssektorns mycket kostnadskonkurrenskraftiga atmosfär, särskilt inom bilindustrin som är i fokus här, försöker tillverkningsföretag oavbrutet att utveckla och använda kostnadsmodeller och metoder för att utvärdera t.ex. deras befintliga produktionssystem eller för att planerar nya investeringar för t.ex. införande och implementering av ny teknik.

De industriella fallstudierna som undersökts i denna avhandling har fokuserat på tillverkning av transmissionskomponenter. Tillverkningsindustrin för transmissioner är en viktig sektor eftersom den tillhandahåller en av de grundläggande mekaniska delarna till industrisegment där rörelse och kraftöverföring behövs. Två tekniker för kugghjulstillverkning; konventionell snäckfräsning av smidesstål och pulvermetallurgi (PM) jämförs ur ett kostnadsperspektiv. Baserat på erforderlig prestanda och kvalitet för applikationer inom bilindustrin har värdeflödena för dessa två tillverkningstekniker analyserats och varje enskilt produktionssteg och deras kostnadsdrivare har jämförts genom användning av den valda kostnadsmodellen, kallad *performance part costing* (PPC).

Den industriella användbarheten för PPC-modellen jämförs med den vanligt förekommande metoden att beräkna standardkostnader, samt dess olika modifierade varianter av industriella tillämningar undersöks genom fallstudier. Fördelar och nackdelar med PPC-modellen och de olika förekommande standardkostnadsmodellerna diskuteras.

PPC-tillvägagångssättet skiljer och separerar värdeadderande kostnader och icke-värdeadderande kostnader. Baserat på gjorda antaganden har analyser av de två olika teknikerna för tillverkning av i princip samma kugghjul visat att PM-teknologin är 12% till 38% billigare jämfört med den konventionell bearbetning av smidesstål. Anskaffningskostnaden för P/S-värdekedjan var emellertid nästan tre gånger högre än för den konventionella fräsmetoden.

List of appended publications

This licentiate thesis is based on the work contained and presented in the following five publications.

1.1 Paper 1

Kianian, B., Andersson, C (2017). Sustainability-conscious powder metallurgy gear manufacturing: an analysis of current manufacturing challenges. *The 7th International Conference on Gear Production 2017, September 14th-15th 2017, Garching, Germany. VDI-Berichte 2294: 1251-1264; Düsseldorf.*

Kianian created the semi-structured interviews questionnaires, planned and executed the case study. Andersson provided feedback on the structure of questions. Both authors participated and carried out the interviews. Kianian wrote the majority of the paper and was responsible for manuscript preparation, and Andersson assisted him in formulation of discussion and conclusion parts. Kianian presented the paper in the conference.

1.2 Paper 2

Kianian, B., Andersson, C (2018). Analysis of manufacturing costs for conventional gear manufacturing processes: a case study of a spur engine gear. *International Gear Conference 2018, August 27th-29th 2018, Lyon, France. Chartridge Books Oxford.*

Kianian created the semi-structured interview questionnaires. He planned and executed the case study with the assistance of Andersson. Kianian created and tailored the cost model in the excel software with the support of Andersson. Both authors were active and participated in the data retrieval processes from the partner company facilities. Kianian was the major contributor in analysis and deriving conclusions based on the available data. Andersson guided him in discussion section. Kianian has the main contributor to manuscript preparation and writing. Kianian presented the paper in the conference.

1.3 Paper 3

Kianian, B., Kurdve, M., Andersson, C (2019). Comparing life cycle costing and performance part costing in assessing acquisition and operational cost of new manufacturing technologies. *26th CIRP Life Cycle Engineering (LCE 2019) Conference, May 7th-9th 2019, IN, USA, Procedia CIRP Journal, volume 80, 2019, pp 428-433.*

The original idea for this comparative case study paper was purposed, planned and executed by Kianian. Kianian invited Kurdve as a co-author to facilitate in-depth LCC understanding. LCC data gathering, equations formulating, and analysing the results were done by Kianian, and Kurdve assisted him in the formulating process. Kianian did the majority of the manuscript preparation and writing before and after the peer-review processes. Andersson and Kurdve assisted him with formulation of the introduction and conclusion sections, and in responding to the reviewers' comments.

1.4 Paper 4

Kianian, B (2019). Comparing acquisition and operation life cycle costs of powder metallurgy and conventional wrought steel gear manufacturing techniques. *52nd CIRP Conference on Manufacturing Systems (CMS 2019), June 12th-14th 2019, Ljubljana, Slovenia, Procedia CIRP Journal, volume 81, 2019, pp 1101-1106.*

The original idea for this comparative case study was purposed, planned and executed by Kianian including systematic literature review, LCC data gathering, equations formulating and analysing the results. Kianian did all the manuscript preparation and writing before and after the peer-review processes including responding to the reviewers' comments. Andersson provided Kianian with a brief feedback on the overall approach in the beginning of the process. Kianian presented the paper in the conference.

1.5 Paper 5

Kianian, B., Andersson, C (2019). Analysis of manufacturing costs for powder metallurgy (PM) gear manufacturing processes: a case study of a helical drive gear. *EcoDesign 2019 Symposium (11th International Symposium on Environmental Conscious Design and Inverse Manufacturing), November 25th-27th 2019, Yokohama, Japan.* To be published as a book chapter by Springer.

Kianian created the semi-structured interview questionnaires. He planned and executed the case study with the assistance of Andersson. Kianian created and tailored the cost model in the excel software with the support of Andersson. Both authors were active and participated in the data retrieval processes from the partner company facilities. Kianian led the data gathering sessions and he was the major contributor in analysis and deriving conclusions based on the available data. Andersson guided in discussion and conclusion sections. Kianian did the majority of the manuscript preparation and writing before and after the peer-review processes. Andersson assisted with responding to the reviewers' comments and manuscript revision. Kianian presented the paper in the symposium.

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List of parameters

Parameter	Description	Unit
$h_{p,M}$	Running hours/maintenance hours	h/h
h_{year}	Hours per year and shift	h/year
i	Interest rate	-
K	Annual cost of producing a product	€
k	Cost per part	€/unit
K_0	Investment	€
k_A	Tool, lubricant and additive costs	€/ unit
k_B	Material cost per part	€/ unit
k_{CP}	Hourly machine cost during production	€/h
k_{CS}	Hourly machine cost during downtime	€/h
k_D	Salary costs	€/h
K_E	Cost of maintenance	€
K_G	Handling and storage costs	€
k_{Mh}	Maintenance cost of equipment/hour	€/h
k_{ph}	Equipment running costs (as energy costs etc.)	€/h
k_{ren}	Cost for renovation	€
K_{RW}	Cost of reworking	€
k_y	Annual cost of production area	€/m2
MD	Market demand (Annual production volume)	unit
n	Estimated equipment lifetime	year
N_0	Nominal batch size	unit
n_{op}	Number of operators	-
n_{pA}	Number of batches connected to a specific tool.	-
N_{ren}	Number of renovations during the lifetime of the equipment	€
q_B	Scrap rate	-
q_P	Speed loss rate	-
q_Q	Rejection rate	-
q_S	Downtime rate	-

t_0	Nominal cycle time per part	min
T_{pb}	Production time for a batch	h
T_p	Required production time	h
T_{plan}	Total paid and planned production time during a given period	h
T_{su}	Set-up time	min
U_{RP}	Utilisation rate in the case of reduced production	-
Y	Area of production and area needed to facilitate production	m2
SPV	Single present value	
e	Escalation rate	%
i	Discount rate	%

List of Abbreviations

A	Availability
ABC	Activity based costing
ABM	Activity-based management
AM	Additive manufacturing
DPDS	double pressing/double sintering
eLCC	Environmental life cycle costing
EP	*Enhetliga principer för självkostnadskalkylering*
EV	Electric vehicles
Fe_3O_4	Iron oxide
GDP	Gross domestic product
HT	Heat treatment
IHS	Information Handling Services
IPCC	International Panel on Climate Change
KTH	Royal Institute of Technology Stockholm
LCA	Life cycle assessment
LCC	Life cycle costing
LTH	Lunds Tekniska Högskola
MIM	Metal injection moulding
MQL	Minimum quantity lubrication
NVH	noise vibration harshness
OEE	Overall equipment effectiveness
OH	Overhead
P	Productivity
PPC	Performance part costing
PM	Powder metallurgy
P/S	Press and sintering

Q	Quality
TA	Throughput accounting
TCO	Total cost of ownership
TDABC	Time-driven activity-based costing
TOC	Theory of constraints
SD	Sustainable development
sLCC	Societal Life cycle costing
SP	Sustainable production
SPV	Single present value
WEDM	Wire electric-discharge machining
WP	Work Package

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1 Introduction

This chapter presents the research conducted in this licentiate thesis by introducing the background and a problem assertion, accompanied by the research purpose and research questions. The chapter concludes with research delimitations and outline.

1.1 Background

The manufacturing industry in Sweden is by far the biggest industry that adds values to Sweden's regions and also to the country as a whole. Statistics from 2017 show the effects of increased value on individual regions of Sweden ranging from 9.2% in Stockholm county to 38,9% in Jönköping county and 20,9% countrywide [1]. This places huge importance on this sector for both jobs and financial benefits for the country through its GDP. The same report details that the manufacturing sector holds the highest percentage of employees in large organisations (250+ employees). Thus, placing them in a key position within the Swedish economy whereby financial health and survival of these firms has a large and lasting effect on the Swedish economy and those employed within it.

Most recently, it has been shown that the second quarter of 2019 shows a rise of GDP of 0,1%, indicating that there is an economic slowdown in Sweden, sparking fears of a possible Swedish recession in 2020 [2][3]. This puts the Swedish manufacturing industry at risk and companies must now focus on optimising process and cost savings to ensure they remain competitive. The Swedish industry, like most sectors, is deeply embedded within a global system so shocks and impacts in the global markets and in international regulations have strong effects on manufacturing companies in Sweden. Sweden is in fact is more highly reliant on exports than other countries [4], and given the increasingly complex interdependent relationships that underpin global trade, this makes Sweden more vulnerable to global shifts and international trade agreements. Some possible future challenges might be; speed of new technology development, vulnerability and slowdown of the EU market, digitalisation and geopolitical tensions [4].

The worldwide awareness of the global sustainability challenge has been increasing year on year, especially since the development of the 2030 sustainable development goals. Even in the last few months, the global climate strikes initiated by Sweden's own Greta Thunberg amassed 7,6 million people in 185 countries

demanding action on CO2 emissions in line with the most recent IPCC report [5]. The IPCC report clearly states that we must limit our global warming to 1,5°C [6]. Thus putting huge pressure on the manufacturing industry who accounted for 19,79% of global emissions in 2014 [7]. These and other factors are putting pressure on manufacturing companies to alter their production methods and pay attention to aspects like environmental impacts, previously seen as a secondary benefit after quality and financial profit. These external pressures and increased competitiveness in the global market create the need to form accurate costing models, which enable process and production optimisations.

The transportation industry landscape is going through a massive transformation due to trends such as autonomous and electrified vehicles. In case of electrified vehicles; internal combustion engines (ICE) would most likely be the prominent power source in motor vehicles until 2030; however, advancement, adoption and deployment of hybrid and electric vehicles (EV) seems to be swifter [8]. The electrification trend has already started to display its ample influence on the automotive industry. New modern power and drivetrains need to be designed and manufactured based on the raising automakers' requirements e.g. higher performance, better noise vibration harshness (NVH) behaviour [9]. Meanwhile, cost must be minimized in order to obtain or secure market competitiveness.

In the highly cost-competitive atmosphere of the manufacturing sector, particularly within the automotive industry, which is the focus of this licentiate thesis, manufacturing firms uninterruptedly seek to develop, adopt and utilise cost models and methods in order to evaluate e.g. their existing production systems or planning new investment for adoption and deployment of new technologies [9]. The challenge for them is balancing the trade-off between the level of details and the likelihood of gathering data (e.g. technical and financial) of adequate quality and quantity from varies operations and systems within their companies [10] [11]. Simpler models and methods are easier to utilise, as a result however, the magnitude of knowledge achieved by them are limited due to the number of parameters included. Whereas, more sophisticated models and methods demand for more extensive data input gathering, nevertheless as a result, they deliver a richer knowledge (know-how) for well-informed decisions [10] [11].

The Swedish industry is not an expectation from the aforementioned dilemma of trade-offs between cost modelling options selections. In Sweden, the foundations of cost accounting are rooted in a model called *'Enhetliga principer för självkostnadskalkylering'* commonly known as EP [12]. This is further described comprehensively in the chapter 2, in section 2.3. There are many cost accounting methods for evaluating manufacturing and production costs, which are also described and discussed further in chapter 2 (frame of reference). E.g., activity based costing (ABC), time-driven ABC, standard costing, and throughput accounting (TA), to just name a few [13].

The industrial case studies, investigated in this licentiate thesis, have gear manufacturing as the focus. The gear and transmission component manufacturing

industry is an important sector as it provides one of the basic mechanical parts to industrial segments where motion and power transfer are needed. Automotive, aerospace, marine industries and industrial equipment are a few examples of these dependant industrial segments [14]. The power transmission manufacturing industry has already partially adopted and deployed some of the sustainable production characteristics, for example, by utilising advanced lubrication and cooling methods, using alternative cutting fluid (e.g. vegetable oils, synthetic esters), implementing advanced flexible and hybrid production and tooling processes [15].

Worldwide each year billions of gears are produced, and Sweden holds a significant share of this as approximately one fifth of the global manufacturing of transmission parts, particularly for heavy vehicles, happens in Sweden [15] [16]. The Swedish gear and power transmission manufacturing industry has a sustainable production vision to produce 30% stronger and lighter automotive gearboxes by the year 2025 with close to 100% transfer efficiencies deploying environmental friendly lubricants and coatings [16].

Metallic gear manufacturing technologies are generally grouped into three categories of 1) chip generating machining processes (e.g. hobbing, milling, shaping and broaching); 2) forming processes (e.g. cold or hot extrusion, stamping, powder metallurgy); and 3) additive (e.g. additive manufacturing, casting) [15]. The scope of this licentiate includes the category 1 (conventional machining processes) and 2 (powder metallurgy). This is elaborated further in section 1.5 (delimitations) below.

- ***Conventional machining processes***, cutting the raw materials to make the gear's tooth root, account for the majority of gear manufacturing activities today and are 'the technologies of choice' [15] [17]. These processes are well established with plenty of machining capacities installed globally. Machining processes are also rather advanced largely to increase productivity over the last decades [18] [19] [20] [21] [22]. Nevertheless, they have inherent limitations in terms of net-shape (forming capabilities) as substantial amount of raw material (e.g. up to 50-60%) needs to be machined away, which leads to high-energy consumption and low material utilisation [23]. These disadvantages result, along with the consumption of large amount of process materials – additives e.g. lubricants and cooling agents, in an increase in total costs and negative sustainability impacts. For further elaboration please read chapter 2, section 2.1.

- ***Powder metallurgy (PM)*** encompasses many technologies e.g. press and sintering (P/S), additive manufacturing (AM), metal injection moulding (MIM) and materials - metal powders mixes, ferrous and non-ferrous (e.g. metallic and alloy materials) in spherical or irregular particles' shapes to form solid functional parts for varies applications [24]. This research focuses on P/S processes for the production of automotive transmission gears. Powder metallurgy (PM) parts are fairly well

established in the manufacturing industry (e.g. automotive) [25] and the majority of PM parts are produced by conventional P/S processes from iron powders (approx. 80% of European PM part production in kilo tonnes in 2016) [26]. Not far off 75% of iron powder produced worldwide is applied in PM and automotive component suppliers utilise more than 80% of manufactured powder parts globally [27].

The last two bullet points introduced the two gear manufacturing technologies, which this licentiate investigated in the rest of this thesis. The overarching research project, the author's research study and its parts, and objectives are introduced below.

1.2 Overarching research project

This licentiate thesis presents part one (cost analysis) of a two part research's work package (WP) which is entitled *'cost analysis and sustainability assessment'*. This is one WP within a bigger research project consisting of five WPs among the following four Swedish universities: Chalmers, KTH, Uppsala and Lund. The overarching research project is called '*Nanotechnology Enhanced Sintered Steel Processing'*, where the main goals and objectives are outlined in the three categories below. The research project is financially supported by the Swedish Foundation for Strategic Research (SSF).

i. Development of a generic platform for novel approaches to realise sintered steel with closed porosity without compromising dimensional control.

ii. Development of a generic platform for analysis and design of PM steel surface properties with particular reference to transmission gears.

iii. Development of a generic methods and models to analyse manufacturing economics and sustainability.

The third goal and objective outlined above is directly investigated in this research's work package, WP5. The intentions in part one in WP5 is to compare the overall processing routes for conventional wrought steel and PM gear manufacturing in order to provide fact-based in-depth knowledge on differences in costs and benefits and link economic outcomes to technical production aspects. The goal and objective for part two is to develop a decision support system (DSS) for sustainability evaluation, which illustrates the alignment between economic outcomes and sustainability impacts. The research agenda for part two is described in detail in chapter 7 (outlook). Nevertheless, since inherently cost analysis and sustainability assessment are inextricably intertwined, there are some paragraphs further in this chapter and the rest of the thesis where sustainability concerns are visible. This clearly can be noted in the appended papers. Figure 1.1 below summarises the research project purposes/what is outlined above.

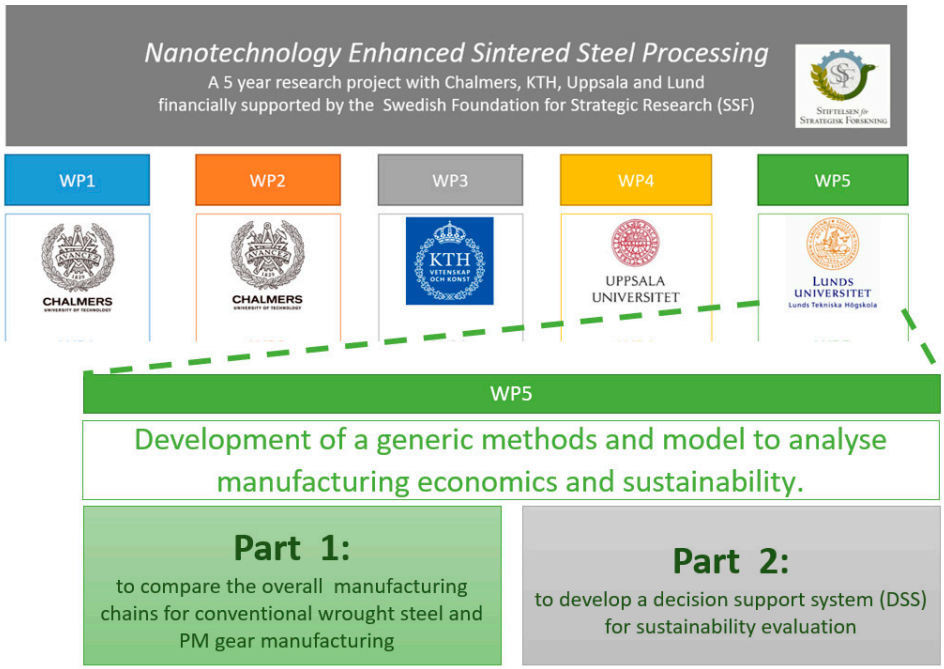


Figure 1-1 Overall research Project outline and position of this licentiate research

1.3 Practitioners challenge statement

The decision making processes for selection of alternative or new manufacturing techniques for part production (e.g. in automotive industry) are normally done with traditional industry cost structures [28]. Nevertheless, the negative sustainability impacts (e.g. degradation of natural resources) of manufacturing activities in the industrial sector and their drastic consequences at a global scale has forced the industry to acquire and implement a more holistic approach when considering the adoption and utilisation of new manufacturing technologies [17] [29].

There are many dimensions to contemplate e.g. profitability, skills supply and allocation, processes knowledge and information, sustainability when a part producer decides to evaluate and compare a range of manufacturing methods for different scenarios. Several examples of these scenarios are; improvement to a company's existing production layout and performance and/or the adoption and deployment of new manufacturing technologies. However, there is a gap in both industry and academia in the availability of comprehensive decision support system (DSS) methods. These methods and tools are needed to support gear manufacturing companies' decision makers in their assessment processes especially when it comes to 1) cost analysis and 2) sustainability assessment [10].

Having said that, this licentiate focuses on the first part, cost analysis, and one of the objectives of this licentiate is to support practitioners (gear producers) with this decision challenge that they have highlighted and are facing on an ongoing basis. Their challenge is to decide which processing routes deliver them the optimal improvements e.g. gear performance boost for the costs they sustain, and what performance level does the final gear truly require [25]. To summarise, this licentiate does not focus on 'how' the material and mechanical properties desired and/or the performance and quality levels required can be reached. It rather focuses on 'what' performance and quality levels can be reached with a particular processing route and its respective production steps and associated costs.

1.4 Purpose and research questions

As explained above, in-depth cost analysis and sustainability evaluation, as DSS methods and tools, for gear manufacturing companies have been under-researched and thus under-developed. Hence***, the research objective of this licentiate thesis is to investigate how different gear manufacturing technologies can be compared from a manufacturing cost perspective, based on their application's required performance and quality. The technologies, which are compared, are conventional wrought steel and press and sintering (P/S) gear manufacturing technologies.***

With the hypothesis, that comparable finished gear's quality and tolerances can be achieved with both techniques, this thesis analyses and compares the manufacturing cost drivers between the aforementioned two techniques to find out the most cost efficient alternative. In order to support this aim, two research questions (RQ) were formulated.

RQ1: What level of detail is required for a cost analysis tool to be able to compare different gear manufacturing technologies rendering the same product performance and quality?

RQ2: What is the manufacturing cost difference between conventional wrought steel and press and sintering (P/S) gear manufacturing technologies?

1.5 Delimitations

The licentiate thesis presented here focuses on a comparative manufacturing cost model, which characterises and analyses cost parameters directly linked to the manufacturing processes. Thus, when calculating the cost the focus is on the two manufacturing processing routes' cost models comparison. Other aspects e.g. patent, intellectual properties, supply chain management, and support functions such as IT are not investigated. This is dictated by the main objective of this thesis, which is to investigate the cost drivers directly affecting the manufacturing systems performance at the shop floor. This results in suggesting activities (improvement scenarios) that potentially can improve the manufacturing system efficiency (e.g. performance) and end part's quality. Regarding the quality assurance, since material cost and OEE parameters are included, cost of poor quality is also included in this licentiate. Having said that, the necessity of considering other aspects in the manufacturing companies (not only focusing on shop floor) e.g. manufacturing management and also considering full life cycle perspective are acknowledged by the present author. This is further discussed in detail in chapter 7 (outlook) and in the appended papers at the end of this thesis.

This research focuses on metallic gear manufacturing, which is generally grouped into three categories of 1) chip generating machining processes (e.g. hobbing, milling, shaping and broaching); 2) forming processes (e.g. cold or hot extrusion, stamping, powder metallurgy); and 3) additive (e.g. additive manufacturing, casting) [15]. The scope of this licentiate includes the category 1 (machining processes) and 2 (powder metallurgy), and regarding the machining processes, turning and hobbing are analysed in the industrial case studies. The main reason for that, is the availability of these processes' equipment in the partner companies and hence accessibility of both technical and financial data. Despite this limitation, both academics and practitioners undoubtedly can appreciate the benefit of accessing to real in-use production data for cost modelling of a commercial product.

Limited time, which dictates the scope of this research and hence the number of conducted case studies is another delimitation. Hence, firstly only a single comparative case was performed comparing a conventional wrought steel manufactured spur gear and a PM manufactured helical gear. If multiple comparative gears will be analysed extending the timeline to a PhD dissertation, themes for each manufacturing technology will be expanded and findings that are more empirical will be provided. Secondly given this licentiate timeframe and the already existence partnership with a company, input data from only one company for a conventionally manufactured gear was obtained. Thus, this case is organisation specific and might be generalized to all organizations who could produce this type of gears utilising the compared processing routes, only when more case studies are performed.

1.6 Thesis outline

Following this chapter, which introduced the importance of this work, this licentiate thesis is structured into six succeeding chapters as follows.

Chapter 2, frame of reference,
recapitulates the literature relevant to the research questions (RQs). This mainly includes research on different conventional wrought steel and powder metallurgy (PM) gear manufacturing technologies aspects, cost accounting methods, and the manufacturing cost model utilised in this research.

Chapter 3, methodology,
elaborates on the overall research methodology, which is used in this thesis, and also outlines the different research methods e.g. case study, semi-structure interview, survey questionnaires, which were applied in the five appended papers. It concludes with a discussion on this research quality.

Chapter 4, contributions and appended papers summary,
summarises the five appended papers in detail, and also presents their connections to the RQs. Moreover, a comparative cost analysis of conventional wrought steel and PM gear manufacturing technologies, which is not included in the appended papers, is presented.

Chapter 5, discussion,
elaborates on the combination of five appended paper's and the additional empirical findings from section 4.7 contributions. Their connections to the reviewed literature in chapter 2 is also presented. This chapter concludes with reflection upon the quality of research and its limitations.

Chapter 6, conclusion,
provides answers to the research questions (RQs).

Chapter 7, outlook,
presents the future work e.g. sustainability assessment of the compared gear manufacturing technologies and alignment of their production steps and associated cost drivers with their sustainability impacts.

2 Frame of reference

This chapter presents a summary of previous research and the theoretical findings of this licentiate thesis. It covers a literature review on varies aspects of conventional wrought steel and powder metallurgy manufacturing technologies, varies cost accounting methods, and the manufacturing cost analysis model utilised in this research.

2.1 Conventional wrought steel gear manufacturing

The importance of transmission components and particularly gear manufacturing from cost and sustainability perspectives is highlighted in chapter 1, section 1.1 (background). According to Information Handling Services (HIS) Automotive, the demand for gear manufacturing has become even greater in comparison to the production demand for vehicles. A 2017 evaluation of transmission component manufacturing anticipated 15% rise in gear demand over the course of seven years from 2017 to 2024 from 95 million to 109 million units respectively [22].

The state of the art manufacturing scheme for transmission parts (e.g. gears) starts with soft machining processes e.g. turning, hobbing, milling, deburring, which are geometrically determined processes based on the machinability of the selected raw material. The raw material is mainly forged blanks with case hardening steel quality. After soft machining processes, in order to enhance the material properties, case hardening is conducted e.g. different furnace processes such as heat treatment (HT), annealing. To complete the manufacturing steps, hard machining processes e.g. hard turning are required before the finishing processes e.g. grinding, honing in order to achieve the gear desired quality e.g. tolerances [16][17] [18].

Conventional gear manufacturing technologies are illustrated in figure 2.1 below. Production technologies are set up with the responsibility of creating an object into its final structure taking into account particular requirements. Regarding machined parts, the produced object must attain its function considering particular conditions over a expounded period of time [18].

'Turning' is one of the principle chip generating machining processes, which is utilised in almost all manufacturing sectors [30]. To start with, for gear manufacturing, the practical/functional gear's surfaces need to be turned to secure an adequate quality in the next production step, which is hobbing [18].

'Hobbing' is the preferred cutting process to manufacture high quality cylindrical gears. During gear hobbing process, each tooth gap is made with the penetration of the tool teeth in the gear's material in the succeeding generating positions. This process is in line with at least one or more threads (also called starts), which are on the hob cylindrical frame, and with auxiliary cutting feed around an axis, the gaps between the gear's tooth are shaped [20].

Heat treatment (HT)' processes have various types e.g. methods and hardware available, which are suitable for both conventional wrought steel and P/S processing routes. Some examples are case hardening, induction hardening, and nitriding [23].

'Hard turning' is a hard machining process utilised by practitioners to final cut hardened steel materials [19]. Hard turning has been compared to grinding process for at least two decades now. It takes into account top-level process reliability in in line with machining time deduction. These two factors need to be obtained alongside the traditional required characteristics, which a component must achieve, e.g. surface roughness and dimensional preciseness [18].

'Grinding' is the elected 'hard-finishing processes' for gear manufacturing. It is an important production step as it dictates the finished part's final geometric preciseness and quality [22]. As a finishing process with unspecified cutting edges utilised by practitioners, grinding is divided into 1) discontinuous profile grinding and 2) continuous generating grinding. For a finishing process with specified cutting edge, 'skive hobbing' is deployed by the practitioners [18].

'Honing' is another continuous hard finishing process, like generating grinding and skive hobbing. Gear honing and skive hobbing processes are not included in this licentiate, hence for further details e.g. their processes characteristics and applications' range, please visit [18] [20] [22].

'Shaving' is a traditional 'soft-finishing process', with specified cutting edges, which can be performed before the case hardening step, in contrast with grinding, honing and skive hobbing processes, which are performed after case hardening [20]. Shaving was a popular process until 1990s mostly because of its economical benefits over alternative hard-finishing processes, which historically were utilised merely when the quality requirement demanded it. Similar to above, gear shaving is not included in this licentiate hence, interested readers please visit [21] [20]

Strategies for the selection of suitable manufacturing steps in conventional wrought steel processing route rely on many factors e.g. cost of machining processes, production school of thought and availability of knowledge (know-how) [20][18]. An ambitious strategy deployed in practice is to achieve the top achievable accuracy prior to case hardening. Then according to the demanded tolerances for the application, case hardening is performed with the objective of eliminating hard-machining processes. Shaving has offered a rather high-profile accuracy before case hardening process, and so has been appealing. However, the technological enhancements of hard-finishing processes, has reduced the competitive advantages of shaving process, which has somehow reached its technological improvement limits e.g. necessity if wet cutting [21] [20].

As mentioned in section 1.1 background in chapter 1, these technologies are advanced largely to increase productivity over the last decade. An example among many, is the dry skiving-grinding process, which starts with skive hobbing and finalises with dry grinding. It is reported that this process with terminating oil from gear finishing processes, has decreased electrical power consumption by 75%. For interested reader, please visit [22]. Nevertheless, conventional machining processes have inherent limitations in terms of net-shape (forming capabilities) as substantial amount of raw material (e.g. up to 50-60%) needs to be machined away, which leads to high-energy consumption and low material utilisation [23]. These disadvantages result; along with the consumption of large amount of process additives e.g. lubricants and cooling agents (although they are often recycled), in increasing in total costs and negative sustainability impacts of a product [22].

The negative sustainability impacts are suggested to be mostly environmental in nature and are associated with air, water, land and noise pollutions [14]. Some of the possible solutions put forward in order to reduce air pollution and enhancing environmental performance are frequent monitoring and analysing of stack emission and fugitive air characteristics, particularly in furnace processes e.g. heat treatment (HT) [31][32][33]. The suggestions above and in addition to what is discussed in the next two paragraphs are also applicable for the powder metallurgy gear manufacturing processing routes, which is described in the next section, 2.2.

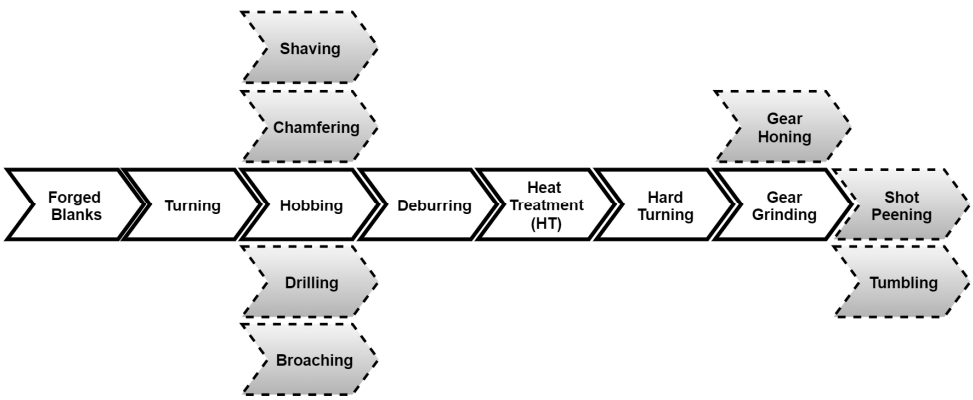


Figure 2-1 Conventional wrought steel gear manufacturing processing route

As mentioned earlier in chapter 1 (see 1.5 delimitations), this licentiate thesis focuses on turning and hobbing for the soft machining processes and grinding for the finishing processes. Many researchers studied solutions to remedy the challenges outlined above, by e.g., comparing the resource consumption of each conventional processing route for gear manufacturing (manufacturing production step mapping). Sen et al suggested the following steps to remedy some of these challenges. For example, gear manufacturing companies should focus on waste reduction (e.g. wastewater discharge) in order to preserve nature and become cost

competitive, using environmental friendly lubricant technology, deploying proper disposal methods for recycling, down cycling, and handling solid waste (including the used lubricants) [14]. Solid waste production levels can be remedied by remanufacturing or recycling. Advanced waste management techniques to collect chips can be used. Wastewater or effluent must be monitored and treated before being withdrawn. Noise pollution is dominantly created during gear machining processes and in particular grinding. This may generate occupational issues such as hearing problems, stress and anxiety for operators, interrupt communication, and thus reduce efficiency and performance [14].

Other researchers noted that finishing processes e.g. grinding, honing and shaving processes have the largest impacts on both cost and sustainability. This is mostly because of heavy use of cutting fluids, high-energy consumption, high tooling cost, high wear thus more maintenance (e.g. tool refurbishment and replacement), waste management and handling [15] [22]. There are some strategic alternatives and solutions to eliminate these problems.

These are;

1) decreasing the usage of hazardous cutting fluids and replacing them with more environmental friendly options such as vegetable oils, and other biodegradable lubricants;
2) implementing more advanced lubrication techniques like minimum quantity lubrication (MQL), cryogenic cooling, dry cutting;
3) utilising alternative gear manufacturing and finishing techniques such as gear rolling, wire electric-discharge machining (WEDM), if it is suitable for the gear size and dimension;
4) deploying optimal machining setting, proper tool materials and coatings [15].

It is noted in section 1.2 of chapter 1, that cost analysis and sustainability evaluation are interweaved, and hence, inferior sustainability performance has also negative cost impacts. Therefore, it is worth to mention it again that is the main reason, for which the solutions reported in this section are also connected to sustainability.

Some elaborated examples of these strategic alternatives and solutions to conventional gear manufacturing challenges, e.g. for hobbing process, can be found in the following studies. Weinert et al 2004 [34], Fratila 2009 and 2013 [35] [36], Fratila et al 2010 [37], Stachurski 2012 [38], Matsuoka et al 2013a and b [39] [40], Zhang and Wei 2010 [41], Filipovic and Stephenson 2006 [42], Tai et al 2014 [43], Winkel 2010 [21], and Tokawa et al 2001 [44]. These studies focused on technical improvements of each process route.

The research examples outlined above have technical development aspects as their focus and the field is well established. There are also many studies focusing on manufacturing cost aspects of the machining processing routes both at macroeconomic and microeconomic levels in addition to the technical aspects. Regarding macro and micro economic cost model levels, visit the section 2.3. Some examples are cutting data optimisation methods and models including e.g. power data by Hägglund [45], which included cost modelling at the macroeconomic level. Johansson [46] has also conduced cutting data and tool life testing and modelling for machining processes, and that has been combined with cost performance modelling at microeconomic level.

Another example including the complete machining processing routes is a comparative manufacturing cost analysis of two gear finishing processes of grinding and shaving. Its result illustrated that shaving is 26% to 46% cheaper in its process cost [10]. The cost's impact of two important cost drivers, being setup time and overall equipment efficiencies (OEE), at the microeconomic level are also analysed. That included the entire processing routes including the soft machining processes of turning, hobbing and broaching [10]. The pros and cons with different cost modelling approaches and also various views on their categorisations e.g. levels are described further on in this chapter in sections 2.3 and 2.3.6.

2.2 Powder metallurgy gear manufacturing

Powder metallurgy (PM) technologies and metal powders are briefly discussed in the previous chapter, see sections 1.1. This section elaborates on the utilisation of PM production capacity to manufacture gears, particularly transmission gears. PM manufacturing technology consists of precision metal forming processes for the production of parts to a (near) net shape, and different type of gears e.g. spur, bevel, helical can be manufactured with PM process routes [8] [47]. This research focuses on press and sintering (P/S) processing route to produce gears. P/S in particular are recognised as resource efficient (e.g. material and energy), and is labelled as green technology, with 5 to 8 times increase in its manufacturing speed, and 95% material utilisation in comparison with conventional wrought steel machining technologies [8].

The PM industry is fairly well established within the manufacturing industry and components produced with its technologies are to high extent utilised in automotive industry. However, its application so far in drivetrains (e.g. transmission gears) is limited since its raw materials (metal powder mixes) mechanical properties are lower in comparison to its counterpart wrought steel gears, mostly because of the inherent porosity in PM parts which are manufactured by P/S processes [25]. Other work packages (WPs) in this research project are currently investigating PM material properties with the aim of nanotechnologies (please visit chapter 1, section 1.2, overarching research project). P/S gear processing routes are comparatively

different from conventional wrought steel gear processing route presented above in section 2.1. The hard-finishing processes e.g. grinding, honing could be the same, but all the production steps beforehand are different [48]. It is outlined previously in chapter 1; section 1.1 and also described in section 2.1 above that conventional wrought steel processing route for gear manufacturing are well established. As a result for example, the mechanical properties achieved by each production step are well known too, and thus based on an application's requirements, a part maker can select the appropriate cost-efficient materials and processes in order to produce the parts. On the contrary for P/S gears processing route, this is not common knowledge [48]. Hence, more detailed explanation of what, for example, material properties, performance and quality can be achieved with each P/S production step is essentially needed.

P/S gears are used in most appliances, which we use every day e.g. kitchen‘s appliances, lawnmowers, cars. Conventional P/S processing routes are sufficiently advanced, and deployed to manufacture standard gears in series production for applications such as hydraulic pump drive gears, balancer gear set, and engine gears. For applications with higher performance requirements such as higher-loaded differential and transmission gears, conventional P/S processing route is additionally advanced either at the experimental or commercial level with the inclusion of added production steps like gear rolling, forged powder metal (FPM) and hot isostatic pressing (HIP) [25] [49] [50]. P/S processing routes for gears production, both for standard and high performance gears are illustrated respectively in the figures 2.2 and 2.3 below.

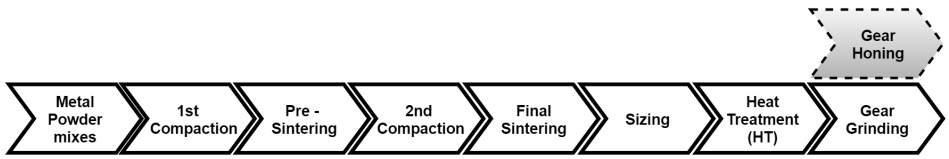


Figure 2-2 P/S processing route for production of standard gears e.g. pump drive and balancer gears

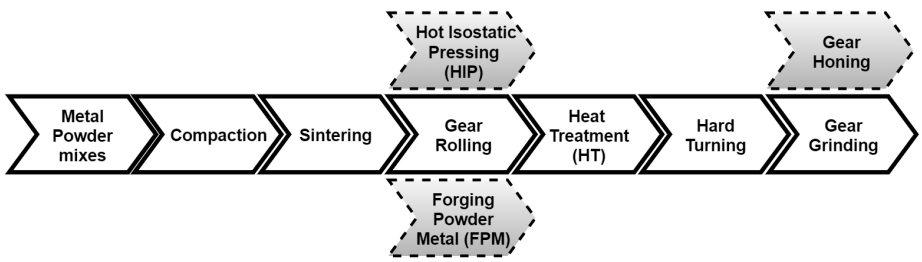


Figure 2-3 P/S processing route for production of high performance gears e.g. differential and transmission gears

P/S processing routes, in figures 3 and 4 including their following production steps are described below and, the performance and quality achieved after each of them is mapped in this licentiate's appended paper 4. Then advantages and disadvantages of each production step with their associated parameters has so far been studied is presented. However, sizing, FPM, HIP and gear honing production steps are excluded from this licentiate due to lack of financial data accessibility to analyse their production steps breakdown costs. These processes are still briefly introduced, and for further detail, visit [51] [27] [24] [48] [52] [25] [50] [53][54] [55]. For gear honing, visit previous section 2.1 in this chapter and its provided references.

Tooling' for compaction process needs to be done with great care in order to maximize the press equipment's performance and not sub-optimise its features potentials. The interconnection relation between tooling and press can lead to reliable compacted parts with e.g. stabile quality, and also the prolonged life span of both press and tool. The press equipment tool basically includes an upper and lower punches and a die. For gear compaction, there is usually a core rod, which creates the bore shape. In case of helical gear, there is also a helical drive system harmonising and controlling the motion of the outer upper punch into the die and rotation of lower punch, which located on bearings [48]. For further detail, visit [56].

'Compaction' is process of pressing ready-to-press alloyed metal powder into its final part (near) net-shape. There are various types of compaction presses available in the market [23], but mechanical and hydraulic presses are utilised to a large degree in P/S processing routes. There are pros and cons in the deployment of either presses, for example, mechanical presses are extra energy-efficient compared to the hydraulic alternative. However, higher accuracy and complexity benefits of hybrid presses including hydraulic adaptors have been reported [51]. In addition to conventional compaction, this process can be performed in two different upraised temperatures, which are called 'warm die compaction' and 'warm compaction' [23].

'Sintering' is a furnace process, which for P/S parts is dominantly performed in belt furnaces with a conveyor belt width of 0.6 to 1 meters [51]. However, for higher temperatures, alternatives such as walking beam and batch furnaces are used. Sintering conditions are determined by five factors:

1) temperature and time,
2) metal powder particles geometrical composition,
3) alloying metal powder formation,
4) compacted powder density and
5) controlled sintering atmosphere arrangement [23].

For further detail regarding energy consumption, its calculation and different inefficiency categories (e.g. radiation, ineffective loading) and their comparison, please visit [57] [58] [59][51].

The P/S processing routes shown in figure 3 above, where metal powders are pressed and sintered twice, is commonly known as 'double pressing/double sintering (DPDS)' and it is deployed in automotive applications for the production of e.g. synchronize hubs, crankshaft sprockets, planetary gear carriers for a couple of decades now [60].

'Sizing' is a similar process to compaction and similar presses are usually utilised. It should be noted that often a section of a part e.g. gear requires sizing. The sizing energy efficiency was assessed to be lower than compaction [51].

'Case hardening' is a HT process, which is also suitable for powder metal. Some examples of its methods are, conventional carburizing, oil quenching, tempering, and low-pressure carburizing. Due to open porosity and diffusion of carbon particles, when case hardening is utilised for metal powder, the P/S has an advantage in its processing time compared to conventional wrought steel [23]. Steam treatment is the extensively utilised HT for metal powders, and the objective is to shrink the powder's open porosity with configuration of iron oxide (Fe_3O_4) [51]. For the P/S processing route, HT parameters need to be optimised and the controlling of the atmosphere is different compared to the conventional wrought steel processing route. These changes are dependent on the part's selected material, weight, size complexity and of course the experience of the HT provider [23].

PM component manufacturers can theoretically utilise various configurations of P/S processing routes included in figures 3 and 4 based on the application's performance (strength) and quality (tolerances) required by their customers. This then dictates the selection of the metal powder mixes used. In addition to this, in practice, the availability of processing routes has a great impact on the selection of raw materials as well. [61] [23] The 'availability' can be combination of technical (know-how) and financial factors.

Recently for instance, in an effort to manufacture full dense powder metal gears with conventional P/S processing route; the DPDS route was complimented with hot isostatic pressing (HIP) process, heat treated with carburizing process and hard-finished with grinding. Thus, the P/S processing routes utilised can be seen in figure 2.4 below.

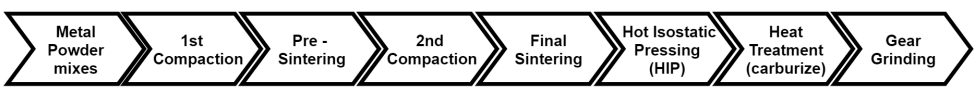


Figure 2-4 P/S processing route including HIP process in [50]

The results are promising regarding the achieved density after HIP (approximately 7.85 g/cm^3), but the demonstrator gear's quality is lower than the reference material due to considerable metal powder's grain growth [50]. In order to highlight the influence of advanced alloying metal powder technologies, it is feasible to achieve similar results as of the examples above through the utilisation of a finer metal powder than the standard pre-alloyed powder (Astaloy^{TM} Mo from Höganäs AB) , in combination with lower lubricant content and high-pressure compaction. For further details, please visit [25] [50].

'HIP' is a process where high temperature (1050 – 1250 ^{0}C) and high gas pressure (mostly Argon at 100-200 MPa) are merged and integrated in order to strengthen metal or ceramic powders [55]. The HIP technology has been utilised for more than 50 years. It has two principle methods regarding its high-pressured gas as follows:

1) mono-lithic
2) wire-wound technology.

Regarding its high temperature, practitioners' experience suggest HIP temperature of approximately 70-80% of the metal powders melting point and 80-90% of sintering temperatures [55]. For more application details, please visit [25] [50] [62].

For 'hard machining' also called hard-cutting e.g. hard-turning, and for finishing processes, both 'hard-finishing' e.g. grinding and 'soft-finishing' processes e.g. shaving, please re-visit the previous section; 2.1 and its references in this chapter.

'FPM' is a one-step stroke forging process, utilised for P/S processing route often in mechanical or screw presses [63] [64]. Flow forging is the best FPM process for metal powder mixes, and gears performance comparable to conventional wrought steel processing route can be gained by utilisation of FPM. This has successfully been practiced in series production in differential gear application [63] [64] [65].

2.3 Cost methods and models

This section includes general cost accounting methods, specific models (e.g. manufacturing cost models) and briefly describes the differences among them. There are many different techniques and methodologies to evaluate manufacturing costs, which are widely dispersed and summarise and explore various methods both holistically and particularly for different applications. For example, Jönsson [13] compared different cost accounting methods and various manufacturing cost models based on their purposes, principles and cost allocation procedures. Manufacturing cost models can be distinguished based on their various characterisations e.g. qualitative and quantitative schemes, microeconomics and macroeconomics approaches, top-down and bottom-up granularity levels, early prediction and late estimation relevancy phases. Interested readers please visit [66] [67] [68]. Schultheiss et al. [68] reported a summary of manufacturing cost models approaches differentiating them from system and process levels and also system ability point of views.

This section (2.3) of the licentiate seeks to give a brief overview of relevant cost models, for in-depth information on each model please see the related references. . The author based his research on comprehensive summaries and comparisons of different cost accounting methods and manufacturing cost models, which was

conducted by Jönsson in 2012 [13], and later on updated by Ståhl in 2017 [69], Schultheiss et al in 2018 [68] and most recently by Windmark in 2018 [29]. These studies have taken into account the models that clearly reported the parameters and calculation methods within their models. Afterward the number of cost components included in each cost model were compared and were mapped against the parameters, which each cost component measured. The results illustrated that the original cost breakdown model developed in 2007 by Ståhl [70] includes more cost components and parameters particularly performance and quality drivers in comparison to others models.

In Sweden as it is mentioned earlier in chapter 1 (see section 1.1) the foundations of cost accounting are rooted in a model called *'Enhetliga principer för självkostnadskalkylering'*, which was first introduced in 1936, and commonly known as EP [12]. EP is utilised for absorption costing, which is a method for assigning all costs created in an enterprise over to every product manufactured. The cost components implemented in EP consists of *direct and indirect material costs*, *direct labour cost*, *manufacturing overhead costs*, *special direct costs*, *sale costs*, and *administration costs* [13]. The manufacturing overhead costs in EP are split into those costs centers, which are intently associated with manufacturing e.g. equipment, maintenance, energy, process materials and facilities, and those that are not e.g. design and product development, laboratory costs. The foundations for these costs' distributions are direct material and labour costs, and labour or machine hours [13] [12].

2.3.1 Standard Costing

Standard costing somehow similar to EP is an old cost accounting method that was introduced approximately in the 1920s. Standard costing is based on cost components of *direct material costs* and *direct labour costs* and *an overhead (OH) mark-up*, which incorporates those costs that are not contained by direct material and labour costs [71]. The standard costing methodology can be seen in figure 2.5 below. The costs are usually modified on yearly bases, and hence revisions, which are deployed in between, are essentially not explicitly shown until the next year's modification. This can be considered as a pitfall since standard costing evaluates the expected costs instead of deploying the real costs, and the modifications are labelled as fixed OH percentages [72].

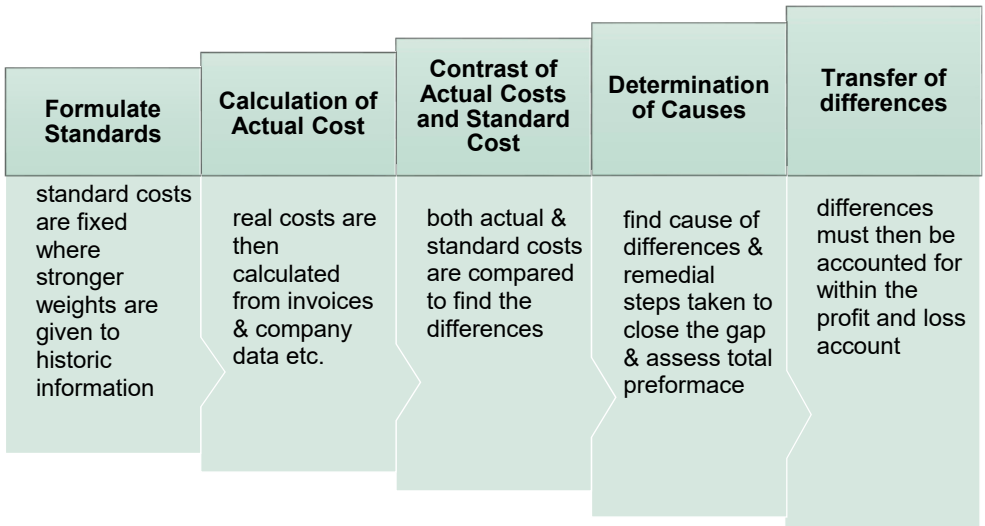


Figure 2-5 Illustration of the standard costing method

2.3.2 Activity-based costing (ABC)

Activity-based costing (ABC) initially proposed by Cooper et al. in 1991 [73] intended to modify some of the difficulties recognised in aforementioned traditional cost accounting methods, which were introduced in early 20th century. At that time when traditional cost accounting methods were developed, going back to 1889, the labour cost, in contrast to today's situation, was the largest portion of produced products' cost and was considered as a variable cost. OH costs at the time was not a large portion of the total cost. Hence investing on an approach or a platform that analyses costs in detail and allocates OH proportions more accurately to each product was not feasible [74]. Whereas, nowadays in the manufacturing industry considering labour cost as a major contributor for the distribution of OH cost is not necessarily desirable. With the rapid technological advancements, many manufacturing companies have now moved away from or are in a transition from an old paradigm of mass production to a new paradigm of mass customisation and hence more flexible manufacturing, and that can increase the OH costs [13].

The ABC method more accurately distributes OH costs by tracking down these costs to activities and afterward linking the activity costs to three levels being; order, product and customer. Hence, rather than clustering various activities into an OH cost stock e.g. administrative OH, manufacturing OH, the cost driver is dissociated into several activities [73]. The ABC method can be split into two steps.

1) In the first step, costs are distributed according to the major activities taking place in different departments in a firm to create the activity cost stocks, entitled 'resource cost drivers'. Some example activities can be seen in Fig 2.6 below.

2) In the second step, the aforementioned distributed costs are associated to cost items e.g., product, customers by extracting activity cost drivers.

Factory sustaining activities	Product sustainaing activities	Batch level activities	Unit level activites
• Plant management • Buildings and land • Heat & lights	• Process engineering • Product specifications • Engineering change notices	• Setup • Moving materials • Purchase orders • Inspections	• Direct labour • Material • Machine costs • Energy

Figure 2-6 Sample activities used within ABC adapted from Cooper and Kapian [67]

Some variations of ABC method over years have been proposed and published e.g. activity-based management (ABM), where the focus is on processes rather than product, and data gathered through ABC instead utilised for performance measurement [75]. Time-driven activity-based costing (TDABC) is another example, which further advanced ABC to address and potentially remedy some of difficulties noted in the implementation of the ABC method [76]. ABC and TDABC are among the most regularly cited cost methods in academia, however, they have not been substantially adopted by practitioners in industry, since they are considered to be complex and time consuming, particularly ABC, mainly because of requirements of activity data or complicated OH distribution evaluation [77]. Further details can be found in [13], and in-depth analyses can be found in [78] [79] [80] [81].

2.3.3 Throughput accounting (TA)

Throughput accounting (TA) commences from the theory of constraints (TOC), and similar to ABC, TA is an example of a new cost accounting method [82]. TOC advocates that ''every system must have at least one constraint'' and ''the existence of constraints represents opportunities for improvement'' [83]. Constraints govern an enterprise's performance restraints, and in the absence of them, a corporate theoretically can earn inexhaustible profits. There are some consensus on the originality of TA and it is mostly linked to two groups of authors [13]. In the former group - Goldratt's work, three operational measures of throughput, inventory and operating expenses (e.g. non-variable cost) are allocated to TA and accordingly net profit and return on investment can be evaluated [84]. In the latter group – Galloway and Waldron, the aim of TA is to maximize profit for the bottleneck processes, and

it consists of parameters both associated to production, but also OH cost e.g. product development. All costs, aside from material cost, are considered as fixed costs in the short-term and are called total factory costs [85]. Further details can be found in [13] and in-depth analyses can be found in [84] [86].

2.3.4 Target and kaizen costings

Target and kaizen costings concepts are included in this section, firstly since, their focuses have historically been in automotive industry in Japan initially, and their variations were adopted and utilised in European and North American automotive industry afterward as well [87]. Secondly, since target and kaizen costings philosophy is very different from those of aforementioned ABC or TA. Cost reduction is of major challenge for the former philosophy, whereas, accurate product costing is the major issue for latter philosophy [88]. Thirdly, during production facilities visits and field trips over a course of two weeks in Japan taken by the author, it was noted that target and kaizen costing methods are still utilised as the main approaches in the automotive industry in Japan as parts of a Japanese cost management system. It should be noted that this cost analyses method stretches to include both product development and production unlike the other models listed here within section 2.3.

Target and Kaizen costings focus on different parts of the value chain; however, they cannot be considered separately since their approaches fulfil the same overall goal of an enterprise, which is moving the company strategy toward answering accurately customer and market demands [89] [90]. Nowadays, these two approaches main goal is to decrease life cycle costs (considering total product life cycle) in order to increase the profitability in a long run. The target costing process starts with the initial question of *'what should the product's cost be?'*, hence a competitive price based on customers' requirement is selected, which is called 'target price'. This is a strategic product positioning based on the enterprise overall policy. Proper profit margin is then subtracted from the target price, which is called 'target profit', and this process can be executed in top-down, bottom-up or mixed approach. Based on that, maximum acceptable costs to gain the target profit is selected, which is called 'allowable costs'. This is without concerning about actual technology and process standard. A moderate 'target cost' is then taken into consideration given sustaining the allowable costs. If this (a desired price) is not achievable in short-term, 'drifting costs' are introduced, which are forced as a compromise based on the market forecasts and standard costs that the state of technologies and process have.

These processes are conducted for both newly developed products and new types of products. Kaizen costing processes then begin with the main aim of decreasing the actual manufacturing cost of a product and span to complete cost reduction optimisations. This is done by implementing continuous improvements possible for each process activity. Further details can be found in [87] [91].

2.3.5 Life cycle costing (LCC)

Life cycle costing (LCC) is another method, which considers the entire product life cycle perspective and it was also introduced in similar time/period to target and kaizen costings (1960s). LCC was originated by US Department of Defence, and since its applications have now been outspread into other domains e.g. consumer products, equipment acquisition in manufacturing enterprises [92]. LCC has three main variations:

1) conventional LCC also called financial LCC
2) environmental LCC (eLCC), and
3) societal LCC (sLCC).

Conventional LCC is the original concept and in some ways is considered similar to the total cost of ownership (TCO) approach. eLCC is in line with life cycle assessment (LCA) when it comes to system boundaries, functional unit and methodological procedures. And, sLCC encompasses monetarisation of other externalities concerning both environmental and social impacts [92].

LCC can be performed for various aims hence the methodological selections and what cost parameters precisely need to be considered in a LCC assessment depends on the goal and scope of the study [93]. Nevertheless, table 2.1 illustrates LCC cost categories and cost components, which are mostly related to and are conducted in machine tools LCC studies. The present author has comprehensively analysed and implemented conventional LCC respectively in appended papers 3 and 4. For further details please visit chapter 4, sections 4.4 and 4.5, and appended papers at the end of this licentiate thesis.

Table 2-1 LCC cost distribution, adopted from the appended paper 3 [92] [94] [95] [96] [97]

Cost component	Cost elements
Acquisition costs	Initial capital costs, equipment costs, reconditioning costs, tool costs, spare part costs, installation costs, education and training costs, costs for buffer/ outsourcing production during installation/reconditioning, costs for ramp-up
Operation costs	Wage and related costs, material costs (incl.. transportation and handling), tool costs, rent costs (incl. e.g. space, heating, ventilation), Energy costs (incl. electricity, gas, compressed air), Media costs (incl. e.g. water, fluids and additives), cost of poor quality, downtime costs, occupancy costs, setup costs
Maintenance costs	Incl. preventive and corrective maintenance, inspection costs (incl. e.g. general, warranty), repair costs, wage and related costs
Disposal costs	Disposal costs for buildings, machinery and equipment (incl. e.g. service fee, landfill fees), costs for recycling materials (incl. e.g. collection, disassembly, taxes, service fees, landfill fees)

2.3.6 Performance part costing (PPC)

The cost model presented here as performance part costing (PPC) was originally developed by Ståhl et al. in 2007 [70] to assess manufacturing cost in sheet metal forming and metal cutting. It is a microeconomic or cost-breakdown model at a system level and is designed to calculate a part cost per unit for a produced batch in discrete manufacturing [69]. One of the main objectives of PPC is to provide essential and applicable information in production development activities focusing on the shop floor. The original model has been modified and further developed since 2007 and it has also been implemented for different purposes e.g. in production locations decisions or selection of alternative production steps [68] [69] [98] [11] to just name a few. The PPC model follows the manufacturing processing route to assess the effect of each production step on the total manufacturing cost of each part. It incorporates technical performance parameters with economic parameters to assess the entire impact of manufacturing performance on cost by concentrating on the factory floor [13].

The formulation of the PPC model is supported by the essential cost drivers e.g. tool, equipment, labour, raw material, maintenance, quality, processing materials, which are needed to complete manufacturing activities from cradle to gate (raw material to finished part). The total manufacturing cost is calculated in an accumulated manner where cost linked to each production step is added as the input cost for the next production step, and the cost of raw material is initially included in the first production step. This procedure enables users to grasp, separate and evaluate to what degrees these costs are caused by both value-adding activities and non-value-adding activities e.g. disturbances such as downtime and quality issues which may occur along the manufacturing processing routes [13] [29]. This procedure remedies some of the changes associated with macroeconomic models where usually aggregated data are utilised and value-added and non-value added times are not differentiated. Nevertheless, macroeconomic models at a system level can precisely evaluate manufacturing cost of a part retrospectively. Whereas, it is harder to evaluate manufacturing costs ahead in time, especially when many varying parameters are undisclosed or change rapidly. Some of these essential parameters (manufacturing cost's drivers) e.g. cycle time, downtime or rejection rate, are interconnected as well [69]. Hence, having the capability of distinguishing value-added activities from non-value-added ones assist the prioritisation in making decision e.g., about which parameters to optimise in order to reduce cost, increase capacity or foster competence developments.

Equation 1, 2 and 3 below respectively illustrate total manufacturing cost per part (k), equipment cost during operation hourly (k_{cp}) and equipment cost during downtime or idle hourly (k_{cs}). For detail descriptions of each parameter, please visit the list of parameters at the beginning of this licentiate thesis, or the tables within the appended papers at the end of this thesis. Equation 1 presented below is the comprehensive version of PPC model including all the cost drivers developed since

2007 [29]. It can be noted from the licentiate's appended papers that different versions of the model in equation 1 are utilised given the nature of the industrial case studies (e.g. data availability and sensitivity) and the object (gearwheel) under the study. However, the foundation principles and the procedures of the PPC model deployed is the same as the original model presented in 2007 [70].

$$\boldsymbol{k} = \frac{k_A}{N_0}\left(\frac{N_0}{(1-q_Q)}\right) + \frac{k_B}{N_0}\left(\frac{N_0}{(1-q_Q)(1-q_B)}\right) + \frac{k_{CP}}{60N_0}\left(\frac{N_0 \cdot t_0}{(1-q_Q)(1-q_P)}\right) \tag{1}$$

$$+\frac{k_{CS}}{60N_0}\left(\frac{N_0 \cdot t_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_{Pb}\right)$$

$$+\frac{k_D}{60N_0}\left(\frac{N_0 \cdot t_0}{(1-q_Q)(1-q_P)(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_{Pb}\right)$$

$$+\frac{1}{MD}[K_E + K_G + K_{RW}]$$

$$\boldsymbol{k_{CP}} = \frac{K_0 \cdot \frac{i(1+i)^n}{(1+i)^n-1} + k_{ren}\frac{N_{ren}}{n} + Y \cdot k_Y + T_{plan} \cdot \left(\frac{k_{Mh}}{h_{P,M}} + k_{ph}\right)}{T_{plan}} \tag{2}$$

$$\boldsymbol{k_{CS}} = \frac{K_0 \cdot \frac{i(1+i)^n}{(1+i)^n-1} + k_{ren} \cdot \frac{N_{ren}}{n} + Y \cdot k_Y}{T_{plan}} \tag{3}$$

K_{cp} and k_{cs} are measured based on the technical and financial parameters such as yearly work hours, equipment technical life time, investment cost, cost of investment e.g. annuity, equipment footprint [70]. The three performance parameters of quality (Q), productivity (P) and availability (A), which are the essential components of overall equipment efficiency (OEE), are included in the equation 1 above. OEE parameters are calculated respectively based on rejection ratio (q_Q), production rate loss (q_P) and downtime ratio (q_S).

It was earlier mentioned in chapter 1 (introduction) in section 1.3 (purpose and research questions) that the comparative manufacturing cost analysis in this licentiate is based on customers' requirements on performance and quality of a given part for a particular application. In this case, the application is gear manufacturing. Hence, the present author's motivation in selection of a cost model for this licentiate study is through the lens of manufacturing performance and quality utilisations and the capability of models to capture these activities. It was also mentioned earlier in this chapter (see section 2.3, second paragraph) that previous comparative studies, which the present author builds his research foundation on, recently summarised various cost accounting methods and manufacturing cost models [13] [69] [68] [29]. These analyses have taken into account the models that clearly reported the

parameters and calculation methods in each model. Based on the result found in [29], the original PPC model developed in 2007 [70] includes more parameters and cost components particularly performance drivers in comparison to the other models. Therefore, the present author selects the presented PPC models in equations 1 to 3 for this licentiate thesis research.

The PPC model is designed fundamentally for discrete manufacturing and batch manufacturing, and hence the two gear manufacturing technologies compared in this thesis comply with these requirements. Nevertheless, it is possible to implement the model for continuous manufacturing by disregarding the setup time, and also for one-part manufacturing by selecting the batch size to be one. However, these cases are not included in this thesis. In the PPC model, SEK (Swedish krona) is used. However, the model is generic and does not rely on the currency unit selected.

3 Methodology

This chapter elaborates on the overall research methodology, which is used in this licentiate thesis, and it also outlines the different research methods e.g. case study, semi-structure interviews, survey questionnaires, which were applied in the five appended papers. It concludes with a discussion on the research quality of this study.

3.1 Research philosophy and view on science

It is worthwhile to define what research and science are in the beginning of this chapter; since the main discussion here will be centred around research design and approaches in a scientific field. Research could be described as series of actions that provide support to the comprehension of an event [99].

Van Aken has divided scientific disciplines into to three groups of [100]:

1. The formal science like philosophy and mathematics
2. The explanatory science like the natural science and majority of the social science
3. The design sciences like the engineering and also medical sciences

The research presented in this licentiate fits into the third group, design sciences, since it is an engineering research and concerns models and methods development and validation.

3.2 Research activities

The research activities undertaken in this licentiate thesis and its five appended papers were conducted between November 2016 and November 2019. Paper 1 contributed to answering the research question 1 (RQ 1) and the rest of the papers (2 to 5) contributed to answering both RQ 1 and 2. The figure 3.1 illustrates the time alignment of the five appended papers and this licentiate RQs through the course of

part one of this research project. The starting point of each coloured box visualises when the empirical data was initially retrieved and when it was publicly presented.

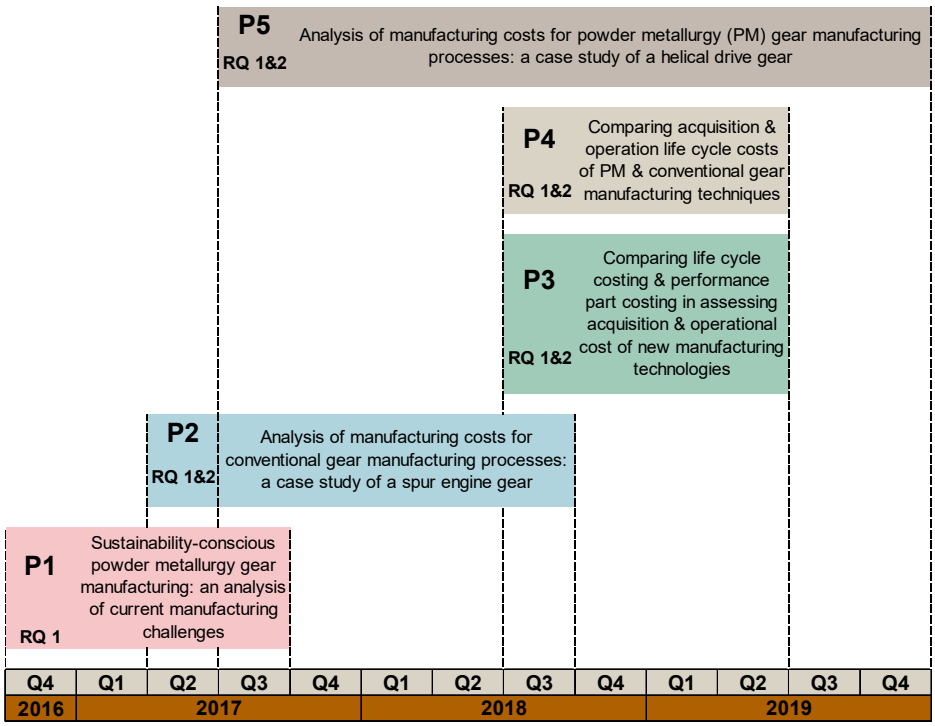


Figure 3-1 Time alignment of the five appended papers and the research questions

3.2.1 Research design and data collection

The overall research approach applied in this licentiate a mix research method, as combination of both different qualitative and quantitative tools are used to approach and answers the RQs [101] [102].

In paper 1 as a starting point of this research project's work package (WP5), a literature review was conducted to understand the state of the industry for both conventional wrought steel and press and sintering (P/S) gear manufacturing technologies. See section 4.2 in chapter 4, for further details on the outcomes. Afterward, an exploratory case study (qualitative) was developed in order to comprehensively map the processing routes and their included production steps for both gear manufacturing technologies, and also to identify the barriers experienced by practitioners associated with these two technologies. In this case study a series of semi-structured interviews with three Swedish companies were conducted. Over a course of four months (Nov 2016 – Feb 2017), nine people have been interviewed either in person or over audio/video conference calls. For further details visit the appended paper 1 and particularly its section 3 (method).

In paper 2, following the conclusion and suggestion provided in paper 1, an industrial case study was designed for the conventional wrought steel gear manufacturing processing route. In order to gather the input data for the quantitative analysis (a comparative manufacturing cost modelling), a mix of qualitative methods were used. These methods were semi-structure interviews, production facilities visits to retrieve data from company's manufacturing execution system (MES) and/or enterprise resource planning (ERP). Based on these processes, a manufacturing cost calculation tool was developed, proposed and applied. For further details, visit section 4.3 of chapter 4, and the appended paper 2, and particularly its sections 2 and 3.

In paper 3, the cost model selected for this licentiate thesis (PPC, visit chapter 2, section 2.3.6) was compared with life cycle costing (LCC, visit chapter 2 section 2.3.5) using both qualitative and quantitative methods. LCC cost components (input parameters) for machine tools application were gathered from literature review, and they were correlated with the associated PPC input parameters. See chapter 4, section 4.4 for further details on the outcomes. Afterward, the industrial case study, which was utilised in paper 2, was further developed to include LCC parameters and perspectives. The method to collect data for cost calculation and comparison was top-down interviews. For further details, visit the appended paper 3, and particularly its sections 2 and 3.

Paper 4 was conducted in parallel with paper 3 and approximately within the same timeframe. The lessons learnt from LCC and the outcomes of the paper 3 case study were also utilised in paper 4. A new case study was designed for a P/S gear manufactured processing route in order to be compared, from LCC perspective, with the gear studied in papers 2 and 3. The methods used to collect input data were semi-structured interview, questionnaires and P/S part makers' production facilities visits. For further detail, visit the appended paper 4. A comprehensive literature review of PM capabilities were also presented. For further details, visit the appended paper 4, and particularly its section 3.2.

Paper 5 was initially conduced in parallel with paper 2 as their objectives are partially similar. For details visit chapter 4, section 4.6. The same industrial case study as the one used in the paper 4 was selected for the paper 5 investigation. In order to retrieve both technical and financial input data, 6 companies and in total 11 people have been interviewed and when there was a knowledge gap in the required data, estimations were made based on the findings from literature. For further details, visit the appended paper 5, and particularly its section 3.

Table 2.1 summarises the selection of methods in relation to research questions (RQs) in this licentiate.

Table 3-1 Research design and data collection for the five appended papers

P #	Paper aim	Research design	Purpose	Data collection methods	RQ s
1	Mapping challenges of conventional and PM gear manufacturing processing routes and to identify the complete set of productions steps wtihin both technologies.	Exploratory case study: Qualitative analysis followed by interpretation.	To understand the 'how' and 'why' of a contemporary phenomenon.	Literature review; 9 semi-structured Interviews among 3 companies; observation.	RQ1
2	Benchmarking of a developed and tailored cost calculation tool with an existing cost model and method used by the case study company in order to analyse manufaturing costs based on the production steps performace	Industrial case study: Quantative and qualitative in parallel, followed by benchmarking, comparison and interpretation.	To test the feasibility of the proposed PPC model for the case study object.	Literature review; 5 semi-structured interviews, iterative production facility visits to retrieve data from data management systems.	RQs 1&2
3	Comparing the selected manufacturing cost method (PPC) with Life Cycle Costing (LCC) in order to identify cost parameters required for conducting well informed production development decisions	Industrial case study: Qualitative and then quantative, followed by comparison and interpretation	To learn LCC through a quantified comparison to the PPC model	Case study (semi structured Interviews), facility visits for direct data gathering, qualiative and quantitative analysis.	RQs 1&2
4	Comprehensively mapping challenges of P/S gear manufacturing capabilities and supplying some empirical evidence of the economic aspects of P/S processing routes for gear manufacturing.	Industrial case study: Qualitative and then quantative, followed by comparison and interpretation	To test the applicability of intergrating the PPC model into LCC	Case study (semi structured Interviews), facility visits for direct data gathering, qualiative and quantitative analysis.	RQs 1&2
5	Comprehensive cost analysis of a gear manufactured by P/S processing route and analysing the capability of the tailored PPC model to assist production development scenarios.	Industrial case study: Quantative and qualitative in parallel, followed by comparison, scenarios planning including sensitivity analysis and interpretation.	To test the feasibility of the PPC model for the case study object.	Case study (semi structured Interviews), facility visits for direct data gathering, qualiative and quantitative analysis.	RQs 1&2

3.2.2 Research quality

Two lenses were applied to ensure research quality and are outlined below. There are some overlap in these terms, however both lenses were used in order to limit any possible research quality issues and support the author in checking his own assumptions and biases.

3.2.2.1 Reliability and Validity

Research with a high quality must be reliable and valid, thus requiring that the methods chosen to answer the research questions (RQs) provide the requisite accurate data in order to assert plausible conclusions [103].

Reliability. Reliability of a research study is based upon four elements:

- *Participant error* – in this research study this could be seen as inaccurate data given to the author from the partner organisation.
- *Researcher error* – in this study this could be seen as errors within the design or use of the customised excel PPC tool created for each of the two manufacturing technologies and their respective processing routes.
- *Participant bias* – this could be anything that limits the capacity of the partner organisations and interviewee's capacity to discern and give a true and accurate account of the circumstances under study.
- *researcher bias* – this could be prior assumptions that cloud the authors judgment either from his prior career or literature review which may limit the authors capacity to see novel themes or patterns arise from his research.

Validity. The validity of a research study can be broken down into three main areas: constructed validity, internal validity and external validity.

- *Constructed validity*. This is a measure of how well the study demonstrates a causal relationship between the research questions and chosen methods used.
- *The internal validity*. This relates to validity of the claims made within the study. Ensuring that the causal relationships used within the study are sound and true and that all of the underlying assumptions within this research were verified and tested throughout.
- *The external validity.* This relates to how generalizable the study's findings can be.

3.2.2.2 Trustworthiness

Another lens to look at research quality is trustworthiness. Lincon and Guba [104], assert that trustworthiness of a study is reliant on four key elements:

- *Credibility*: Is the data gathered within the study complete and true?
- *Transferability*: Are the findings applicable to other cases in other locations and time periods?
- *Dependability*: Was the harvesting and analysis of data consistent and repeatable?
- *Confirmability*: Was the author neutral in his methods and actions throughout this research study?

4 Contributions and appended papers summary

This chapter summarises the five appended papers in detail, and also presents their connections to the research questions. Moreover, a comparative cost analysis of conventional wrought steel and PM gear manufacturing technologies, which is not included in the appended papers, is presented.

4.1 Summary of papers sequences

This licentiate' research activities were initiated with the start of paper 1, which conducted a literature review to learn more about conventional wrought steel and PM gear manufacturing technologies and the limitations associated with each of them. Semi-structured interviews were in parallel performed to validate and strength the literature reviews outcomes. Afterward, two industrial case studies, reported in papers 2 and 5, were outlined in order to compare the gear manufacturing costs associated with these two techniques. Hence, technical drawings including gear data e.g. number of teeth (z), outer and inner dimensions were communicated with the partner companies in order to select case study' objects. The gearwheels were selected based on 1) reasonable preciseness and 2) the final gear's performance and quality requirements for comparability purposes.

Based on this process, in paper 2, the conventional wrought steel gear manufacturing cost was analysed in-depth utilising the tailored PPC model. Despite the fact that the original plan was to conduct a similar study for a P/S gear in parallel to paper 2; that was not possible at that time due to an extensive lack of data availability. The author's experience here has supported one of the main findings of the paper 1, obtained from the literature review and author's interviews, addressing the lack of PM technical and financial data availability.

Paper 3 was also linked to the tailored PPC model utilised and its conducted case study in paper 2. In addition, papers 3 was further developed to analysis the life cycle thinking capabilities of the PPC model. This was done by comparing and contrasting PPC approach to life cycle costing (LCC) approach considering their applications and included cost parameters. The paper 3 findings were empirically tested in two case studies, one in the paper 3 for the conventional wrought steel gear

processing route, and one in paper 4 for P/S gear processing route. The objectives of the paper 4 were to:

- Firstly, to revisit the findings of the paper 1 after almost 2 years of its publication to update the state of the art and the industry for P/S gear manufacturing technologies.
- Secondly, to conduct an empirical case study similar to the one in the paper 3, but for P/S gear processing route.
- Thirdly, to compare the outcomes of the papers 3 and 4.

In paper 5, based on the findings of all the previous four papers, a P/S gear manufacturing cost was finally analysed in-depth utilising the tailored PPC model. The case study gear was the same as the one utilized in the paper 4.

Table 4-1 Summary of main features and outcomes from the five appended papers

Paper	Main Contribution to RQ 1	Main Contribution to RQ 2	Main contribution to overall project
1	Mapping the processing routes for both gear manufacturing technologies in order to identify the production step cost drivers and the associated challenges.	Same as the one for RQ 1	The findings was the starting point for both cost analsyes and sustainability assessment parts in order to create the research agenda for this work package (WP5).
2	Identifying the breakdown cost parameters needed for a detailed fact based cost analysis for conventional wrought steel gear manufacturing.	The initial breakdown manufacturing cost analysis for conventional wrought steel gear manufacting tobe used in the final comparative in section 4.7 of this chapter.	Directly provides an example of cost analysis method used in industry and highlights the associated challenges.
3	Comparing and contrasting two cost accounting methods (PPC & LCC) to ascertain weaknesses and propose hybrid solutions to ensure a high level of detail cost analysis model to be used in future papers	Utilsing the two cost accounting methods (PPC & LCC) to analyse the wrought steel manufacturing process route.	Comparison of the chosen PPC cost model with a broader life cycle perspective for the conventional wrought steel gear.
4	Showing the importance of taking a life cycle persepctive when comparing the two manufacturing techologies and outlining the key variable of aquisition costs	Analysing the acquistion cost comparion between the conventional wrought steel and P/S processing routes which helps with the rationalisation of comparative study in section 4.7 of this chapter.	Based on the learnings from Paper 3, a comparison between conventional wrought steel and P/S acquisition costs was conducted.
5	Identifying the breakdown cost parameters needed for a detailed fact based cost analysis for P/S gear manufacturing.	The initial breakdown manufacturing cost analysis for P/S gear manufacting tobe used in the final comparative in section 4.7 of this thesis.	Utilised the PPC model to analyse the associated manufacturing costs for P/S processing route.

4.2 Paper 1

Title: Sustainability-conscious powder metallurgy gear manufacturing: an analysis of current manufacturing challenges.

4.2.1 Brief description and overall objective

The objective of paper 1 is to identify and compare the production steps for both conventional wrought steel and powder metallurgy (PM) gear manufacturing. This includes mapping the challenges and opportunities in both manufacturing processing routes, with the purpose of providing knowledge on the parameters needed for manufacturing cost analysis aligned with sustainability.

4.2.2 Results

From mapping both conventional wrought steel and P/S gear manufacturing processing routes, and reviewing their production steps, it can be clearly noted that the conventional wrought steel route is longer (this could also means longer setup time), material utilisation is lower, and poor lubrication capability of conventional lubricant and cooling systems gives rise to excessive tool wear. PM has two main competitive advantages of 1) (near) net-shape and 2) shortened processing routes. These two advantages could potentially increase the business case advantages as well, by e.g. investment cost savings (plant's space, operational costs – labour, disposal energy). Wrought steel machining processes to produce gears are well established and today are the main methods to manufacture gears. PM processes are already used to produce gears (not to a large scale), however, not for heavy-loaded gears within the automotive industry, despite all the aforementioned advantages. Three technical and four non-technical barriers to PM gear adoption and deployment were identified.

The most significant technical barrier is PM materials porosity, which leads to lower PM gear performance in comparison to a forged gear. Some typical examples are PM gear's inferior pitting resistance strength and tooth root and bending stress. The second technical barrier is PM pressing technologies' dimensional limitations, and the third barrier is economies of scale (e.g. batch size vs. high PM tooling expenses). The first and foremost non-technical barrier is the misperception and less favourable mind-set towards PM among practitioners. The second non-technical barrier is in-house manufacturing policies, high initial capital investment and the acquisition of new competences. The third non-technical barrier is a lack of harmonized and consistent material data for PM, and the forth barrier is lack of education and training in PM gear manufacturing.

4.2.3 Discussion and conclusion

There are scores of scientific literatures and case studies in companies on how to improve efficiency and productivity of conventional machining processes, and PM is lagging behind in this regard. There are few PM studies focused on economic comparison either by scientists or practitioners, and there are few corporate PM feasibility studies e.g. material properties testing and full transmission validation testing. The PM economic comparison studies are, to high degree, conditional on the scenarios and the cost model approaches used in the study. Manufacturing companies use various cost models to calculate their products' production costs roughly based on numerous estimations, and these models are usually internally developed. There is a lack of a fact-based generic model, which any company can utilise to both benchmark against their own model, and to adopt for their product portfolio.

4.3 Paper 2

Title: Analysis of manufacturing costs for conventional gear manufacturing processes: a case study of a spur engine gear.

4.3.1 Brief description and link to previous appended paper 1

Based on the conclusion and suggestion made in paper 1, the lack of a fact-based generic manufacturing cost model, the purpose of paper 2 is to investigate both the advantages and disadvantages of applying a performance part costing (PPC) method in comparison to the current method used for analysing and calculating gear manufacturing costs in a partner company. A case study is designed where a spur engine gear is selected for this comparison. The cost parameters in the method used in the company (modified standard costing) are compared with those in the manufacturing cost calculation tool tailored in this licentiate thesis (based on PPC).

The participating company is a Swedish sub-contractor to the commercial vehicle industry, and it is in search of a cost calculation methodology that provides a richer decision-making support for its production development scenarios. That was the company's motivation to collaborate in this work. The object selected for this case study is an engine spur gearwheel with an annual production volume of 6,500 units.

4.3.2 Result

The case study company uses a modified version of standard costing, where the main cost parameters included are direct material cost, direct labour cost and overhead (OH). The standard costing is typically used for future cost estimation, performance assessment, and budget preparation in organisations. One of the main disadvantages of standard costing is that greater parts of the cost drivers are hidden in the OH, and when the main objective is to come up with production system optimisation (e.g. improvement opportunity scenario planning), standard costing is not up to the task. This is because, as the result of this case study also indicates, the majority of the cost parameters are not linked to their costs pool properly. That makes it very complicated to find the right activity behind a cost and hence harder to find an alternative or suggest an optimisation process. Thus, any parameter, which is concealed in OH, is a lost improvement opportunity.

The conventionally manufactured case study spur engine gear is illustrated below with all its production process routes in figure 4.1. The results after comparing the implemented proposed model with the model used in the company shows a 6.3% difference in total manufacturing costs between the two models. The proposed model has the higher number calculated, and that can be explained by the fact that the proposed model includes overall equipment effectiveness (OEE) parameters

(availability, performance and quality), but the model currently implemented in the company does not, and that itself is also a drawback for the company used model.

Figure 4-1 Processing route for the case study gear – manufactured conventionally

The result also shows significant differences among the cost distribution between the two models' cost parameters, despite the fact that the total manufacturing costs are similar. When analysing the share of each cost parameter against total manufacturing cost with the purpose of optimisation and improvement prioritisation, different strategies can be reached when looking into the results of these two models. The knowledge gained from the company model are limited since most of the main cost drivers, which can be identified otherwise using the proposed model e.g. tool cost (13% of total share), equipment cost during downtime/idle (7% of the total share) are hidden in indirect manufacturing cost OH or indirect material cost OH. Hence, these costs are not visible as improvement opportunity, and cannot be calculated neither explicitly nor accurately.

4.3.3 Discussion and conclusion

OEE is not included in the model used in the company as mentioned earlier in comparison to the proposed model, and that is one of the main differences between these two models. Inclusion of OEE supports the analysis with indicating the cost impact of reduced downtime or increase quality yield. As a hypothesis and a scenario, if OEE parameters of availability and performance were assumed to be 100%, the manufacturing cost calculated with the proposed model would be 4% cheaper than the model used in the company, instead of originally being 6.3% higher. The main reason for which the cost calculated with these two models are not the same is because the cost drivers hidden in OH are distributed so unevenly, that the identified cost parts used in proposed model are estimates and there is some level of uncertainty need to be considered here.

Nevertheless, from inclusion of OEE it can be noted how availability, performance and quality factors influence the total manufacturing costs. For example, the equipment cost during downtime/idle and labour cost can be reduced with optimising the availability and performance. The potential improvement scenarios, which has been identified after presenting the comparison of these two models to the company representatives, are; increasing the automation level, reducing manual labour cost, reducing equipment downtime and increasing tool utilisation.

Some of the advantages of implementing the developed and proposed model in comparison to the current model used (standard costing) by the company, which is extremely common in manufacturing sector, are:

- manufacturing costs drivers are more accurately allocated,
- mark-ups (e.g. OH) are eliminated,
- more in-depth knowledge about each cost driver is provided to support decision-making such as analysing, comparing and prioritising between different production development scenarios.

With utilization of the proposed cost model, each manufacturing processing route can be separately assessed based on its production steps and associated cost drivers, and that provides a clear breakdown of how optimisations within each processing route can affect the overall manufacturing costs.

4.4 Paper 3

Title: Comparing life cycle costing and performance part costing in assessing acquisition and operational cost of new manufacturing technologies.

4.4.1 Brief description and link to previous appended papers

The overall purpose of paper 3 is to compare the performance part costing (PPC), utilised in paper 2 above, with life cycle costing (LCC) considering their calculation methods including their parameters and applications. Based on the paper 2 findings and cost modelling literatures, which both argue the trade-off between selections of simpler cost models or models that are more complex. With the simpler cost models, which usually contain a fewer parameters limited level of knowledge can be obtained, and with more complex models, which usually require more efforts in retrieving input data (if ever it is possible), richer knowledge to make well-informed decisions can be obtained. Paper 3 aims to advance the PPC model with learnings from the LCC model. Since, the purpose of the research project is to analyse gear manufacturing costs for the selection of alternative cost-effective technologies, LCC is an appropriate method to consider.

The participating company is looking for a cost calculation methodology, which provides a richer decision making support for production development scenarios. The company is currently using a modified version of standard costing, and it has not practiced LCC prior to this study. Hence, its motivation to take part in this study is to create LCC knowledge with assessing the acquisition and manufacturing costs of the selected gear in this work. The company is a Swedish sub-contractor to the commercial vehicle industry, and the case study object is a spur engine gear with the annual production volume of 6,500 units.

4.4.2 Result

In order to compare LCC and PPC calculation methods and included parameters, firstly, the input parameters or cost components and elements for each method need to be mapped. PPC has established input parameters and they can be easily listed. In comparison, the cost components, which need to be included in an LCC study varies among different models and case studies and is rather limited by the data availability and aim of the studies. Based on a literature review on the LCC studies for machine tools, some similarity in cost elements in an aggregation levels noted, hence LCC cost elements retrieved and suggested for this comparative study. Secondly, the scope of each model needed to be the same. Since the PPC model focuses on a single actor in a manufacturing value chain and in this case, gear manufacturer, among three different type of LCC, the conventional LCC, which has a single actor perspective has chosen for this comparison.

The findings, after correlating LCC cost components with the related PPC parameters, indicate that acquisition, operation and maintenance costs in LCC are fully covered by PPC model. Hence, the majority of LCC components are accounted in PPC; however, since PPC is a manufacturing cost model, which shows a snapshot of a firm current production activity, and its objective is to optimise the production activities and its associated decisions within the factory walls, it does not incorporate the majority of disposal costs. For the same reason, in contrast with LCC that estimates future life cycle costs associated with the system under the study and convert them to their present values (discounting techniques), PPC model does not utilise discounting nor any similar techniques.

Timing is another difference between these two models, PPC includes and analyses the effect of production time factors such as cycle time, setup time, batch production time. These parameters are not always included in LCC, e.g. in a literature review of machine tools LCC studies; only setup time is found. However, LCC instead encompasses ramp-up costs and training and education costs, which can be added to PPC, but are not included as a default. As both models have to rely on varies cost assumptions and estimations, although in different degrees, uncertainty and sensitivity analysis is an essential part. The process is somehow similar in both models. The PPC allocates upper and lower margins of error for each cost driver, and this not only includes fixed numbers, but maximum and minimum values are also allocated based on the market intelligent and interviews with production and process engineer and higher management in this case study.

The developed LCC calculation encompasses the acquisition, operational and maintenance costs as shown in equations 4 and 5 below. End of life costs (e.g. disposal costs) assumed to be near zero, suggested by the partner company, considering selling their scrap parts and equipment and their related financial gains. Based on the results of paper 2, which highlighted advantages of implementing PPC model instead of standard costing e.g. manufacturing costs are more accurately allocated to the activities and elimination of mark-up such as overheads. And, since one of the results of this paper shows that, the entire LCC operation costs is covered by PPC model, this study uses PPC model to calculate LCC operation costs.

$$\text{LCC} = \sum_{c=1}^{3}(\text{Acquisition costs}) + (\text{Operation costs} \times \text{SPV*}) + (\text{Maintenance costs} \times \text{SPV*}) \quad (4)$$

$$\text{SPV*} = \left[\frac{1+e}{1+i}\right]^{n} \quad (5)$$

4.4.3 Discussion and conclusion

In general, the findings of paper 3 suggest that these two models, LCC and PPC, cannot replace each other, since their focuses are different. The PPC model focuses on defining and analysing the current manufacturing conditions and planned decisions. LCC also aims to act a decision support system (DSS), but in evaluating, the total costs related to buying or making, owning and disposal of a product or system. Timing of the analysis is another factor, which differentiates these two models. As it mentioned in the result section above, the PPC focus is on current manufacturing activities of a company in their currently utilised production systems. However, LCC has two different types when it comes to timing called ex ante LCC and ex post LCC. Ex ante LCC is a prospective approach rooted in evaluations and judgement, and it is typically used in the initial phases of decision-making processes e.g. in planning scheme for a new investment. Whereas, ex post LCC is a retrospective approach rooted in definite gained outcomes, and it is typically used at the end of a project.

PPC in nature is a modular model and can be implemented in different manufacturing settings and its calculation methodology in formulated and described comprehensively in both academic and practice arenas. Nevertheless, the findings of paper 3 and other literatures suggest that comparing different LCC studies with each other found to be difficult as parameters that are included in LCC evaluations varies among different studies, and, could be sometimes, based on scientist or practitioner's interpretations.

When the purpose of a cost analysis is to evaluate different manufacturing technologies alternatives, only focusing on manufacturing costs instead of a full life cycle perspective, could lead to avoiding or neglecting other major aspects and their associated costs. Hence, paper 3 suggests that using PPC model alone is not sufficient, and PPC instead can be utilised as a part of a LCC analysis as the case study in this paper illustrated. Alternatively, PPC model can be further advanced to adopt a holistic perspective and learn from LCC approach to encompass a cradle to grave strategy.

4.5 Paper 4

Title: Comparing acquisition and operation life cycle costs of powder metallurgy and conventional wrought steel gear manufacturing techniques.

4.5.1 Brief description and link to previous appended papers

The overall purpose of paper 4 is to compare powder metal (PM) gear production cost with wrought steel gear production cost (machining processes) from a life cycle perspective considering their acquisition and operational costs. This paper is built on the findings of all three previous papers summarised above in this licentiate, and its main focus is on the PM production capabilities (e.g. processing routes options). Some of the findings of papers 2 (section 4.3) and 3 (section 4.4) regarding conventional wrought steel gear manufacturing cost analysis and its life cycle costing (LLC) have been directly used for the purpose of comparison with PM gear manufacturing in paper 4. A case study is designed where a R&D PM gear and the same wrought steel gear, which was analysed in the two previous papers, were compared from the LCC acquisition and operational perspectives.

4.5.2 Result

PM gear manufacturing technology capabilities with their production setups and output performance and quality is mapped, and most of the PM production processing routes are described briefly as the result of the literature review. Paper 4 argues that beyond displaying PM production and processes technical advantages; there is a lack of showing PM production and processes economic aspects. And that, could act as a barrier to PM mass adoption and deployment. This understanding from the literature review was confirmed from interviewing PM part producers as well. They have emphasised on their customers increasing demand on reducing manufacturing costs and highlighting PM cost advantages.

The study hypothesis was that there are not many publicly available studies and data (either technical or financial) on PM economic aspects, and that has been tested and confirmed after an attempt to conduct a systematic literature review. The results were very limited and not even sufficient for the continuation of the systematic literature review, e.g. no LCC on PM gear manufacturing (or PM components) could be found. Having said that, paper 4 sought to tackle this knowledge gap by providing some empirical data from comparing PM and conventional gear manufacturing. The result of the case study shows that acquisition costs (incl. initial capital cost, equipment cost, reconditioning cost, tool cost, installation cost, education and training cost) for PM gear manufacturing is almost three times higher than of those for the conventional machining processes. This result is in line with previous

studies' findings indicating PM costly initial capital cost, especially PM tooling cost, in comparison to machining processes.

4.5.3 Discussion and conclusion

P/S may have some technical advantages over its counterpart in gear manufacturing e.g. higher materials utilisations, lower energy consumption, faster cycle time and better noise vibration harshness (NVH) behaviour of the final gear produced by its technology, in order to justify its higher investment cost. Paper 4 suggests that the PM community (e.g., gear manufactures) need to strive for more competitive advantages to illustrate P/S benefits to discern P/S from other competitive technologies in the market.

As reported above the LCC acquisition costs for both P/S and conventional gear manufacturing techniques are assessed and compared. However, unfortunately, due to a large gap in data availability, LCC operational cost calculation could not be performed for PM and no other previous similar studies could have been found. Hence, no realistic assumption could have been made to conduct such a cost calculation and this in addition to lack of data, could hinder showing PM market competitiveness. Despite these limitations, some of the key findings of the paper 4 are; a comprehensive illustration of PM processing routes and its associated full technical capacity to compete with well-established machining processes. In addition, putting forward some quantitative results based on empirical data to support bridge the knowledge gap in PM economic aspects, which has been first hypothesised and later on validated by the authors based on an attempt to conduct a systematic literature review.

4.6 Paper 5

Title: Analysis of manufacturing costs for powder metallurgy (PM) gear manufacturing processes: a case study of a helical drive gear.

4.6.1 Brief description and link to previous appended papers

The main objective of paper 5 is very similar to that of paper 2 reported above (section 4.3) with the exceptions of instead of focusing on conventional gear manufacturing cost as the paper 2 has done, paper 5 focuses on PM gear manufacturing cost analysis. Another difference is that paper 2 implemented the developed performance part costing (PPC) model as a benchmark to the existing model utilised in the case study company to calculate manufacturing cost. Paper 5, however, utilises the PPC model capability of defining and simulating different production scenarios to assess the economic influences of two scenarios on the total PM gear manufacturing costs. The scenarios are 1) automation of gear rolling process, and 2) improvement of overall equipment effectiveness (OEE) parameters, together with a scenario in which energy price (in this case electricity price) increases. The object selected for the study is a helical 4th drive gear, which is the same R&D gearwheel as the one used in the paper 4 case study.

4.6.2 Result

Figure 4-2 PM processing route for the case study helical gear

The manufacturing processing routes for the helical gearwheel analysed in this study is illustrated in figure 4.2 above. A modular excel cost assessment tool was created based on the input from the case study participants and the literature review findings. The excel tool calculates the total P/S manufacturing cost based on the given production steps and its associated cost drivers.

Based on the result, each production step can be analysed individually to assess the influence of each cost driver on the total P/S manufacturing cost. This could provide the case study companies valuable in-depth knowledge on their process optimisation based on their available resources and priorities. Gear grinding (incl. washing of the final gearwheel) is the most significant production step with a share of 35% of the total PM manufacturing cost calculated in this study. The high cost of gear grinding can be explained by its high investment and labour costs. In addition, the selected helical gear in this study is a complex part with 12 holes (to reduce

weight), which may increase the finishing machining cost. Material cost (25%) and heat treatment (HT) process (17%) are next two major cost driver and production step for this study gear. HT was outsourced in this case study, and only its purchase price was available.

The designed cost calculation tool, based on the PPC model, has the capability of defining and simulating different production development scenarios. The two improvement scenarios, which have been evaluated in this case study, and a scenario where the electricity price is increased, are reported in the discussion section below.

4.6.3 Discussion and conclusion

The first scenario is automation of the second densification process (gear rolling). The process development and equipment investment costs for automation of gear rolling add 26% to the equipment capital costs. The overall equipment effectiveness (OEE) of gear rolling reduces by 5% after automation, which might be due to automation disturbances. Despite the considerable automation development cost for gear rolling, its influences on both gear rolling process cost and total PM gear manufacturing cost are marginal being respectively 0.6% and 0.04% cost reductions per part.

OEE measurement is an important part of the PPC model, and can provide insight on e.g. the cost influence of reducing downtime and increasing part quality. OEE improvement is the second scenario is this paper. OEE is calculated based on the measurement of availability (A), performance (P) and quality (Q) parameters in production systems. In this study the PM industry practical OEE of 69% (A: 70%, P: 100%, Q: 98%) is compared with low OEE of 50% (A: 55%, P: 96%, Q: 95%) and the hypothetical world-class OEE of 85% (A: 85%, P: 100%, Q: 99%) in order to evaluate the influence of changes in OEE on the PM gear manufacturing cost.

The last scenario is not essentially an improvement case, but rather it investigates the significance of change in the energy price in this case electricity (EL) price. Swedish statistics indicated a rather stable EL price for the Swedish industrial customers for the last 32 years with one occurrence where the EL price almost doubled. Two cases of doubling and quadrupling in EL prices are selected in this study. The biggest impact is on the sintering with 7% and 21% increases in its production step cost (per part) with respectively doubling and quadrupling the EL price. This could be explained by the fact that furnace processes like heat treatment and sintering are shown to be the dominant energy consumers among production steps.

Sensitivity analyses based on the lower bound and upper bound values were conducted, and their outcomes were compared with the base case analyses and their values. Regarding gear rolling automation, the results indicated that automation could be financially efficient to a level that does not have a negative impact on the gear rolling performance. Regarding OEE improvement, the significant influences of OEE parameters on manufacturing cost per part were shown in this case study too, similar to the previous case studies like the one shown in the paper 2.

Table 4-2 Gear rolling automation sensitivity analysis

Gear rolling process automation scenario	Automation investment cost	Total PM gear manufacturing cost per part	Gear rolling process cost per part	Equipment cost during operation	Equipment cost During downtime
Lower bound value	▲ 20%	▼ 0.2%	▼ 3.4%	▲ 19%	▲ 51%
Base case value	▲ 27%	▼ 0.04%	▼ 0.6%	▲ 25%	▲ 59%
Upper bound value	▲ 33%	▲ 0.08%	▲ 12%	▲ 30%	▲ 67%

Tables 4.2 and 4.3 summarize the results of sensitivity analyses for the both scenarios.

Table 4-3 Overall equipment effectiveness (OEE) sensitivity analysis

OEE improvement and sensitivity analysis	Total PM gear manufacturing cost per part	Gear grinding cost per part	Sintering cost per part	Gear rolling cost per part	Compaction cost per part
OEE 50%	▲ 19%	▲ 43%	▲ 32.5%	▲ 19%	▲ 11%
OEE 85%	▼ 9%	▼ 19%	▼ 16%	▼ 10%	▼ 7%

4.7 Additional empirical findings – comparative cost analysis

4.7.1 Brief description and link to all the appended papers

A comparative cost analysis of conventional wrought steel and P/S gear manufacturing technologies, which is not included in the appended papers above, is presented here. As the starting point, there are some basic assumptions considered for the purpose of applicability and fairness of this case study, which are outlined as follows. The main assumption is that the manufacturing location is in Sweden and general parameters associated with it for both manufacturing techniques are the same. These general technical and financial data are outlined in the table 4.4 below.

Table 4-4 General data selected for both gear manufacturing technologies

Data point	Amount	Unit
Throughput time	25	days
Annual volume	400,000	units
Batch size	30,000	parts
Cost of capital	7%	%
Facility rent	Confidential	Currency / m2
Electricity cost [105]	0.5	SEK / kWh
Annual work time	5200	hours
Labour cost	Confidential	SEK / hour
Currency exchange rates	10.7847	Euro to SEK
	9.78626	USD to SEK

In the PPC model utilised here, the Swedish currency (SEK) is used; however, the model is generic and independent of the chosen currency unit. A currency exchange rates to US dollar ($) and Euro (€) were also embedded in the tailored cost calculation tool. These exchange rates were taken as the average exchange rate over the last 30 days to balance out for exchange volatility and were accessed on October 2019.

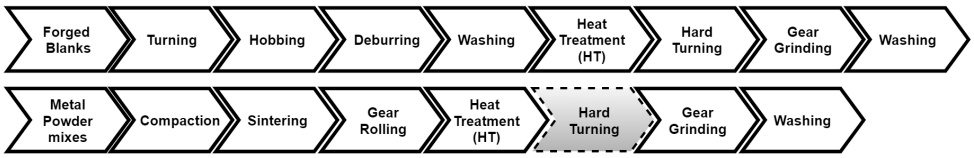


Figure 4-3 Conventional and P/S processing routes compared for gear manufacturing

The top processing route illustrated in the figure 4.3 above is the same one utilised in the appended paper 2 for conventional wrought steel gear manufacturing. The bottom processing route shown in figure 4.3 is the modified version of the P/S gear manufacturing, which were utilised in the appended paper 5. The modification made the P/S processing route more comprehensive and appropriate for the purpose of this comparison. The differences are the inclusion of hard turning process after the case hardening (e.g. heat treatment) process and before hard-finishing process of gear grinding.

The material costs used in this PPC model are material cost per part and thus are completely reliant on the purchase price of the raw material. As this is a function of the procurement department's capacity to ensure the best price, the material costs were excluded from the main comparison to be able to visualise only the shop floor manufacturing differences across both processing routes. Instead, the raw material purchase price and material utilisation percentage was compared separately for the two chosen gears.

Two separate scenarios were created to compare and contrast the inclusion or exclusion of the following variable; P/S processing route including hard-turning production step cost. For the P/S processing route, hard turning is not always required due to the gear design and its near net shape produced after the compaction process. For the P/S gear selected, 4th drive helical gear, the final topography (internal spline) of the gear means it does not need hard turning, thus the main scenario here is with hard turning excluded. For other topographies, hard turning can be performed before the hard-finishing processes e.g. grinding, hence, the author decided to include this option in scenario 2 for generalisation purposes.

Three other key assumptions should be mentioned here. Firstly, case hardening was assumed to be the same cost for both processing routes as in both cases it is outsourced and thus like material costs, the associated costs with the case hardening is under the direct control of the procurement department and their ability to strike the best deal with their case hardening supplier. Secondly, the maintenance cost driver has been excluded from both processing route models due to big lack of enough technical and financial data, for both compared processing routes, to simulate this cost driver to the required level of accuracy. Thirdly, quality assurance has been excluded as the quality calculation was not comparable for both processing routes due to a lack of data for the cost of poor quality on the P/S side. This will be further elaborated in the discussion and conclusion chapters 6 and 7 in connection to both research questions (RQs) in particular to RQ 1.

4.7.2 Result

The modified versions of the tailored cost calculations, which were built based on the PPC model and utilised in the appended papers 2, 3 and 5, are also utilised in this study. A new comparative cost calculation tool with cost driver's breakdown structures for both gear-manufacturing technologies was designed.

The two scenarios run through the PPC comparison model are listed below in table 4.5. The total manufacturing cost per part, in the original scenario is 42% cheaper for the selected P/S processing route in comparison to conventional wrought steel processing route. In figures 4.4 the breakdown of the cost differences for each production step is shown across the horizontal (left to right) and the differences for each cost driver are shown in the vertical (top to down).

It should be noted that the soft machining production steps (turning, hobbing, deburring, marking and washing) within the conventional wrought steel processing route is compared here with the compaction, sintering and gear rolling production steps of the P/S processing route.

This percentage (%) cost difference for the P/S gear processing route is an accumulation of multiple cost savings across different cost drivers as seen in figure 4.4 below. For example, the equipment costs during operation are 38% cheaper for the P/S processing route. Similarly, the P/S wage cost is 43% cheaper when compared to its counterpart.

Finally, a comparison in table 4.6, 4.7, 4.8 is shown with graphs depicting each manufacturing technology individually to show the capacity of this PPC tool to enable decision makers to view two possible processing routes side by side to realise possible areas of improvements e.g. production optimisation. Material costs were again included in these graphs to show the full cost of each gear per part. The first table 4.6 shows the percentage cost allocation across all the production steps for each gear. Table 4.7 shows the aggregated costs of each production step across all cost drivers. Finally, table 4.8 shows the cumulative costs as the gear moves through the production steps for each processing route.

Table 4-5 List of scenarios run through the comparison models and the corresponding percentage (%) difference between the conventional wrought steel and P/S manufactured cases.

Scenario #	Name	Description	PM Hard Turning	Material costs	% difference of the total manufacturing cost per part
1	Baseline	All cost drivers considered; case hardening cost is the same for both P/S and conventional; maintenance and quality are excluded for both processing routes and P/S hard turning and material costs are excluded	OFF	OFF	-38%*
2	PM hard turning ON	Same as scenario 1 with PM hard turning cost included (same costs as conventional)	ON	OFF	-12%*

**minus % means P/S gear manufacturing is cheaper than conventional wrought steel manufacturing processing route.*

Comparison of P/S to Conventional Manufacturing per part

Original Scenario: P/S Hard Turning is OFF, Material is OFF

		Production Steps within Processing Routes			
		Soft Machining	Case Hardening	Hard Turning	Grinding and Washing
Total manufacturing cost	*-38%*	*-36%*	*0%*	*-100%*	*0%*
Breakdown of Cost drivers	Totals				
Tool cost	-45%	-7%	0%	-100%	0%
Equipment cost during operation	-38%	-52%	0%	-100%	0%
Equipment cost during downtime	-34%	-46%	0%	-100%	0%
Wage cost	-43%	-51%	0%	-100%	0%

Scenario 2: P/S Hard Turning is ON, Material is OFF

		Production Steps within Processing Routes			
		Soft Machining	Case Hardening	Hard Turning	Grinding & Washing
Total manufacturing cost	*-12%*	*-36%*	*0%*	*0%*	*0%*
Breakdown of Cost drivers	Totals				
Tool cost	-3%	-7%	0%	0%	0%
Equipment cost during operation	-28%	-52%	0%	0%	0%
Equipment cost during downtime	-25%	-46%	0%	0%	0%
Wage cost	-11%	-51%	0%	0%	0%

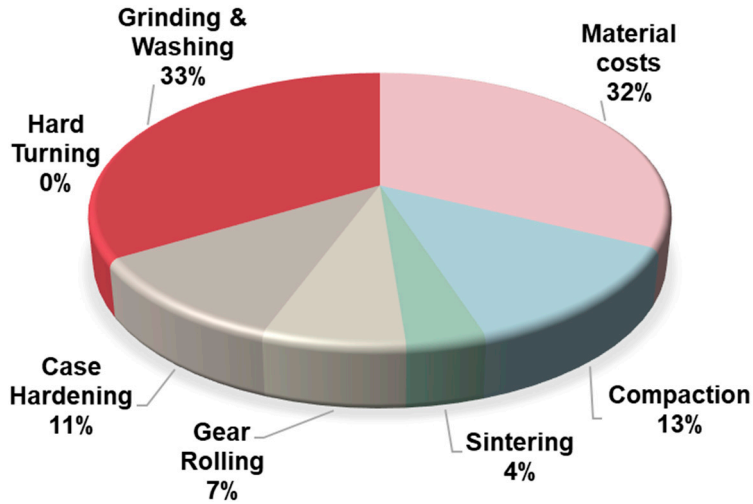
Figure 4-4 Percentage comparison between conventional and P/S manufacturing processing routes for the two chosen gears for scenario 1 & 2.

Note a negative % denotes that the P/S route is cheaper than conventional process route

Table 4-6 Share of total gear manufacturing costs from both the Conventional wrought steel and P/S manufacturing processing routes compared within this study.

Share of total gear manufacturing costs per part for incl. production steps of each processing route

P/S processing route



Conventional wrought steel processing route

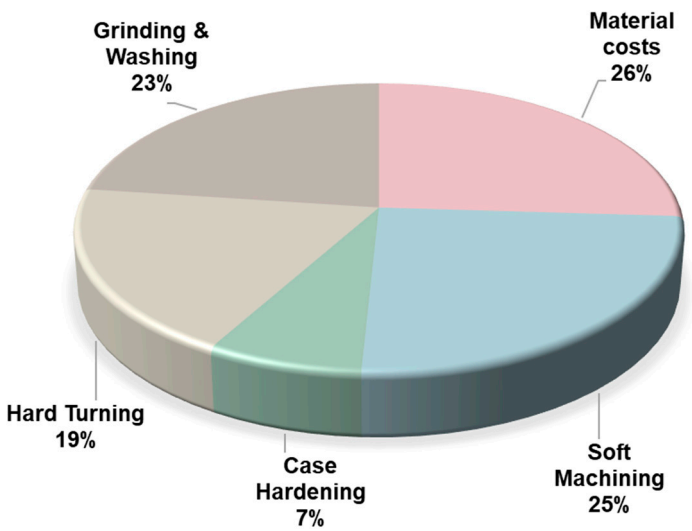
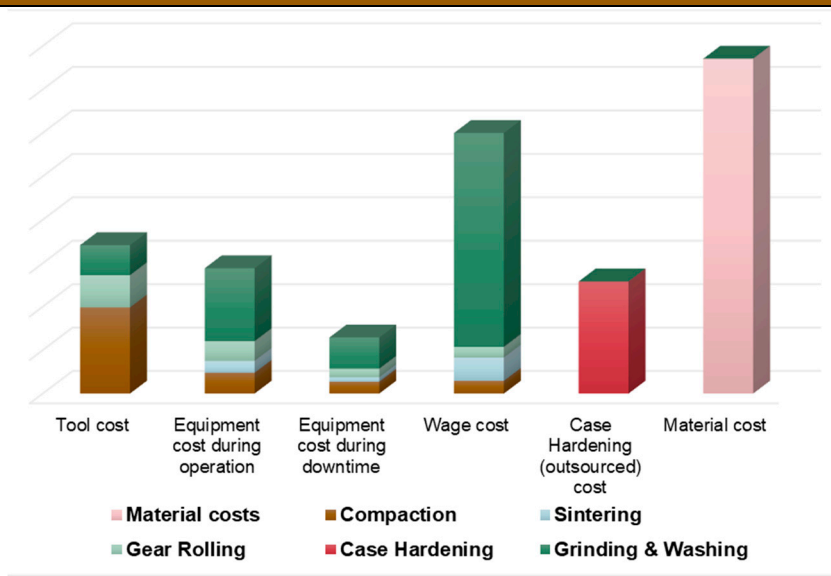


Table 4-7 Individual results from both the Conventional wrought steel and P/S manufacturing processing routes production steps cost contributions to each cost driver

Production steps cost contributions to each cost drivers for each processing route

P/S processing route



Conventional wrought steel processing route

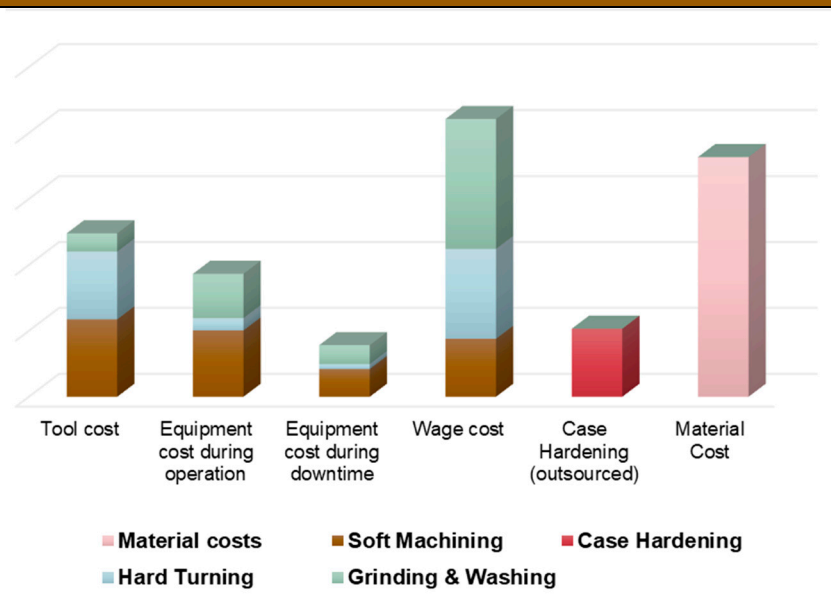
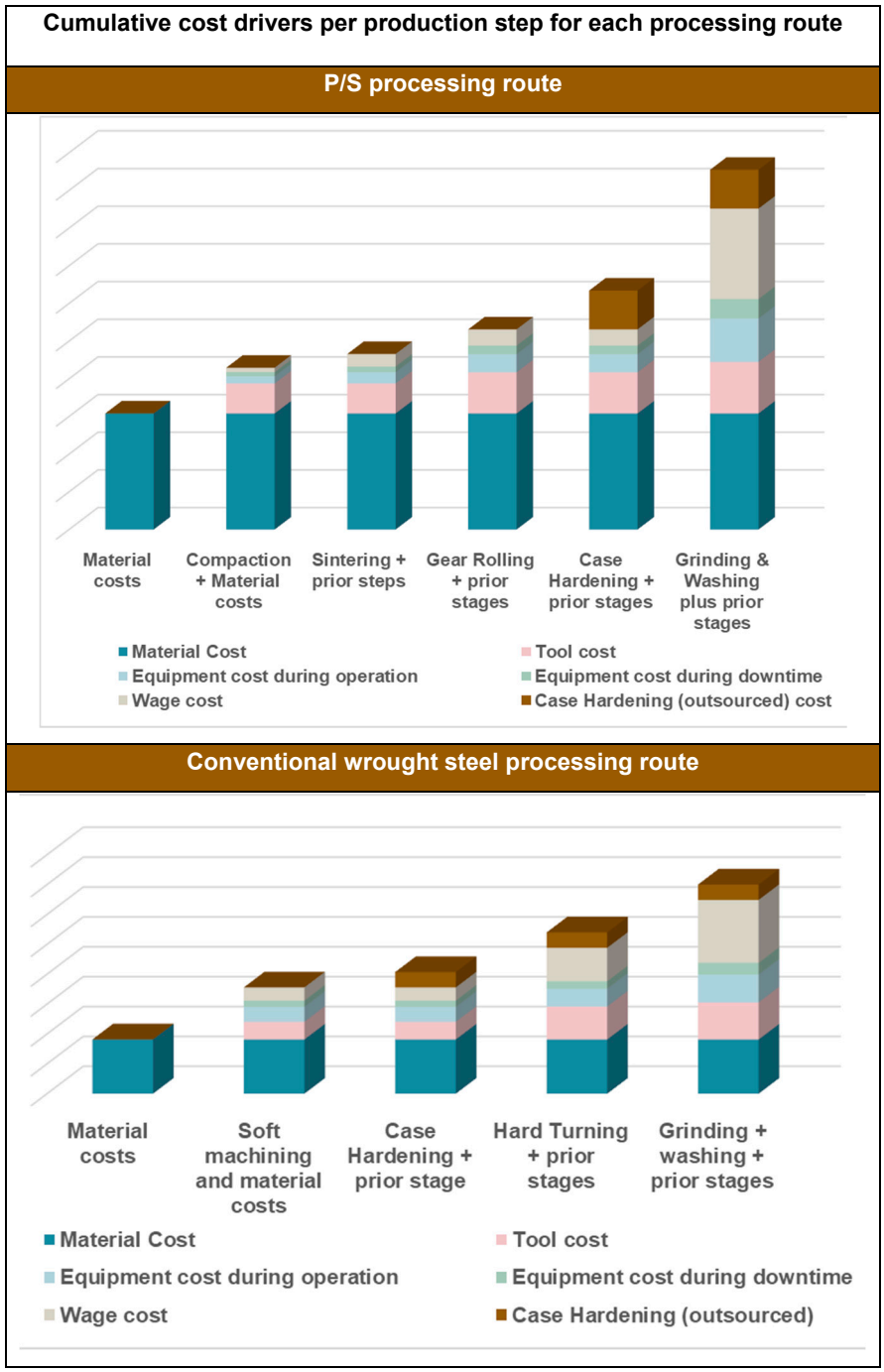


Table 4-8 Individual cumulative results from both the Conventional wrought steel and P/S manufacturing processing routes compared within this study



4.7.3 Discussion and conclusion

The following section discusses the comparison between both processing routes through their cost drivers by utilising the PPC model.

4.7.3.1 Material costs

Findings from the comparison of both purchase prices of the raw material utilised within each processing route, gave an unexpected and interesting contribution. It was found that the metal powder per kg was 13% cheaper at an annual volume of 400,000 parts, than that of its wrought steel forged blanks per kg. This finding was not seen in the literature, which pointed to a higher cost per kg of mixed metal powder [23]. The findings did however confirm the literature claims [23] of benefits for P/S through high material utilisation. In the case of the two studied processing routes, the P/S material wastage was in the region of 2-3% whereas the conventional wrought steel was in the range of 35-40% material wastage. As the cost of raw material is not controlled at the shop floor, instead, it is set through the procurement department; it shows the importance of taking a comprehensive and life cycle perspective when comparing gear manufacturing costs and the effects of raw material purchase price on the businesses bottom line.

4.7.3.2 Comparison across cost drivers:

Tool cost:

Tool cost had the lowest cost difference of all the cost drivers as P/S is only 3.4% cheaper than that of conventional wrought steel manufacturing when the effects of hard turning are excluded. Tool cost is the third largest cost driver for both P/S and conventional processing routes as seen in table 4.7 above. For P/S tooling costs of the compaction production step in the studied helical gear is rather high due to the required complexity of the tool for the given topography. For a simpler gear wheel be it helical or not, the compaction tool could be much simpler and thus costs would be lower [48]. For the conventional processing route, high tool costs are assumed to be a function of high investment costs along with a frequent refurbishment requirement due to the high manufacturing volume in question. Further investigation must be carried out about the effect of tool wear and tool lifespan on the comparative tool costs.

Equipment cost:

In the appended paper 4 above it was shown that, the initial investment into P/S is very high, almost three times higher than its counterpart. Despite that fact, this comparative study illustrates that the manufacturing costs are cheaper for P/S with the assumption that the same quality and performance can be achieved. The equipment cost during operation is 38% and during downtime is 34% cheaper for the P/S processing route per part. Obviously, when hard turning is not included within the P/S processing route, the equipment cost savings are higher. However, when hard turning is included, the P/S equipment cost savings are due to the soft

machining processes, which are 52% during operation and 46% during downtime. This is not surprising as the literature stated that P/S manufacturing costs would be cheaper than of conventional wrought steel soft machining production steps being soft turning, hobbing and deburring for this case [23].

Wage Costs:

Here again, the P/S processing route is cheaper in terms of wage costs when compared with the conventional wrought steel processing route. Specifically, the soft machining processes of the P/S (compaction, sintering and gear rolling) are 51% cheaper than the comparable the conventional route (turning, hobbing and deburring). Within the PPC model wage costs are a function of labour hours and salary costs, cycle and setup times and OEE for each production step. In the case of the P/S they have less staff required due to higher levels of automation, but the biggest impact is due to greatly reduced set up and cycle times. Within this comparison, OEE percentages were set to be the same so this is not a factor in this cost benefit for P/S.

These findings are further discussed in section 5.2.2 as they directly relate to the answering of research question 2.

5 Discussion

This chapter elaborates on the combination of five appended paper's and the additional empirical findings from section 4.7 contributions. Their connections to the reviewed literature in chapter 2 is also presented. This chapter concludes with reflection upon the quality of research and its limitations.

5.1 Original contribution of the research

This section is divided to two sub-sections of firstly, industrial impacts and secondly scientific impacts whereby the contribution to academia is discussed through the lens of the two research questions. It should be noted however, that some of the gained knowledge is so interconnected, the author found it hard to divide the contributions between these two categories.

5.1.1 Contribution to industry

Some of the direct industrial applications and benefits of this work can be summarised as follows:

5.1.1.1 Utilising a richer and broader cost-based decision support tool, for gear manufacturing companies, for analysis of production development scenarios.

This study put forward a customised manufacturing cost calculation tool for the processing routes in question and improvement opportunities for each cost driver were visualised, and the impact of their consequences were measured for the specific case study processing routes. This was one of the main motivations to undertake this work for one of the partner company's in this research project. The company sought to create knowledge, and adopt a new cost modelling method for their portfolio of products. The outcomes of the case study in the appended paper 2 provided the company with new knowledge and a structured cost method, which illustrated each cost driver's share of total manufacturing cost of the in-production gearwheel in question. After disseminating these findings to the company, one of the production steps used within the company and its associated equipment were

prioritised for improvement. This was the 'turning' process, and reducing its cutting tool's wear, and hence increasing its lifespan has been and still under investigation at the company. The granularity of the utilised model enabled the partner company to see an improvement opportunity that would have otherwise remained hidden if they had only had access to their in-house standard costing method.

Despite the fact that, the aforementioned cost calculation tool was customised for the paper 2 case study company, it is a modular tool and applicable to both other part makers, not only gear, in other areas of the manufacturing industry tool. The pre-requisition is the availability of technical and financial input data. In part two of this research study, the author will build upon the current model to create a Decisions support system whereby this tool has an integrated user application making it easier to use by companies.

5.1.1.2 Introducing LCC to the partner gear manufacturing companies and showing the industry at large the applicability of such a model.

The partner companies, in both conventional wrought steel and P/S gear manufacturing, have not practiced an LCC approach prior to these case studies. Hence, the knowledge created in this case study regarding the LCC methodological steps integrated with the companies input data has also been shared back with the partner companies.

Specifically the LCC approach had not yet been compared with the selected PPC model, to the detailed level, which it was presented in the appended papers 3 and 4. In addition to the created knowledge from LCC and PPC cost parameters comparison and contrast, in two industrial case studies the applicability of integration LCC and PPC were shown providing real in-use data. These levels of detailed and quantified knowledge were not publicly available to academia previously, to the best of the author's knowledge. The comparison of LCC and PCC approaches also adds new value to the cost models and methods literature review, which was presented in chapter 2 (frame of reference) in section 2.3.

5.1.1.3 Comparative acquisition and manufacturing costs analysis of conventional wrought steel and P/S gear manufacturing processing routes.

This is the major contribution of this research to practitioners so far, which was disseminated explicitly in the appended paper 4 for acquisition costs analysis and in this licentiate's chapter 4, in section 4.7 for manufacturing cost analysis. The results shown in 4.7, within its assumptions and limitations, has extended the industry partners knowledge on the comparison of the economic aspects of gear manufacturing for both processing routes investigated. These included both cost advantages and disadvantages in both manufacturing processing routes and their associated production steps. Practitioners and some industrial experts have confirmed these claims, when the results were illustrated to them. Please visit the section 5.2.1 for more detail information.

5.1.2 Discussion of findings related to - RQ1

RQ 1: What level of detail is required for a cost analysis tool to be able to compare different gear manufacturing technologies rendering the same product's performance and quality?

5.1.2.1 Discussion on the current company cost allocation method

The gear manufacturing companies within this research study use standard costing or various modified versions of it. For example, in one of the modified versions of standard costing, operation and equipment cost (currency/part) were also directly included unlike traditional standard costing, where these costs are allocated to overhead (OH) as mark-ups like indirect manufacturing cost. In another example, some of overall equipment effectiveness (OEE) parameters, quality (Q) and availability (A) costs were also directly included in the modified version. This discussion point is based on the gained knowledge from 6 different companies, and 11 interviewed people. Moreover, informal dialogues with other manufacturing companies have also corroborated this. Furthermore, this finding that industry is mostly using standard costing or variations of it, is also aligned with the findings within the literature review reported in 2.3.

The drawback of utilising standard costing has been shown to be its use of cost driver allocation at a high accumulated level, thus the majority of the direct manufacturing costs (excluding direct labour and direct material costs) are allocated on mark-up basis. The design of OH mark-ups also varies greatly between companies and what is included within OH is not necessarily clear to the user of the standard costing either. An example from the case study analysis is that calibration equipment or testing measurements are in the same mark-up (indirect manufacturing costs) as production clothes and accessories for staff on the shop floor. These things are not comparable and combining them means the user loses the ability to discern possible options for improvement. This implies that you cannot utilise this method for improvement scenario development. For that another more detailed method must be used.

Another challenge with standard costing is the fact that it puts a strong weight on historical information, so it is very good at retroactive costing. The challenge with this can be, in current very dynamic gear manufacturing applications, the gear manufacturing ecosystem is rapidly changing, given the current economic slowdown and sustainability challenges. Hence, gear manufacturers are striving to adopt new and different processing routes to achieve the same performance and quality levels, where some of the production steps are not well knows and many of the variables are undisclosed. Because of this fact, you cannot rely on historic data alone, instead a more accurate and detailed performance driven manufacturing cost driver approach is needed. In standard costing it has been experienced by the author that performance and quality cost drivers were concealed within OH mark-up. Hence, they cannot be adequately studied to put forward potential optimisation options.

5.1.2.2 Applicability of the chosen PPC model for this study

Unlike the standard costing method used by the partner companies, the chosen PPC method has a significantly increased level of detail and ability to give a more accurate appraisal of manufacturing costs. Mark-up issues are avoided as all of the cost drivers are broken down and calculated separately. Specific cost drivers for quality and maintenance give opportunities to users to quantify these costs. Similarly the level of detail given within the tool and equipment cost formulas enable the user to really ascertain which element of the production step is associated with the highest portion of the manufacturing costs. In this way, the granularity of the model allows decision makers to visualise the complete production process from raw material through all production steps to the final product.

Another benefit of this model is its generalisability so the same set of equations can be applied to multiple processing routes. In the case of this research two customised yet comparable excel models were created based on the PPC method and equations which then enabled both individual investigation into each processing route and comparison between both routes also. The models also gave the author flexibility when generating alternative scenarios to ascertain the benefit of alternatives. Once the models were built, the author conducted several iterative scenario tests to see the effect of different variables on the final part cost.

In paper 3 the author conducted a study comparing LCC and PPC which gave rise to an interesting finding that the PPC could nest within an LCC as the generic and comparable cost calculation method for manufacturing costs.

5.1.2.3 Drawbacks of the chosen PPC model for this study

The disadvantages of using the selected PPC model was known before starting the research based on prior literature reviewed. The same set of challenges were experience during this research when the model was tailored and applied to a specific company. The main challenge is that the model is very comprehensive and many parameters for each of the cost drivers across each production step are required. These cost drivers are interconnected and influence each other so understanding of these facts for industrial partners requires education and training. And that makes the data gathering very challenging and a long drawn out process as practitioners in the partner companies sometimes do not understand their own cost philosophy. That was especially true for the manufacturing department personnel who's focus is on production and not allocation of costs. Sometimes a similar lack of knowledge was seen within the finance or procurement department who have knowledge gaps regarding the production and shop floor elements to carry out detailed accurate costings. This means that vertical and horizontal integration and communication of knowledge is lacking within companies and more competence development is needed for both finance, admin and shop floor staff.

The author compensated for this challenge through communication with the case study companies.

5.1.3 Discussion of findings related to – RQ2

RQ2: What is the manufacturing cost difference between conventional wrought steel and press and sintering (P/S) gear manufacturing technologies?

5.1.3.1 Discussing the initial cost investment from paper 4

The result of this research case study has shown that P/S acquisition costs are nearly three times higher than that of conventional wrought steel gear manufacturing. The costs included within this cost calculation were starting capital costs, equipment costs, reconditioning costs, tool costs, installation costs and education and training costs. The literature review also suggested similar findings but with limited empirical evidence [48].

The evidence from RQ2 becomes even more important now, since papers 1 and 4 highlight the significance of life cycle thinking to remedy the high investment costs of the P/S processing route by showing the possible manufacturing cost advantages. The P/S processing route manufacturing advantages were also reported in previous studies pointing out the shortened processing routes and higher energy and material utilisation [50] [53]. These are connected to shorter cycle times for different production steps for example heat treatment, case hardening in P/S [23]. However, the numerical evidence backing up the claims made by industry of this economical advantage had not been published publically prior to the finding in the appended papers, particularly in papers 1 & 4, and section 4.7 of this licentiate.

5.1.3.2 Material costs

General perception among practitioners is that forged blank wrought steel cost per part is cheaper than PM raw material (metal powder mixes) cost before utilisation [23] However, in this particular case study, the P/S metal powder mix was cheaper. It can be argued that a single case cannot be generalised, however, it should be noted that this is real in-use production data and it shows the importance of raw material procurement. In the case of the material costs difference per part between these two processing routes after utilisation, there are case studies reporting P/S cost advantages [23].

Hence, the influence over the material cost differences per part between these two processing routes lies between two parties.

- Before utilisation: meaning raw material purchasing price, which is under procurement department control.
- After utilisation: meaning when the raw material is processed through completed production steps, which is under product and production development departments' control.

The P/S metal powder was 13% cheaper per kg than its wrought steel forged blank counterpart. This combined with percentage savings for P/S processing route due to lower

material wastage in this case study, 2-3% for P/S and 35-40% for conventional wrought steel. These factors together show an advantage for P/S with respect to material cost.

5.1.3.3 Discussing the differences between the two processing routes at the production steps level:

Comparing P/S and the conventional wrought steel gear manufacturing processing routes at their production steps level, at least for the investigated gears within this study showed an advantage toward P/S. This is with the assumption that the same performance e.g. strength and quality e.g. tolerances as of conventional wrought steel gears can be gained by P/S. The author designed two scenarios shown in section 4.7.2 of chapter 4, which alternated having hard turning costs included or excluded within the manufacturing cost comparison. For detailed numerical analyses, please see figure 4.4 and table 4.5. The breakdown of these findings are discussed below.

Soft machining production steps

The production steps compared before case hardening are turning -> hobbing -> deburring for a conventional wrought steel gear, and are compaction -> sintering -> gear rolling for a P/S gear. Manufacturing cost reduction by 36% through utilisation of P/S gear processing route is shown in this study. This cost reduction is mainly due to higher manufacturing speed (cycle time), shorter setup time and higher material utilisation and energy efficiency particularly in compaction and gear rolling production steps. These findings are in-line with previous studies reported in the frame of references in chapter 2, sections 2.1 and 2.2 for example in [50].

Case hardening

In this case study both P/S and conventional wrought steel case hardening step is outsourced. The purchasing prices were provided, and regardless of that, it was considered they have the same cost. However, literature is shown that due to metal powder inherent porosity and changes in the case hardening parameters, the cycle time for P/S case hardening is shorter. Hence, its production step cost is lower [23]. This fact could point toward the bigger advantages for P/S through cost savings.

Hard turning

P/S utilised fewer production steps since the hard machining process of hard turning was not needed in this specific case, which is a helical gear with an internal spline included in the compaction step. Even if hard turning was needed due to a different gear topography, the P/S advantage is still valid but to a lesser degree. This is due to advantages within the soft machining production steps as discussed above.

Hard finishing

Grinding including washing is selected in this case study, and the same cost for its production step is considered as the same set of equipment can be utilised for both processing routes. Washing is included to ensure full removal of any residue after grinding.

5.2 Challenges experienced during this research

Some of the challenges experienced in the data retrieval processes are as follow. Despite the fact that these challenges are intertwined with the objective of the RQ 1, what is outlined below are rather reflections of the author's experience, during the reported case studies, with data gathering practicalities when even access to both technical and financial input data were granted by partner companies via e.g. NDA.

Data retrieval challenges in both conventional wrought steel and P/S gear manufacturing processing routes have had impacts on the quality of this licentiate research as a limitation. This was initially anticipated in the early stage of this research project, hence research questions (RQs) were specifically formulated to tackle and reflect upon this data acquisition challenge. That was the main objective of RQ 1, and one of RQ 2 objective was to shortening this lack of available knowledge with providing some empirical evidence from the comparative case studies.

In case of the conventionally machined gear, the main challenges were;

- Finding accurate parameters and making balance between the quality and quantity of input parameters. For example, maintenance cost had to be excluded from the comparative cost analysis case studies, due to impracticality to gather the minimum input parameters to perform the analysis.
- Company-based data resources: several existing data resources, and involvement of various departments. The challenge arose due to unclear responsibilities, and lack of resources etc.

In case of P/S gear, this challenge was due to immaturity in available knowledge (know-how) for the high performance P/S gear manufacturing processing routes.

- The P/S processing route was not conducted within one single company. If there was one company who has all production steps in house, they would not share their data as in this highly competitive manufacturing environment this information is proprietary and highly protected through copyrights.
- The high performance e.g. heavy load gear manufacturing application of P/S still required further technical development [50] [53] [52] and consequently the economic feasibility has yet to be publically proven. Regarding the technical aspect, during the course of this research study (Nov 2016-2019), many new advancements within cooperate research have been developed [23] [48] [50] [52] [53]. These are reported in the chapter 2, frame of references. They can be seen to mirror the findings of this research around operationalising the P/S processing route for high performance gears.

5.3 Quality of research

5.3.1.1 Reliability and Validity

Reliability. The PPC model used as the cost analysis instrument within this study has been tested previously, and used in different contexts. It generalisability as one of its strengths and the equations within it are well described used consistently in line with prior studies. Regarding validity;

Constructed validity. The author ensured that the constructed methods were sound and enabled accurate cost analysis as required to answer the research questions. This was through a close working relationship with partner companies. A close working relationship ensured valid data collection as there is high levels of trust between the parties and buy in on both sides for an accurate resulting model.

The internal validity. Within this licentiate, this was also strengthened by continuous testing of the authors and data providers' assumptions. For example, the author conferred with his technical advisor on his own assumptions when there was disparities between the data from partner organisations and that found within literature reviews. In this way, that author could reflect upon his data. Since, there were many learning loops within this licentiate, there was a chance to re-test assumptions, and improve on the financial accuracy of the models (PPC and LCC) used.

The external validity. This choice was made by the author in conjunction with industry and academic experts. Great care was taken to ensure that these gears were in fact comparable and representative of both manufacturing technologies as currently used in industry. The main limiting factor for data collection was access to P/S processing route information as data availability proved to be a big challenge during this licentiate. Limited generalisations of the findings can be made due to two key challenges. The first, only a single comparative case was conducted comparing a conventional wrought steel manufactured spur gear and a P/S manufactured helical gear. If multiple comparative gears were analysed, themes for each manufacturing technology could be generalised. However, this single comparative case study offers empirical evidence, which could be combined in the future with other comparative cases to ascertain trends. The author has already initiated new industrial case studies and the results will be included in the PhD dissertation. The second, input data from only one company for a conventionally manufactured gear was obtained. Thus, this case is organisation specific and cannot be generalised to all organisations who could produce this gear. The author has also established connection with a new industrial partner to gather input data and develop further a new case study, and the results will be included in the PhD dissertation.

5.3.1.2 Trustworthiness

Credibility of the data was of paramount importance to the author and so a great deal of time was invested into creating a relationship with the project partners in order to ensure that accurate data was used to as closely as possible depict the reality of a gear manufacturing environment experienced by practitioners.

Multiple sample points were used to request data from the partner organisations so that previous data could be re-checked and in some cases, assumptions could be questioned and improved on. Triangulation was also used by way of multiple methods data retrieval. The author first undertook a review of literature to ascertain plausible parameters and numbers for the required data, then interviews and on-site visits were used to gather data. In many cases, there were multiple researchers present during the interviews and so there was a means of double checking the data and findings.

Once the data was populated into the models (cost calculation tool) the outcomes where then sent back to the partner organisations and reviewed to ensure that the original data was accurate and complete in an iterative way. Finally, in the final step of this licentiate a comparison between conventional wrought steel and P/S gear manufacturing techniques was undertaken. At this point, all of the original data was again rechecked for accuracy by the author and the partner companies to insure that an accurate and consistent comparison was achieved.

Transferability is linked to the external validity of the licentiate as stated above. The choice of gears within both the P/S and conventional wrought steel manufactured gears was of high importance. For more information, please see above external validity section above.

Dependability was achieved through multiple iterations with the author and his academic advisors and through direct comparison with in house cost calculation of the partner company in the case of conventional wrought steel gear manufacturing. The author's customised cost calculation in excel was error checked regularly and compared to older versions to ensure that the data was being handled in similar ways and that the formula were used consistently across all models.

Confirmability, similarly to internal validity and reliability was reinforced by triangulation of both data collection methods and multiple research actors. The author looked to constantly limit his own biases and judgements when designing the data collection methods (interviews and on-site visits) through peer-review process of the author's interview questions prior to use, asking open ended questions to allow for participant led data and always testing the author own assumptions back against the data received from industry and academic experts.

6 Conclusion

This chapter answers the research questions (RQs)

RQ 1: What level of detail is required for a cost analysis tool to be able to compare different gear manufacturing technologies rendering the same product's performance and quality?

A cost break-down approach is required at the manufacturing shop floor level, which distinguishes and separates the costs occurred based on value-added activities and non-value added activities along the manufacturing processing routes under study. Hence, in this approach the cost analysis at the aggregated level is avoided. This is particularly advantageous in the current gear manufacturing industry ecosystem, especially for high performance, e.g. heavy-loaded applications and when cost need to be assessed a head of time. This is due to the high level of uncertainty in the fluctuations of manufacturing cost drivers especially for P/S processing routes, where many of varying parameters are undisclosed.

The selected cost model, performance part costing (PPC), was shown to support the level of detail required for this gear application and enable improvement development through scenario analysis. During this licentiate, it was also shown through a comparison of PPC and life cycle costing (LCC), that the life cycle thinking is vital and PPC model can be integrated to LCC as the manufacturing cost calculation tool.

RQ2: What is the manufacturing cost difference between conventional wrought steel and press and sintering (P/S) gear manufacturing technologies?

The gear performance, e.g. tooth flank and tooth root, and gear quality, e.g. tolerance achieved by conventional wrought steel manufacturing technologies are well-known. However, not the exact same gear performance can be obtained by P/S manufacturing technologies [50] [52] [53]. P/S gear quality and surface structure, nevertheless, has been shown to be achievable through additional cost creating hard-finishing processes [65].

Given the assumption made and reported in this licentiate, the acquisition cost for the analysed P/S processing route were almost three times higher than that of the analysed conventional wrought steel processing route. Regarding the manufacturing

cost comparison of two gears manufactured with these processing routes shown in figure 6.1 below, the result indicates 12% to 38% possible cost savings for the P/S. It must be noted that this is only one single comparison and more case studies have to be conducted before any generalisations could be drawn.

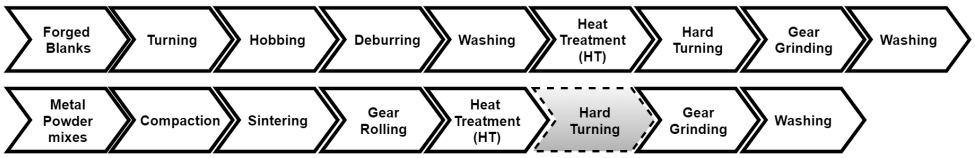


Figure 6-1 Conventional and P/S processing routes compared for gear manufacturing

Further studies already under investigation are looking at the cost comparison for alternatives P/S processing routes for comparable conventional gears. These includes production steps such as hot isostatic pressing (HIP) and forging powder metal (FPM), as research points towards these having improvements in gear performance and quality. For example, helical transmission gears with angles of 32^0 to 34^0 utilizing FPM have obtained a gear quality – tolerance of DIN Q9 before a finishing process e.g. gear grinding or honing [65]. Another example indicates that the results are promising regarding the achieved density after HIP (approximately 7.85 g/cm^3) [50]. However, the cost perspective is still unknown or is not publically available.

7 Outlook

The future work e.g. sustainability assessment of the compared gear manufacturing technologies and alignment of their manufacturing cost drivers with their sustainability impacts will be presented in this chapter.

The 1992 United Nations Conference on Environmental and Development inferred that the utmost cause of an uninterrupted natural resources degradation is the unsustainable route of production and consumption [106]. The manufacturing industry is the paramount contributor to unsustainable production; nevertheless, it has also the capability to contribute particularly to sustainable production (SP) and sustainable development (SD) generally. Considering sustainability challenges globally e.g. concern about climate change, there is growing consensus in a global scale to lessen greenhouse gas (GHG) emissions [24]. 64% of GHG emissions (e.g. CO_2) are associated with energy/process, and manufacturing industry is accountable for 35% of these emissions [107] [108]. The industrial sector consumes nearly 33% of total energy demand globally, which majority of it is utilised to produce bulk materials e.g. metal powders [109].

Steel PM emissions share in industrial emissions is currently small; however, this could change and become more notable due to the high pace advancement, adoption and deployment of emerging manufacturing technologies like metal additive manufacturing (AM) and its new material development. [24]. E.g. between 2017 and 2018, sale of AM equipment for metal parts increased by 29.9% and AM metal powder materials sale and profit increased by 41.9% [110]. Given the increase importance of sustainability issues and future associated risks to manufacturing due to e.g. tighter legislations and tougher pricing policy, it is not only the fact that material and energy conservations are indispensable to SD and SP, but also they are vital to manufacturing companies' existence [111].

The PM industry in general has been regarded as energy and material efficient since at least last three decades by many studies, which have sought for alternative sustainable production steps [59] [57] [58]. This approbation is still verified by more recent studies [24] [27] [51] and in comparison with other PM manufacturing technologies, P/S production steps have been properly characterised concerning their energy and material efficiencies [24]. Although most of these studies acknowledged sustainability issues or at least the environmental aspects, neither

comprehensive environmental assessment nor life cycle perspective have been conducted or considered in their investigations.

As the next step, part 2 of this research's work package (visit chapter 1, section 1.2) in order to contribute to the field with the main intention of reducing the aforementioned gaps, the present author will conduct both qualitative and quantitative research to align the sustainability dimensions to the utilised cost model (PPC) and its manufacturing cost drivers. This will include conducting a review of current sustainability frameworks for production, and utilising this knowledge to align both qualitative and quantitative sustainability assessment into the PPC cost assessment. This will be done in to assess the sustainability impacts of carrying out the selected gear manufacturing activities given their cost drivers are known.

This work will then be combined into a decision support system (DSS) for selection of lower manufacturing cost alternative. When building such a tool, there are risks and associated uncertainties, and hence a sensitivity analysis will also be conducted based on predicted and expected costs.

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