UNIVERSIDADE FEDERAL DE SANTA CATARINA
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VARIABLE COMPRESSION RATIO ENGINES: A MECHANISM APPROACH

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Esta Dissertação foi julgada aprovada para a obtenção do Título de "Mestre em Engenharia Mecânica", e aprovada em sua forma final pelo Programa de Pós-Graduação em Engenharia Mecânica.

Florianópolis, 29 de Março 2016.

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Aos meus pais e à minha esposa que me inspiram hoje e sempre.

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I have no idols. I admire work, dedication and competence.

Ayrton Senna

RESUMO

Os motores de taxa de compressão variável (VCR) têm se tornado uma oportunidade para a adequação frente às novas leis de redução de consumo de combustível e emissão de poluentes. Acredita-se que os motores VCR são capazes de unir tanto eficiência quanto alto desempenho. É objetivo desta pesquisa investigar as oportunidades de desenvolvimentos futuros no âmbito dos motores de taxa de compressão variável. A seguir, um breve resumo do trabalho e suas seções são apresentadas. **Introdução:** A introdução tem por objetivo apresentar a tecnologia de motores de taxa de compressão variável, suas características e justificativas para a pesquisa. Além disso, discutem-se os objetivos, as delimitações do trabalho e, brevemente, a metodologia adotada. **Revisão de Bibliografia:** Neste capítulo apresenta-se a metodologia de desenvolvimento de produtos conhecida por modelo PRODIP (BACK et al., 2008). Todas as etapas e características são discutidas e criticadas em relação ao trabalho que se almeja desenvolver. Metodologias de projeto de mecanismos também são apresentadas focando-se nos trabalhos de Yan (1999) e Tsai (2000). Além disso, discute-se a respeito da metodologia proposta por Murai (2013), a qual foi desenvolvida junto ao Laboratório de Robótica da UFSC e tem se mostrado muito importante para o desenvolvimento de novos mecanismos. Por último, uma metodologia de pesquisa de patentes também é apresentada. Esta metodologia também foi desenvolvida junto ao Laboratório de Robótica da UFSC e está de acordo com os escritórios internacionais de patentes. Juntamente à metodologia de busca de patentes, encontra-se uma breve explicação sobre a estrutura de uma patente e características gerais de de uma pesquisa de patentes. **Motores de Taxa de Compressão Variável:** O terceiro capítulo é dedicado ao levantamento de estado da arte dos motores VCR. Primeiramente mostra-se uma classificação de motores reconfiguráveis e o enquadramentos dos motores VCR nessa classificação. Então, aborda-se a literatura (livros e artigos) para investigar testes experimentais e simulações a respeito do tema além de classificações anteriores deste tipo de motor. O levantamento de estado da arte continua analisando produtos lançados no mercado e as principais empresas por trás desta tecnologia. Por último os resultados da pesquisa de patentes são mostrados. Foram analisadas 1163 patentes resultando em 127 conceitos diferentes de motores VCR. Baseando-se nesta pesquisa e a comparando com outros autores, este trabalho propõe uma nova classificação para os motores VCR, os quais podem ser divididos em 7 grandes classes. As cadeias cinemáticas de todas as classes de motores VCR são analisadas com o objetivo de investigar suas respectivas car-

acterísticas estruturais e funcionais. Além disso, a reconfigurabilidade em motores VCR é discutida. **Desenvolvimento de Motores VCR:** No quarto capítulo são definidos os requisitos estruturais e funcionais por meio do levantamento do estado da arte e por comparação com os trabalhos de Freudenstein and Maki (1983) e Tsai (2000). Os requisitos são então utilizados para enumerar e selecionar cadeias cinemáticas com potencial de se desenvolver motores de taxa de compressão variável. Por fim, discute-se o potencial para inovação destes motores. **Estudos de Caso:** Neste capítulo, três cadeias cinemáticas em potencial definidas no capítulo anterior são estudadas com o objetivo de exemplificar o desenvolvimento de novos motores VCR de acordo com a abordagem sistemática do Laboratório de Robótica da UFSC.
Palavras-chave: Motor; Taxa de Compressão Variável; Mecanismo; Cadeia Cinemática

ABSTRACT

The variable compression ratio (VCR) engine has become an opportunity to overcome the new consumption and emissions laws. Researchers believe that the VCR engine can unite both efficiency and performance. This research aims to investigate the opportunity of further developments within the VCR field. In order to accomplish that, a review of design methodology is provided. First an overview of product development methodology is presented focusing on the PRODIP Model (BACK et al., 2008). Then, it is discussed the mechanism design methodologies such as Yan (1999) and Tsai (2000). Also, the methodology proposed by Murai (2013) is applied. In addition, a patent survey methodology is provided. A state of the art survey analysed the information available in the literature, the market and the patents database. The patent survey was conducted analysing 1163 patents and resulting in 127 different VCR engine designs. Based on that survey and comparing with several authors, this research proposes an enhanced classification of the VCR engines, which contains 7 major classes. The kinematic chains from all classes of VCR engines are analysed in order to investigate the structural and functional characteristics which are compared with previous works from Freudenstein and Maki (1983) and Tsai (2000). This information is used to discuss the reconfigurability of VCR engines, to define the proper design requirements and to generate new potential kinematic chains for innovative designs of VCR engines. At last, three case studies are presented with the objective of exemplifying the development of novel VCR engines using the UFSC Robotics Lab systematic approach.

Keywords: Engine; Variable Compression Ratio; Mechanism; Kinematic Chain

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LIST OF ABBREVIATIONS

CAD	Computer-aided Design
CR	Compression Ratio
DOF	Degrees of Freedom
ECU	Electronic Central Unit
HCCI	Homogeneous Charge Compression Ignition
IPC	International Patent Classification
QFD	Quality Function Deployment
REP.	Representation
SVC	Saab Variable Compression
TDC	Top Dead Center
UFSC	Universidade Federal de Santa Catarina
VCR	Variable Compression Ratio
VS	Variable Stroke
WIPO	World Intellectual Property Organization

LIST OF SYMBOLS

M	Mobility of a kinematic chain.
r_c	Compression Ratio of an Internal Combustion Engine
η	Efficiency of an Internal Combustion Engine
γ	Relation between specific heats
λ	Order of the screw system
ν	Number of independent loops

CONTENTS

1 INTRODUCTION

This dissertation is the result of a research regarding reconfigurable engines, specially focused on Variable Compression Ratio engines, or shortly, VCR engines. Throughout the document the reader can find information about the market of VCR engines, the simulations and tests published in the literature and the existing designs protected by patents. It is important to emphasize the patent survey which was conducted in order to investigate the existing designs in this field. The patent survey was performed according to a patent search methodology, which originated an enhanced classification of VCR engines and helped the understanding of its main characteristics. A mechanism design methodology was applied in order to develop innovative VCR engines with special attention to the definition of structural and functional requirements. The feasible kinematic chains are derived according to the design requirements. Finally, three case studies are provided in order to show how an engine concept can be designed from the kinematic chains.

In order to follow this work, it is expected from the reader a basic knowledge in mechanism theory.

1.1 VARIABLE COMPRESSION RATIO ENGINES

Nicolaus Otto arguably created the internal combustion engine for commercial purposes in 1876 (GANESAN, 2012). Since then, this field experienced several improvements and inventions. For instance, different operation cycles were created, several fuels became available, different materials were introduced, the production methods evolved and the electronics played an important role in the optimization of the engine operation points.

Even with several improvements in engine design, there are always opportunities and need for innovation. Nowadays, one of the challenges for the automotive industry is to meet the emissions and fuel consumption standards. In Europe, the passenger vehicles have to meet a 25 km/l average up to 2020[1]. In USA, the passenger vehicles must be able to perform a 23 km/l average up to 2025[2]. In Brazil, the government will provide tax discounts for manufacturers able to meet the new standards for 2017, which are 17,26 km/l average for petrol and 11,76 km/l for ethanol[3].

Several authors believe the Variable Compression Ratio engine (VCR)

[1] Amending Regulation EC 443/2009 - European Parliament

[2] USA National Highway Traffic Safety Administration - Federal Register Vol 77 no. 199

[3] Brazilian Law no. 7.829 from 2012

could be the technology to meet those standards. Eriksson and Nielsen (2014) believe the VCR engines could take two steps towards improved engine performance :

i) The removal of the design trade-off between compression ratio (efficiency) and engine knock;

ii) The possibility of significant downsizing and supercharging for improved fuel economy.

Gupta (2012) states that modern engines have to satisfy the customer requirements for a high power output as well as for low fuel consumption and both objectives can be accomplished by a VCR engine. Rajput (2005) observes that a fixed compression ratio engine cannot meet the various requirements of high specific output . Hence, the development of variable compression ratio engine seems to be a necessity.

The thermal efficiency (η) of the ideal Otto Cycle is calculated from

$$\eta = 1 - \frac{1}{r_c^{1-\gamma}} \tag{1.1}$$

where r_c is the compression ratio and γ is a the ratio between constant pressure and constant volume specific heats. Equation (1.1) shows that the higher the compression ratio, the higher the efficiency. The graphic representation of Equation (1.1) is provided in Fig. 1, which is a theoretical air-cycle approach. Thus it is clear that increasing the compression ratio has an interesting effect in the engine effiency.

Moreover, a fixed CR engine is a compromise between efficiency, performance, knocking and other factors. For petrol engines, the CR it is usual to be around 10:1. On the other hand, a 12,5:1 CR is used for ethanol engines. However, in Brazil the multi-fuel vehicles are common which makes the CR decision a bit more complicated. Table 1 shows the values of CR for some Brazilian market cars. This data can be easily found at the manufacturer specification sheets. A VCR engine could also improve the multi-fuel capabilities of the engines used in Brazilian vehicles.

In a VCR engine, a high compression ratio would be employed at low loads operation to maximize the efficiency. On the other hand, the low compression ratio would be used at high-loads to avoid knock. According to Nilsson (2007), the benefits of variable compression ratio is more significant combined with downsizing and supercharging. Thus, it is possible to have either an efficient and powerful engine at the same time (NILSSON, 2007).

The VCR engines technology seems to be an interesting field to research and develop. Hence, the next sections and chapters will focus on

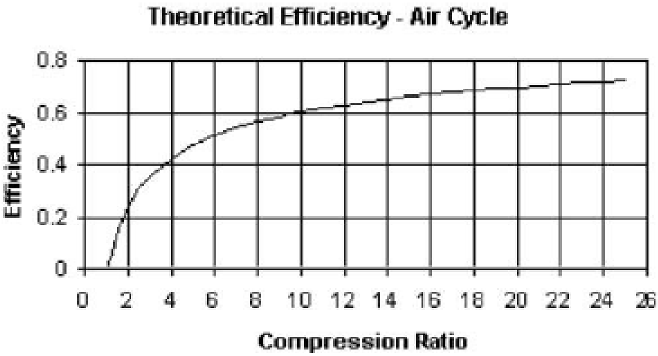


Figure 1: Theoretical efficiency of an engine according to the compression ratio. Adapted from Shaik, Moorthi and Rudramoorthy (2007).

Table 1: Values of CR for some examples of Brazilian market vehicles.

Vehicle	**CR**
Fiat Uno	11,6:1
GM Celta	12,6:1
Fiat Palio	11,7:1
VW Gol	11,7:1
Ford Ka	11,8:1
Renault Clio	12,0:1
GM Agile	12,4:1

discussing several topics related to the VCR engines and necessary tools do develop them.

1.2 MECHANISM DESIGN METHODOLOGY

If such a innovative technology needs to be developed, it is desirable to have a proper design methodology to use as a guide. A mechanism oriented design methodology was proposed by Murai (2013) while working at UFSC Robotics Lab.

Murai (2013) investigated the design methodologies developed by Hartenberg and Denavit (1964), Yan (1999) and Tsai (2000) in order to propose the methodology depicted in Fig. 2.

Such methodology shown in Fig.2 is suitable for the development of

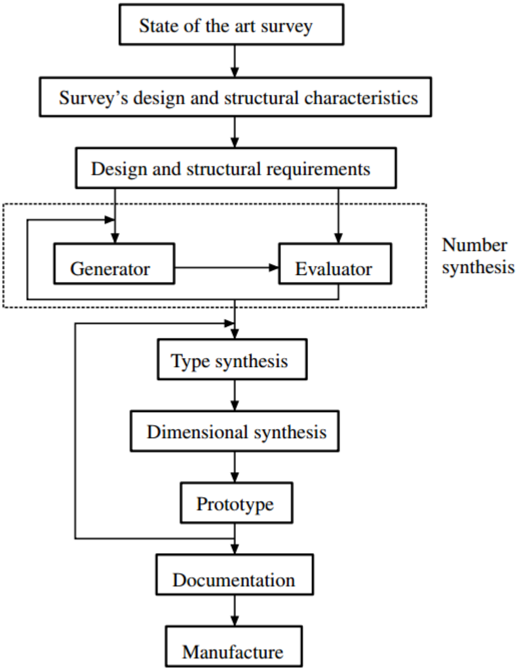


Figure 2: Mechanism design methodology proposed by Murai (2013) and used at UFSC Robotics Lab.

VCR engines and it will be further discussed and explained. In addition, the PRODIP Model (a design methodology developed at UFSC and proposed by Back et al. (2008)) will be discussed since it brings important information about product development.

This present work also describes a patent survey methodology by explaining the main steps and presenting a case study for a patent search in VCR engines. This methodology is being used in several research projects at the UFSC Robotics Lab and it is necessary in order to derive the state of the art of the desired technology.

1.3 WORK PURPOSES

The purpose of this work is to continue the research regarding the mechanism design in UFSC Robotics Lab. Such contribution is obtained by using the methodology proposed by Murai (2013) and expanding it with a patent survey methodology. This methodology is then applied to Variable Compression Ratio Engines.

It is also a purpose of this work to create a proper understanding of the Variable Compression Ratio engines. To do so, a complete state of the art survey will be presented, highlighting literature, products and patent information. The specific goals within these purposes are:

- to review the design methodologies both for product and mechanism design;
- to perform a state of the art survey including literature, products and patents;
- to define the structural and functional requirements for the mechanism development;
- to apply the structural requirements in order to generate an atlas of possible VCR engine kinematic chains;
- to apply the functional requirements in order to select the feasible kinematic chains;
- to derive an atlas of feasible kinematic chains;
- to present the most promising kinematic chains;
- to exemplify the development of a VCR engine by means of case studies.

1.4 WORK DELIMITATIONS

As stated in previous sections, this work is limited to researching the Variable Compression Ratio alternative engines (piston-crank). However, a research in the field of internal combustion engines can be related to several topics such as thermal engineering, lubrication, manufacturing, materials science, electronics, control or mechanism theory, for example.

Since it is not possible to perform a proper research in several areas in short time, this research it is focused in mechanism theory. This means that the state of the art survey and requirements definition are done in a way that all information is ”translated” into mechanism characteristics. Those characteristics will be used in order to enumerate all possible kinematic chains and to select the feasible ones.

Moreover, the term ”development” might lead to a misunderstanding. Usually, a product/machine development transforms the sketches into CAD models, simulations and optimization and then into 2D drawings and manufacturing. However, this is not the goal of this research. ”Development” in the present context means the definition of design requirements, enumeration of kinematic chains and selection of feasible and innovative mechanisms.

Please keep in mind that this work is delimited to defining new concepts of VCR mechanisms. Therefore no dimensional synthesis will be presented.

1.5 JUSTIFICATION

The fuel and emissions standards are getting tougher each year in several countries and the VCR engines could be the technology to overcome and satisfy those standards. With such a technology it would be possible to have either a economic and powerful engine at the same vehicle.

Furthermore, the Chapter 3 shows that the development of VCR engines have been growing. Since 2000 the number of filed patents regarding VCR engines have been increasing and the majority comes from well established automotive manufacturers.

Variable Compression Ratio engines are also reconfigurable mechanisms, an area that has been brought to attention in the last year both for the robotics and mechanism science researchers.

Thus, it is reasonable to believe that the VCR engines are an interesting field to propose innovative designs.

1.6 WORK STRUCTURE

This document is organized so the reader can better understand all the steps that were part of the research project. Thus, the chapters are structured as follows:

Chapter 1 is an introduction of Variable Compression Ratio technology. Some information about its importance and characteristics is presented. The mechanism design methodology is also briefly discussed. In addition, the objectives, delimitation and justifications of this work are presented.

Chapter 2 is about design methodologies. It shows the importance and relevance in adopting a design methodology as a guide. Moreover, it exposes an industrial product design methodology, the so called PRODIP Model, which was proposed by Back et al. (2008), the objective is to understand the main steps regarding the development of new devices. Then, some mechanism orientated methodologies are discussed focusing on a methodology proposed by Murai (2013) during his researches in UFSC Robotics Lab. Finally, a patent search methodology is shown, since it represents an addition in the previous discussed methodologies.

Chapter 3 concerns on the state of the art survey for the Variable Compression Ratio engines. It starts with the definition of reconfigurable engines focusing on the VCR engines. Then, a literature review presents tests and simulations from papers and other publications that emphasize the benefits, results and previous classifications of VCR engines. Then a market analysis is provided showing some products that are already available to the public mainstream media sources. A patent survey regarding the VCR technology is presented highlighting the main concepts and the new proposed classification. At last, the reconfigurability of VCR engines are discussed.

Chapter 4 presents a discussion regarding the design requirements for the development of innovative Variable Compression Ratio engines. The design requirements are compared with the works of Freudenstein and Maki (1983) and Tsai (2000) since they also developed mechanisms for variable stroke engines, which are also reconfigurable engines. Firstly, the topological characteristics, such as mobility, screw system and number of loops are discussed. Then, the structural characteristics are determined, so the kinematic chains can be evaluated. An enumeration an selection of kinematic chains is also performed where one can find the most promising kinematic chains for development of VCR engines. Then the potential for innovation is discussed for each class of VCR engine.

Chapter 5 presents three different case studies. Some promising kinematic chains are chosen in order to exemplify the UFSC Robotics Lab systematic approach of mechanism development. For each kinematic chain, the definition of certain links (engine block, connecting rod, crankshaft, piston and VCR control) are discussed according to the design requirements.

Chapter 6 is dedicated to the conclusions. The main steps regarding the research in VCR engines are reviewed, as well as the main results. Final considerations and further steps of this research are also presented.

2 DESIGN METHODOLOGIES - A MECHANISM APPROACH

Usually, the goal during the mechanism design phase is to achieve a product or device that can be handled by different users. When a product is developed, it will be produced according to several processes. Moreover, it is important that the new device meets the users and customers desires.

Thus, a mechanism design is not only about sketching links and joints. It is, certainly, a much complex process in which the lifetime of the product, user desires and several requirements must be considered so a device prone to succeed can be achieved.

In order to do so, it is recommended to adopt methodologies that can guide the designer during all the design phase. This section will discuss about those methodologies. First, a product design methodology will be presented. Then a mechanism oriented methodology will be proposed and finally a patent search methodology will be discussed, since is an important tool to derive the state of the art of certain technologies.

Keep in mind that those technologies are used as a guide. It is interesting to understand its tools and the main steps, however a research product must be able to adapt, rethink, create innovation, discuss new theoretical concepts and not just deliver an engine concept at the end.

2.1 DESIGN METHODOLOGIES

As previously stated, the design phase should be guided by a defined methodology so the designer can address all the relevant topics in a proper manner. Dimarogonas (2001) states that machine design is also an art, the number of unknown parameters is usually higher than available data. This uncertainty can be eliminated by optimization methods, and/or by good technical judgment of the designer.

Thus, the machine design methodology has the objective to help the designer to find the best tradeoffs for a given engineering problem, allowing the creativity, ingenuity and innovation to be a part of the process.

Back et al. (2008) proposed an important design methodology, the so called PRODIP Model. This methodology is focused in the development of industrial products, which suits well for the development of Variable Compression Ratio engines.

The PRODIP model can be divided in three major phases, as shown in Fig. 3.

Figure 3: The PRODIP Model: A product design methodology developed in UFSC and proposed by Back et al. (2008).

The Planning phase is responsible for the definition of scope both for product and project. Thus, it can be divided in two steps (BACK et al., 2008):

- **Product Planning:** This phase will define the idea of product that a design team will develop. In some cases, a technology mapping is necessary in order to understand the relevance of a certain topic.
- **Project Planning:** This phase is dedicated to establishing timetables, deadlines, milestones, leaders and the general organization of the project overall.

The Design phase gathers all the activities regarding the product design itself. This phase starts with just a device idea and should end with a product ready to start the production. Thus, it is divided in four major steps, as also depicted in Fig. 4 (BACK et al., 2008):

- **Informational Design:** In this phase the project specification and requirements are defined in order to guide the technical development of the product. It is commonly used the Quality Function Deployment in order to establish the most important design requirements.
- **Conceptual Design:** This phase is dedicated to generate conceptual solutions for the product. It is a creative phase where the alternatives are generated and evaluated both technically and economically. The Pugh Matrix is often used to select the best solutions.
- **Preliminary Design:** Here, the chosen solution is developed according to its layout: parts arrangement, forms, geometry, materials, production processes are defined in this step. Simulation and optimization are tools that are commonly used to help defining the product
- **Detailed Design:** In this final phase, a complete revision of the project is made. Then, some minor adjustments are made and some prototype tests are performed. Once everything is solved, the documentation both for product and production is prepared.

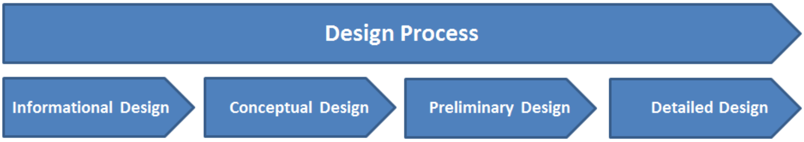


Figure 4: The phases of Design Process from PRODIP Model. Adapted from Back et al. (2008).

According to Fig. 3, the following design phase is called Implementation. In this moment, the project is prepared to go into production. Topics regarding the manufacturing and quality control are addressed. The assembly line is tested and adjusted as necessary. Finally. the product is launched in the market and its validation is performed according to the requirements and scope defined in the early steps of the project.

The methodology proposed by Back et al. (2008) is complete, however there are several steps that do not fit in this research project. Keep in mind that is not intention of this work to develop a detailed product ready for production. It is though, to define design requirements, to investigate the potential for innovation and to propose new concepts that can be used for further developments. In other words, this research is about the Informational and Conceptual Design from the Design Process, depicted in Fig. 4.

Therefore, it would be interesting if the mechanism theory concepts could be added in the design methodology. This is the topic for the next section.

2.2 MECHANISM DESIGN METHODOLOGY

As long as any product, the mechanism design depends on several factors such as ingenuity, creativity and experience of the designer. The idea is to unite mechanism theory with design methodology and to provide a less human dependent tool and therefore achieve a more efficient manner to derive mechanisms for a given task.

Murai (2013) makes an important review on mechanism design methodologies and also proposes a new one which is more focused on the research projects of UFSC Robotics Lab. This is an interesting methodology to follow and, therefore, it will be explained in this section. But firstly, the methodologies from Yan (1999) and Tsai (2000) will be briefly discussed.

2.2.1 Yan's methodology

The methodology proposed by Yan (1999) is based on graph representation of kinematic chains. The mechanism structural characteristics are defined by a state of the art survey. Then all kinematic chains are generated through a number synthesis and its properties will be similar to the ones found in the state of the art search. This methodology is depicted in Fig. 5 and can be organized into the following steps:

- to perform a state of the art survey within the existing designs that fulfil the design requirements. To derive the structural characteristics;
- to make a generalization of the existing mechanisms by expanding their joints into revolute joints;
- to generate the atlas of generalized kinematic chains. This step is equivalent to the number synthesis. So the resulting kinematic chains should have the same characteristics as the existing designs;
- to generate the atlas of feasible specialized chains. Thus, this step is equivalent to the type synthesis since the types of each kinematic pair are chosen. When a specialized chain satisfies the design requirements it is called a feasible specialized chain;
- to perform a dimensional synthesis of each feasible specialized chains. In this step the links size are defined;
- to create an atlas of new designs by separating the existing from the new designs.

Is is possible to notice that the Yan (1999) methodology just takes into account the number of links and joints as input for the number synthesis. On the other hand, it does not take into account the number of loops and screw system order. Keep in mind that selecting the type of screw system it will restrict the type of kinematic pairs that can be chosen.

The number of loops is also usually hard to define. Then, numerous kinematic chains are generated with different number of loops. The analysis should initiate from the chains with lower number of loops to check if they meet the design requirements. If that does not occur, then a higher number of loops should be analysed.

By not using the screw system order might be an advantage of this methodology. However, when the screw system is already known, this methodology can not make use of it. In addition, this methodology uses the state of

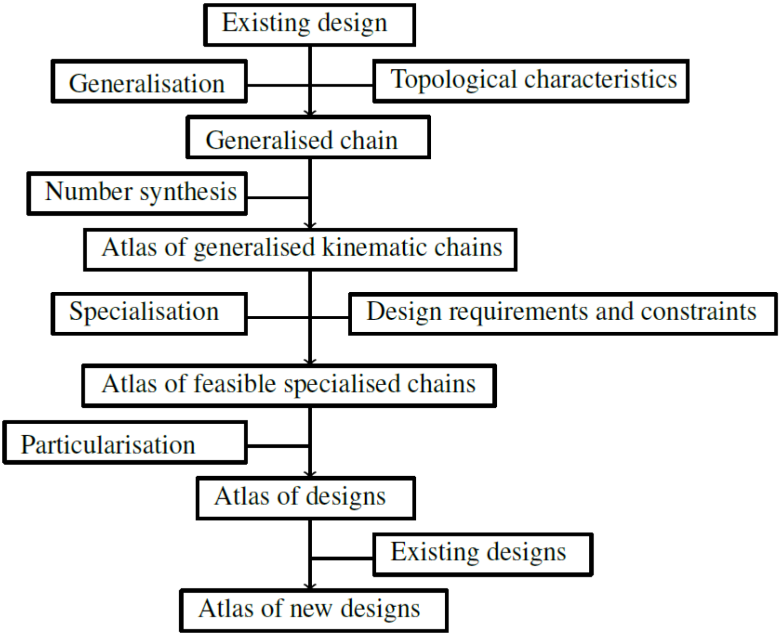


Figure 5: Mechanism Design Methodology proposed by Yan (1999)

the art survey to derive the design requirements which will make the results limited to the existing designs.

2.2.2 Tsai's methodology

Both Yan (1999) and Tsai (2000) have similar methodologies, however Tsai (2000) does not restrict the structural characteristics to the state of the art survey. Moreover, Tsai (2000) uses a generator and an evaluator working interactively. The generator will create the kinematic chains based on structural requirements. The evaluator will analyse those kinematic chains according to functional requirements defined by the designer. This methodology is depicted in Fig. 6 and can be organized according to the following steps:

- to identify the customer functional requirements;

- to define the structural characteristics;
- to review the functional characteristics and check if they can be transformed into structural characteristics in order to be input data for the generator;
- to generate the kinematic chains e evaluate them according to the defined requirements;
- to select the promising mechanism to perform the dimensional synthesis, optimization, simulations, prototyping and documentation;
- to start the production phase.

One of the advantages of Tsai (2000) methodology when compared to Yan (1999) is the iterative process of the generator and the evaluator. This iteration can be related to an optimization routine. The evaluator work as a filter, since it avoids unfeasible kinematic chains to be carried from the beginning till the end of the process. However, the evaluator only works properly if the design requirements are well defined.

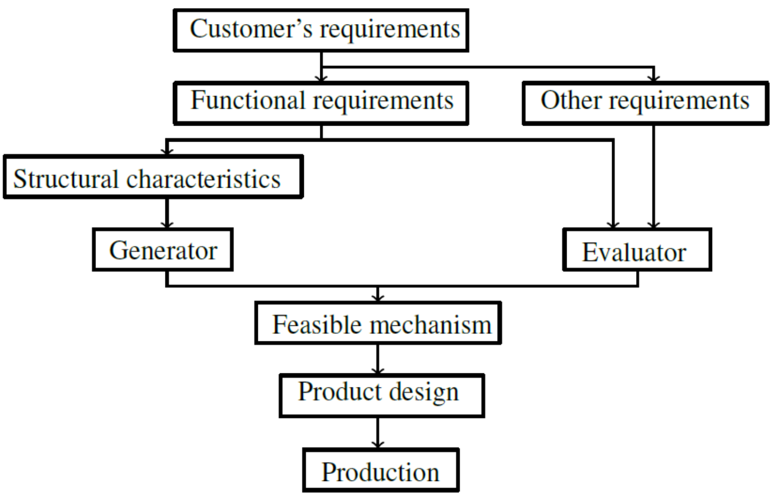


Figure 6: Mechanism Design Methodology proposed by Tsai (2000).

2.2.3 Murai's methodology

The methodology proposed by Murai (2013) is a combination of both methodologies presented beforehand. Similarly to the Yan (1999) methodology, a state of the art survey is done. The objective is to obtain a list of existing designs that satisfy the design requirements, to provide a better understanding of the topic and to guide the designer through the project decisions (MURAI, 2013).

According to Murai (2013), the designer must analyze some aspects of the existing designs such as mobility, screw system, number of independent loops, and several other characteristics in order to understand which can be transformed into structural and functional requirements.

Murai (2013) also explains how the main characteristics can be defined with little or no dependency on the designer:

- **Screw System:** Once the survey is done, the relative motions of the points of interest[1] are analyzed for each device. Usually, this analysis is done in respect to the mechanism fixed link. Then, it is possible to understand in which screw system the mechanism to be designed will work on.

- **Mobility:** Usually, the mobility for the device is known. It can be determined analyzing the desired motions and how they can change. This property can also be analyzed according to the survey results.

- **Number of independent loops:** This property is related to the mechanism complexity, which will be also related to the complexity of the desired motion. The survey can also guide this decision, however it will usually provide a range of plausible values. The synthesis can be done by selecting a low value and verifying if the resulting mechanism are capable of executing the desired motion. If not, the number of loops is increased and the process repeats.

Thus, this methodology is depicted in Fig. 7 and can be organized according to the following steps (MURAI, 2013) :

- to make a state of the art survey. The designs that satisfy the design requirements or execute similar functions should be considered. It is also important to list the customer requirements;

[1] Point of interest is a link that has the main influence in whole mechanism. In an engine can be the piston or in a vehicle suspension can be the wheels.

- to identify the design and structural characteristics of the devices and mechanisms of the survey;
- to determine the structural and design requirements for the project based on the characteristics of the survey;
- to select three structural characteristics from the requirements and use them as input in the generator;
- to generate all possible mechanisms;
- to evaluate the mechanisms and eliminate the unfeasible ones;
- to select the type of each kinematic pair once a feasible mechanism or a few feasible mechanism are chosen;
- to perform the dimensional synthesis;
- to make a prototype. Evaluate if some adjustments in the type or dimensional synthesis is are required;
- to proceed with the documentation once the prototype satisfies the design requirements;
- to start the manufacturing process.

Notice that the mechanism orientated design methodologies also include the manufacturing process. However, when compared to the PRODIP Model (Back et al. (2008)) they lack in depth since none present the necessary steps to go into production nor what to do while the product is launching in the market.

Nevertheless, this is not an issue for this research. As stated before, the objective of this research is to find potential for innovation in VCR engines, to establish proper design requirements and not to achieve an engine ready to production. Thus, the mechanism design methodologies provide a far better comprehension about what to do during the mechanism synthesis and how to transform general design requirements into structural and functional characteristics.

Combining the Informational and Conceptual Design tools from PRODIP Model with the Mechanism Design Methodology from Murai (2013) will provide an opportunity to define proper design requirements.

Another common ground among the mechanism design methodologies is the state of the art survey. Also the PRODIP Model mentions a technology mapping in order to investigate the relevance of a given new product.

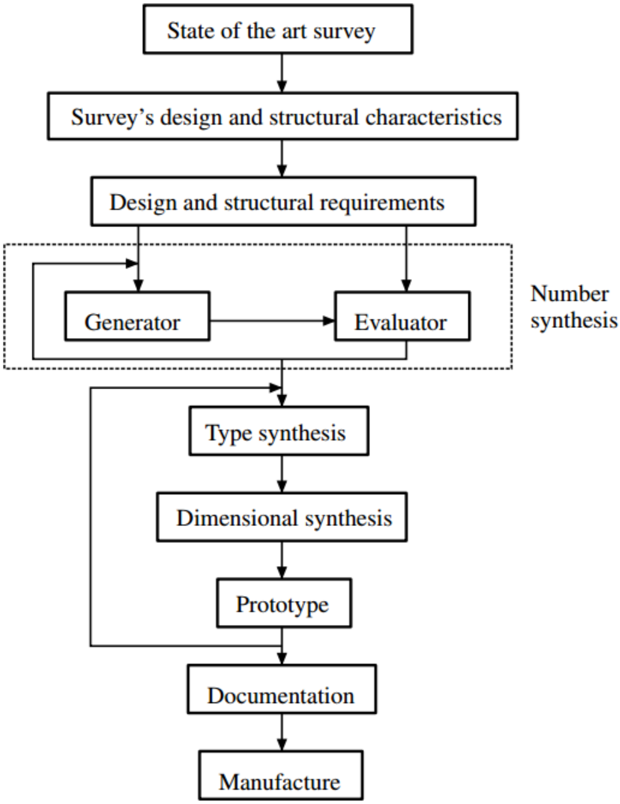


Figure 7: Mechanism Design Methodology proposed by Murai (2013).

Usually, a state of the art survey is conducted by searching articles, books, congresses proceedings press releases, manufacturer websites about a certain technology and/or product. However, there are technologies, such as the VCR engines, which have few information at the mainstream sources. Therefore it is necessary to go deeper into the patents files in order to find protected technologies that are not already available in the market.

A patent survey is not a common task, it is needed attention and a proper methodology which is the topic for the following section.

2.3 PATENT SURVEY METHODOLOGY

Section 2.2.3 introduced the importance of a state of the art survey and the necessity of a patent survey. The present section will discuss the patent survey methodology in more details. Firstly, an overview about patents is given in order to provide to the reader a better comprehension about the topic. Then the methodology itself is presented, followed by a case study.

2.3.1 Overview about patents

- **Priority Date:** It informs when the invention was firstly submitted. All the rights for the idea start counting from this date. With this information it is possible to understand, for example, whether a patent is valid or not.

- **Inventor(s):** it is the person (or the group of persons) who developed the idea.

- **Assignee(s):** It is who will detain the rights of application of a given patent. It can be the inventor himself, a company or an institution. This information is used in order to map which companies are the leaders in a specific topic.

- **International Patent Classification (IPC):** It is a 8 digit code mixing numbers and letters that classifies the patents. When the most promising IPC's are known the patent search enhances in quality and reduces the number of application to look for. It is one of the most important information when a patent survey is being conducted. For example, the IPC F02B75/04 represents the following technologies:

  - **F**: Mechanical Engineering, lighting, heating, weapons, blasting.
  - **02:** Combustion engines, hot-gas or combustion-product engine plants.
  - **B:** Internal combustion piston engines; combustion engines in general.
  - **75:** Other engines, e.g. single-cylinder engines.
  - **04:** Engines with variable distances between pistons at top dead-center positions and cylinder heads

- **Description and Drawings:** This the part where the designer can obtain the details about the technology. The working principles, main parts, interactions and configurations are available in this part.

- **Claims:** For a patent application the claims are the most important part. It is exactly what the inventors and assignees want to protect. Basically, if it is not in the Claims, it is not protected. Thus, it is an opportunity for the designer to find a device (or an application for a device) that is described in a patent but is not legally protected.

Since the patent has drawings, descriptions, classification codes and claims, the reader might think that a patent survey should be simple task. Notice that a patent is a public document, but the companies put a great effort into writing the document so their competitors do not find their innovative technologies. Moreover, the patent application has its own vocabulary, which it usually complicated and commonly written in a non-direct manner. Please refer to some examples below:

- It is supposed to be descriptive and not objective: A simple table can be described as a planar support surface.

- Even in technical topics, the well established terms are changed: A prismatic pair is described as ”slidably connected to”.

- The descriptions are generalist and expand the application: A vacuum cleaner can be described as a suction device.

- Common words: device and apparatus. Usually those words are used to try not to give a hint of the technology. For example, an engine could be described as a device containing a piston, cylinder, connecting rod and a crankshaft.

Another way to make the patent search harder is the technique called Patent Wall. It is common within the Asiatic companies and consists in filling several patents regarding the same technology but with differences in some minor areas, such as: actuation, synchronization, application or even with different sub-systems such as cooling or lubrication. This tactic increases exponentially the number of results and the researcher might get lost if there is no methodology available to filter those patents.

Another reason why the patent search it is not simple is the number of patents application each year. Fig. 8 shows the number of patent applications from 2010 to 2015 for each continent[2]. It is possible to notice that just in 2014

[2]The statistics about patents is provided by WIPO (World Intellectual Property Organization). For more statistics regarding patents please refer to http://ipstats.wipo.int/ipstatv2/

it was more than 7 million applications. Thus, it makes almost impossible to search patents by an exhaustive manner.

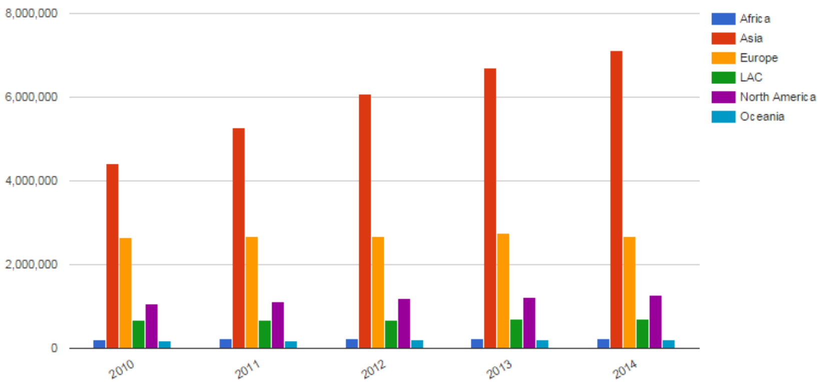


Figure 8: Number of patents applications from 2010 to 2014 for each continent. Adapted from (WIPO, 2015).

2.3.2 UFSC Robotics LAB Patent Survey Methodology

Thus, in order to perform a proper patent search and to achieve interesting results a patent survey methodology is needed. UFSC Robotics Lab developed such a methodology which has been successfully applied in many research projects and it is in accordance with the European Patent Office recommendations. This patent survey methodology is also mechanism orientated, so the designer can obtain the structural characteristics and use them as design requirements as necessary.

The steps of UFSC Robotics Lab methodology are organized into the following topics.

- **Preliminary Search:** This step is dedicated for the designer to know the topic of research. It is, then, a wide-focused approach looking for general related terms in document title and/or abstract. The search parameters such as keywords, filters and data-base must be recorded. The results should be analyzed evaluating both quantity and quality.
  - Quantity means the number of results. Generally, the more results, the more opportunities to understand the problem.

  - Quality means if the results are showing devices as expected. It might happen that a given search term gives results both for the biology and engineering field, for example.

- **Preliminary Search Analysis:** The search parameters and its results are analyzed to determine which combination yields the best results. Extract from the results the patents IPC's, assignees and priority dates. Then it is possible to grasp if the technology is new, which are the leading companies and the most common IPC's they are classified. By this point the designer should have a good understanding about the field, the working principles and the common designs, for example.

- **Detailed Search:** depth-focused approach using optimized search parameters. In this step, the search will be focused on the IPC for example, with combinations of search terms. Commonly the data-bases offer a very useful search-engines for advanced searches.

- **Detailed search analysis:** In this step is expected to have less results but with higher quality. Even with advanced search parameters, there are some results that will not fit into the researched technology. For that reason, the designer should analyze the results one by one and filter the undesired ones.

- **Mechanism Analysis:** Each individual patent is analyzed according to a mechanism orientated point of view. Information such as mobility, number of loops, screw system and also priority date and patent status are listed.

- **Technology Mapping:** In this step the designer should make a classification of the results. Characteristics such as mobility, number of loops and actuation can be used to make groups out of them. With a proper classification and mapping it is possible to understand the potential for innovation for a given technology.

Fig. 9 shows a diagram for the above explained methodology. Notice that both the preliminary search and the detailed search contain feedback loops. This means that several preliminary searches should be run in order to achieve a proper initial overview. Then, several detailed searches are necessary in order to go through different IPC's or manufacturer, for example.

The next section exemplifies this present methodology with a case study regarding a patent survey for VCR engines.

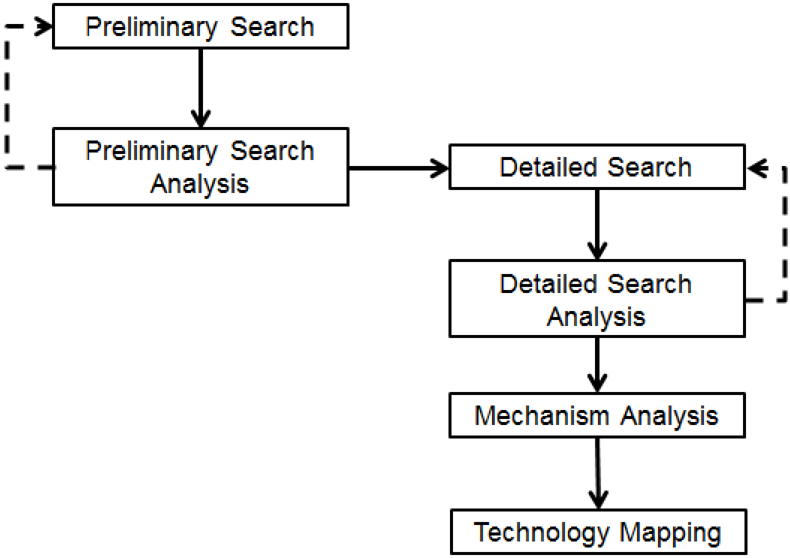


Figure 9: Patent Survey Methodology from UFSC Robotics Lab.

2.3.3 Case Study: Patent survey for VCR engines

An interesting example of a patent survey are the Variable Compression Ratio engines. First, there is few information available from articles, books and manufacturers websites. Thus, a patent survey was the only way in order to understand if the VCR topic was worth researching.

This section will briefly explain the patent survey for the VCR engines regarding the steps mentioned in the Section 2.3.2.

- **Preliminary Search**

During the preliminary search the initial search term was ”variable compression ratio”. This search in Google Patents database[3] would return more than 2 million results, for example.

By analyzing some results it was possible to find patents related to engines, televisions, chemistry and several other fields. Within the engines related results it was possible to find patents regarding electronics, lubrication, timing, and proper new engine concepts.

[3] For more information about this database please refer to https://patents.google.com/

Another tested search term was VCR. However, the results were more biased for Video-cassette Recorder, that old device used for watching films in the television.

Then one more round of search was made by filtering the results for ”variable compression ratio” that included ”engine” in the patent description. This reduced the results for approximately 1000 patents to analyze.

- **Preliminary Search Analysis**

Evidently it is not wise to deeply analyze 1000 patents one-by-one. It is much time consuming and the results would be better if a detailed search was made. In order to do that, about 50 patents were analyzed in order to understand the technology.

In this moment it was possible to find patents regarding electronics, control, lubrication, and proper new engine designs. Also, it was possible to notice that a variable compression ratio could be achieved in so many different ways.

In a first glance it was clear that Honda, Nissan and Hyundai were lead manufacturers and there were several patents regarding the same concept, characterizing a Patent Wall.

The strategy adopted was to list the IPC’s so the detailed search could lead more closely to the new engine designs.

- **Detailed Search**

During the detailed search, it was used mainly the IPC’s listed in the previous step. Within the advanced search tools from the databases it was possible to search for patents inside an IPC that contained the word engine in the description and that it was not classified as a secondary IPC related to electronics, for example.

Thus, using several combinations of advanced searches the number of results dropped to about 300 results.

- **Detailed Search Analysis**

The quality of these 300 results was far better than those previous 1000 patents. By running a deep analysis it was possible to conclude that all the patents were about engines, almost all were about engine concepts but still there were some patents to exclude.

Therefore it was excluded patents that were from the same manufacturer and represented the same mechanism. It happens that the manufacturer patented the same concept in different countries, or some patents regarding patent wall were still present. The detailed search still brought some results regarding lubrication and control, so those were also excluded.

At the end, 127 different engine designs were found. By different, it means that the patents are from different manufacturers, of if the manufacturer is the same, the engine mechanism is different between them.

- **Mechanism Analysis and Technology Mapping**

Those 127 results were analyzed regarding the mechanism theory. By doing that it was possible to propose an enhanced classification for the variable compression ratio field and to extract several characteristics that were used both to classify and to generate design requirements. More details of the mechanism analysis and technology mapping will be given at Section 3.4 and Chapter 4.

2.4 CONCLUSIONS

In this chapter it was presented several design methodologies that can help the designer defining proper design requirements, selecting the feasible kinematic chains and dealing with the trade-offs. Thus, the methodology proposed by Murai (2013) will be used as a guide during the developments of Variable Compression Ratio engines in Chapter 4. For instance, Chapter 4 presents the definition of structural and functional requirements, the enumeration and selection of kinematic chains.

In addition, it was also discussed in this chapter the importance of a patent survey methodology. It is clear that a patent search it is not an ordinary task, but it rather requires attention, focus and a method. Chapter 3 emphasizes the importance of such methodology because without a patent survey it would not be possible to have a proper state of the art overview for the Variable Compression Ratio engines and neither a decent technology mapping. Moreover, the patent survey originated an enhanced classification of VCR engines (which is also present in Chapter 3) and helped the definition of design requirements in Chapter (4).

3 VARIABLE COMPRESSION RATIO ENGINES

This chapter aims on setting a proper state of the art overview of the VCR technology. This will help understanding the structural and functional requirements, the potential for innovation and the reconfigurability in the VCR field. In order to do so, the state of the art is divided in three major topics:

- **Literature Review**: It is responsible to gather the main results about simulation, testing and previous classifications of VCR engines from books, articles or congresses proceedings, for example.

- **Market Analysis**: It presents press releases, news and general public information about the products/prototypes that have been developed by the main manufacturers.

- **Patent Survey**: There are several VCR engine concepts which have not been published to the market or in the literature, but can be found in the patents database. Therefore a complete patent search was conducted and the main results are shown in the Patent Survey section together with a revised classification of the technology.

However, before starting the state of the art survey itself, a brief explanation about reconfigurable engines will be provided.

3.1 RECONFIGURABLE ENGINES

According to Kuo, Dai and Yan (2009), the reconfigurable mechanisms are the ones which can change its configuration during operation. Therefore, an engine is reconfigurable if it can change its mechanisms configuration while running. Notice that the classification is dedicated to the mechanisms. Evidently, an engine can change several parameters inside the ECU but that does not modify the mechanism itself.

An engine has two main mechanisms which can be reconfigurable, the valve train actuation and the piston-to-crank mechanism. Notice that piston-to-crank mechanism is a way to generalize the slider-crank mechanism, since some concepts of reconfigurable engines do not make use of the common slider-crank mechanism.

The valve train reconfigurable engines are not on the scope of this research, but it regards those engines which can vary the valve timing or lift during the engine operation. This technology is widely known in the automotive industry and has been equipped in passenger vehicles for the last three decades.

The piston-to-crank reconfigurable engines are not already used in the open market and there are several researches and developments being conducted by the engine manufacturers. Those engines can be classified into four major types:

- **Variable Stroke Engine (VS)**: This type of reconfigurable engine is able to change the engine displacement during operation. Fig. 10 shows an example of VS engine developed by Freudenstein and Maki (1983).

- **Atkinson Cycle Engine**: This engine uses a mechanism in order to make the power stroke larger than the intake stroke. The idea is to reduce the pumping losses and increase the engine efficiency. Fig. 11 shows an example of Atkinson engine developed by Honda (WATANABE; KONO; NAOE, 2005).

- **Homogeneous Charge Compression Ignition (HCCI) Engine**: The objective of this engine concept is to burn any fuel by compression ignition, *i.e.* as a Diesel Cycle engine. One of the ways to accomplish that is to adjust the compression ratio in order to achieve the right pressure and temperature for the auto-ignition to happen. Thus, a VCR engine can be used.

- **Variable Compression Ratio Engine (VCR)**: This type of engine changes the compression ratio in order to increase efficiency or performance. The VCR engines are the object of study of this research and will be further explained throughout this document.

The UFSC Robotics Lab is continuously researching the reconfigurable engines. It all started with the Variable Compression Ratio engines presented in this research. Then a research project with BMW allowed to start the research within the Atkinson Cycle engines[1].

[1]Due to the non-disclosure agreement, it is not possible to give further information about the results

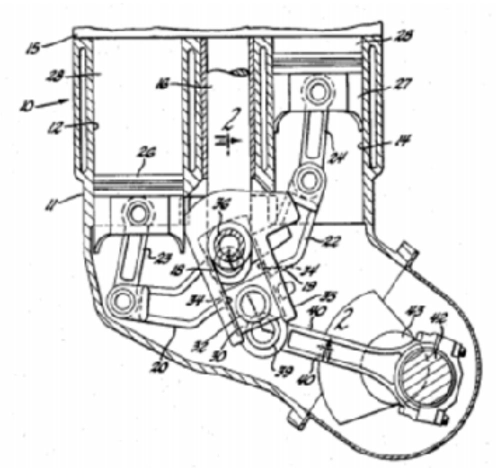


Figure 10: Example of Variable Stroke Engine, it can change the engine displacement during operation. Adapted from Freudenstein and Maki (1983).

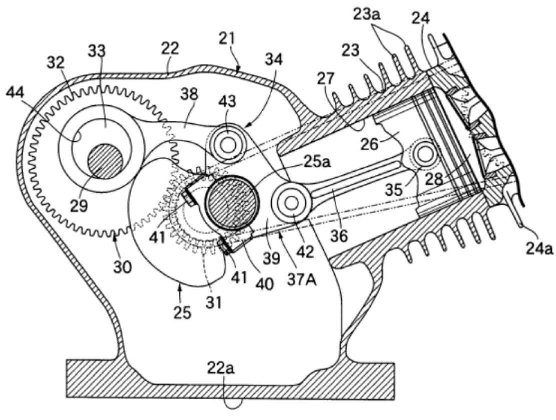


Figure 11: Example of Atkinson Cycle Engine. The power stroke is longer than the intake stroke. Adapted from Freudenstein and Maki (1983).

The objective of this section is to discuss the papers and following publications that emphasize the benefits and results of the VCR engines. This section is divided, thus, in experimental and computational simulation tests and previous classifications of VCR engines.

3.2.1 Experimental Tests

Christensen, Hultqvist and Johansson (1999) studied a single cylinder Engine which could vary the CR from 10:1 to 28:1. The objective was to study the Homogeneous Charge Compression Ignition and the Multi-Fuel capability of an engine. The research concluded that almost any liquid fuel could be used to generate power and that the NOx emissions were very low. However, the important result regarding the Compression Ratio is that the efficiency increases with CR (Fig. 12) and for gasoline, almost no smoke was generated using such a VCR engine. Moreover, it is possible to notice the influence of the fuel within the CR results. Notice that for pure Diesel fuel, the variation of CR has few impact into the efficiency result. On the other hand, for pure Gasoline Fuel the efficiency is more sensitive to the CR variation.

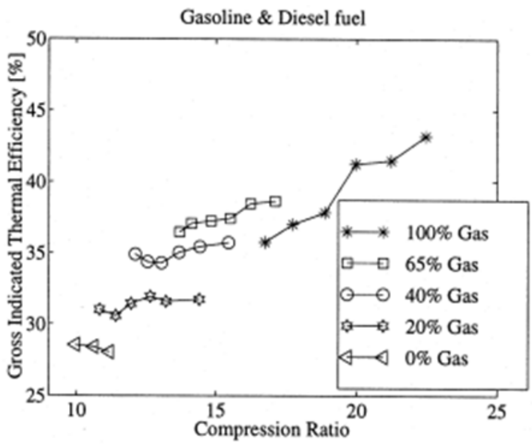


Figure 12: The results of a VCR engine being used as a HCCI engine. The efficiency increases with CR. Adapted from Christensen, Hultqvist and Johansson (1999).

Haraldsson et al. (2002) used a 5 cylinder 1.6L SVC engine from SAAB which is able to vary the compression ratio from 8:1 to 14:1. More information about this engine is available in Section 3.3. The objectives of this research was to investigate the trade-off between inlet air-temperature and compression ratio, and to find the load/speed range for HCCI (Homogeneous Charge Compression Ignition) operation. The main result regarding the VCR engine is that the engine thermal efficiency increases with CR.

Nilsson (2007) understands the VCR engines as a mean to meet demand on lower fuel consumption standards for the future. The VCR can also be seen as an extra Degree of Freedom to prevent engine knock. Nilsson (2007) has used the SAAB SVC Engine, using petrol as fuel and a CR ranging from 8:1 to 14:1. The focus of the research was on the optimization of engine parameters, for instance the ignition angle, CR, fuel flow, etc. Even though, the author could also conclude that the efficiency increases with CR however it decreases for CR higher than 17:1.

3.2.2 Computational Simulation Tests

Ozcan and Yamin (2008) studied the behavior of an engine both for variable stroke and variable compression ratio mechanisms by means of computational simulations. The engine model used in the simulations was a single-cylinder, four-stroke, water cooled, spark ignition engine, based on Freudenstein and Maki (1983) VS engine mechanism. Even though the main objective was to study the variable stroke engines, the compression ratio could be varied from 6,82:1 to 10:1. Ozcan and Yamin (2008) states that it is possible to achieve a 50% more powerful engine with lower compression ratios, as shows Fig. 13. On the other hand, the higher the compression ratio, the higher the engine efficiency. According to the study, it is possible to achieve a 10% more efficient engine. In addition, the fuel consumption dropped 5%, however the pollutants level increased at low compression ratios. Once more, the simulation concluded that is possible to achieve both powerful and efficient engines with the Variable Compression Ratio technology (OZCAN; YAMIN, 2008). It is important to keep in mind that the results in Fig. 13 shows the increase of power related to CR. However, to achieve such impressive numbers some other parameters are changed such as ignition timing, amount of injected fuel and valve timing. Even though, these parameters are constantly changing during an operation of a fixed CR engine.

Yamin and Dado (2004) also simulated a four stroke engine based on Freudenstein and Maki (1983) model. The objective was to investigate the effects of the variation of engine stroke and compression ratio into the engine

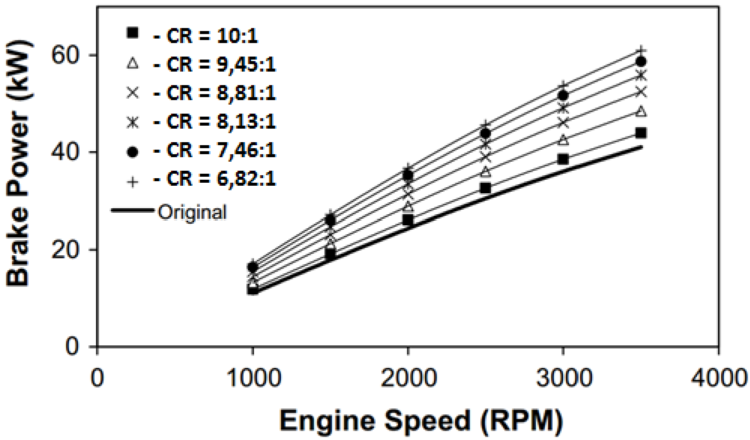


Figure 13: Results of the simulation in VCR engines. The power increases with the decrease in Compression Ratio. Adapted from Ozcan and Yamin (2008).

power, cylinder pressure, volumetric efficiency and several other parameters. According to Yamin and Dado (2004) the advantage of a VCR engine is that the engine performance can be optimized for a full range of driving conditions, such as acceleration, speed and load. At low power levels, the CR is high, so the fuel efficiency benefits can be captured. On the other hand, at high power levels, the CR is kept low in order to prevent knock.

3.2.3 Previous VCR Classifications

During the last decades, researchers and manufacturers developed several engine concepts that were able to vary the compression ratio. Several authors proposed different classifications in order to facilitate the comprehension of the VCR topic.

Shaik, Moorthi and Rudramoorthy (2007) were one of the earlier authors to propose a classification to the VCR engine topic. However, they do not mention how the classification was obtained and their five types of VCR engines are based in specific car manufacturer designs rather than in a general results analysis. The five groups of VCR engines defined by Shaik, Moorthi and Rudramoorthy (2007) is listed below:

- **Moving the crankshaft axis:** The compression ratio is varied by means of an eccentric between the engine block and the crankshaft.

- **Modification of the connecting rod geometry:** A multi-link mechanism between the connecting rod and the crankshaft is used to achieve a VCR engine.

- **Moving the cylinder head:** This concept combines a cylinder head with cylinder liners into a monohead construction, which pivots with respect to the remainder of the engine and thus, changes de compression ratio.

- **Variation of combustion chamber volume using a secondary piston or valve:** A secondary piston is integrated into the cylinder head in order to vary the combustion chamber volume and therefore, the compression ratio.

- **Variation of piston deck height:** This concept also varies the combustion chamber volume by changing the position of the piston in relation to the connecting rod.

- **Moving the crank pins:** This concept also uses an eccentric bearing in order to vary the compression ratio. However, it is located between the crankshaft and the connecting rod.

Nilsson (2007), on the other hand, does not make a formal classification of the VCR engines. The objective of this work was to test a VCR engine in particular, the other concepts did not receive special attention. He states that, apart from SAAB SVC engine, there is four more VCR engine concepts. These concepts are listed below in which both the classification and the description were given by Nilsson (2007):

- **Secondary Piston:** The combustion chamber has a small secondary piston that is used to change the compression ratio.

- **Connecting Rod Linkages:** The conventional con rod is replaced with a two piece design in which an upper member connects with the piston while a lower member connects with the crankshaft.

- **Movement of crankshaft or crank-pins**: The crankshaft position is moved with respect to the cylinder head, or the crank-pins are moved eccentrically in respect to the connecting rod.

- **Variable piston height:** The compression ratio can be increased by increasing the height of the piston. If the top of the piston head is not fixed to the rest of the piston, the height of the piston can be controlled by the supply of engine lubrication oil.

Radonjic (2010) was the first author to present proper classification of VCR engines. He divides the VCR engines in three major groups, with sub-classifications inside each one. However, Radonjic (2010) does not give further explications about each class, just some figures are provided to exemplify the types of VCR engines. His classification is listed below:

- **Eccentric bearings of**:
  - Main Journal
  - Crank Pin
  - Piston Pin
- **Variable connecting rod geometry**:
  - Multi-link rod-crank
  - Variation of connecting rod length (mechanical or hydraulic system)
- **Variable dimensions of the piston or combustion chamber**:
  - Variable piston deck height
  - Variable combustion chamber volume
  - Two crankshaft phased piston engines
  - Moving cylinder head

Wos et al. (2012) has a proper classification of VCR engines. His work is based on principles to vary the compression ratio and not in specific design from one or another manufacturer. Wos et al. (2012) is the first to present schematic drawings to explain his classification, as shows Figure 14. According to Wos et al. (2012), the VCR engines can be classified into the following types listed below:

a) articulated monohead

b) piston of variable deck height

c) eccentrics on crankshaft bearings

d) multi-link rod-crank mechanisms

e) secondary moving piston or valve in cylinder head

f) gear-bases crank mechanisms;

g) precisely shifted cylinder block;

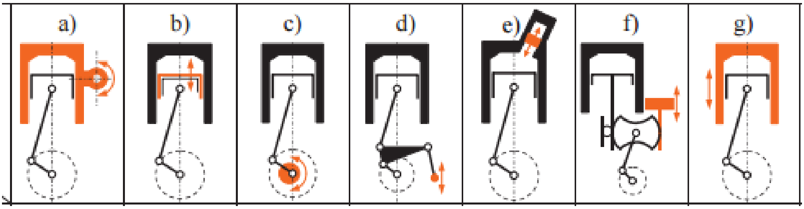


Figure 14: Schematic representation of the classification proposed by Wos et al. (2012). Adapted from (WOS et al., 2012).

Gupta (2012) dedicates a section for the VCR engines in his book. The VCR engines are divided into five types, which are listed below:

- Auxiliary chamber in cylinder head
- Piston with variable compression height
- Adjustable connecting rod length
- Eccentric main crankshaft bearings

A comparison between all those classifications will be given in Section 3.4 where it is shown a Patent Survey which results in an enhanced classification of the VCR engines.

3.3 MARKET ANALYSIS

Most of the VCR engines is still under confidential status. There are many manufacturers developing it, as presented in Section 3.4, but just a few publish the results and concepts in their press releases. Thus, the next sections will present the VCR engine designs that went to public knowledge up to this date.

3.3.1 SAAB SVC Engine

The first well known manufacturer to release a concept of a VCR engine was the Swedish company SAAB. It was called the SVC engine (Saab

Variable Compression) and, according to the company website, the SVC engine could reduce the fuel consumption of a conventional naturally aspirated engine by up to 30% while at the same time providing impressive performance (SAAB, 2000). Some numbers of the SVC engine regarding power and torque are given in Table 2.

Also according to SAAB, the SVC engine was comprised of a cylinder head with integrated cylinders, which is known as the monohead and a lower portion consisting of the engine block, crankshaft and pistons. The compression ratio is varied by adjusting the slope of the monohead in relation to the engine block and internal reciprocating components. This alters the volume of the combustion chamber with the piston at top dead center, and therefore, changes the compression ratio (SAAB, 2000).

Fig. 15 shows a schematic view of the SAAB SVC engine. The image on the left represents the engine with the highest compression ratio. On the right side, the engine is set with the lowest compression ratio, and it is possible to notice that the monohead is tilted.

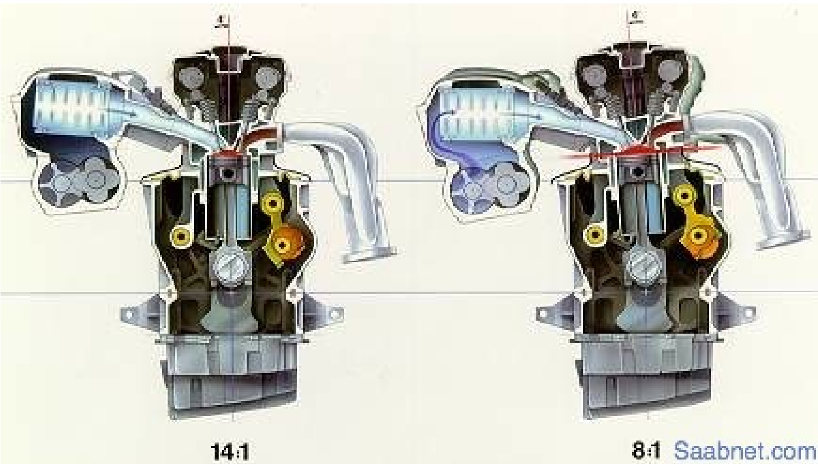


Figure 15: Schematic picture of a SAAB SVC engine. It is possible to see the tilting monohead which changes the compression ratio. (SAAB, 2000)

Fig. 16 shows an image of the engine developed by SAAB. By the outside, it looks like a conventional engine. By the image (Fig. 16) the SVC engine seems quite ready for production. Section 3.2.1 showed that this engine has performed several tests from different researchers. Even though, there were no news about it being used in a regular series production vehicle.

Table 2: Characteristics from the SAAB SVC Engine. (SAAB, 2000)

Max. Power	150 HP
Max. Torque	200 Nm
Number of Cylinders	5
Engine displacement	1.6 l
Compression Ratio Range	8:1 to 14:1
Engine Consumption	Up to 30% less

Figure 16: Picture of a SAAB SVC engine. (SUFFERN, 2013)

3.3.2 Nissan VCR Engine

Nissan also has a press release regarding its concept of VCR engine. According to the Japanese manufacturer, the new engine mechanism enables both high power of turbo engines and a low fuel consumption of a aspirated engines (NISSAN, 2011).

Unlike SAAB release, Nissan does not give numbers of its engine but states that by applying a multi-link mechanism, significant improvement of engine vibration coupled with friction reduction have been obtained (NISSAN, 2011).

Fig. 17 shows the concept of VCR engine from Nissan. On the left side, it is possible to see the multi-link mechanism. The control shaft positions the whole mechanisms and therefore, changes the compression ratio. On the right, the Japanese manufacturer compares the vibration of its VCR engine with the conventional engines and the V6 engines.

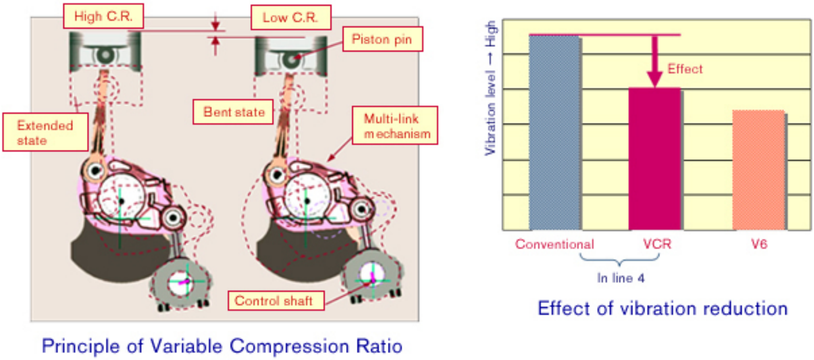


Figure 17: Concept of Nissan VCR Engine. It is possible to notice the multi-link mechanism and the effect of vibration reduction. (NISSAN, 2011)

3.3.3 Gomecsys VCR Technology

Gomecsys is a Dutch engineering company which focus on developing fuel saving engine technologies. Within these technologies there is a concept of a VCR engine. It uses an eccentric coupling between the crankpin and the big end of the connecting rod to promote variation of the CR. The eccentric link position can be modified by a set of gears and a shaft that enters the crankshaft from the front of the engine. According to Gomecsys website, its VCR concept is able to vary the compression ratio from 8:1 to 18:1 and it can save up to 18% of fuel when compared to a fixed CR engine (GOMECSYS, 2015).

The Dutch company still have not put its engine on the market, however a partnership with PSA Group is permitting some prototypes to be tested on the roads. Even though, Gomecsys does not provide a date for the product release.

Fig. 18 represents a schematic view of Gomecsys concept. The eccentric link (A) between the crankshaft and the big end of the connecting rod changes the position of the engine TDC (Top Dead Center) and, thus, the compression ratio.

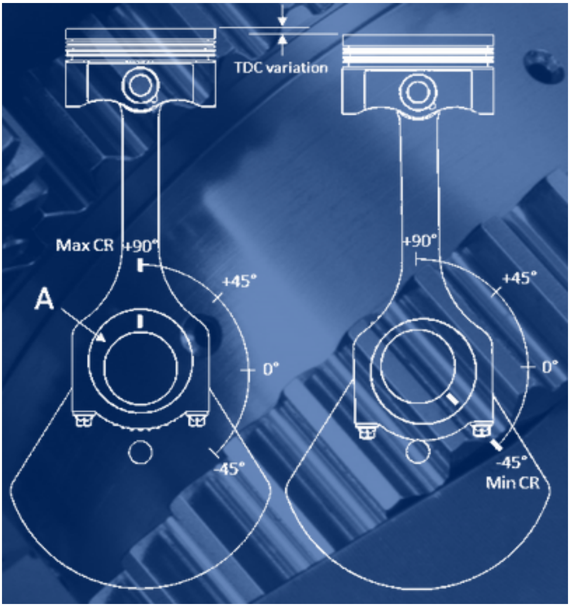


Figure 18: Concept of VCR engine from Gomecsys. It is possible to notice an eccentric link (A) between the crankpin and the connecting rod. Its actuation changes the engine TDC and therefore, the compression ratio. (GOMECSYS, 2015)

3.3.4 MCE-5 VCRi Engine

MCE-5 is a French engine developer which is claiming a brand new VCR engine. According to its official website, the MCE-5 VCRi engine optimizes the efficiency, performance, pollutant emission levels and cost price (MCE-5, 2015). Table 3 shows some numbers regarding power and torque of VCRi engine. The torque and power levels are quite impressive when compared to the ”conventional” 1.5 l engines. MCE-5 also claims up to 30% less fuel consumption when compared to fixed CR engines.

According to (MCE-5, 2015), there are already some engine prototypes being tested both in road vehicles and in test rigs.

Fig. 19 shows a schematic figure of the VCRi engine. By the outside its concept has almost the same package as a conventional fixed CR engine. However, inside the block it is completely different. This concept applies several geared joints in order to change the compression ratio. Please refer to

Fig. 19 and notice two pistons. The one on the right is used for compression ratio adjustment. The one on the left is the proper *combustion piston*. Notice that this piston it is not connected to a connecting rod[2].

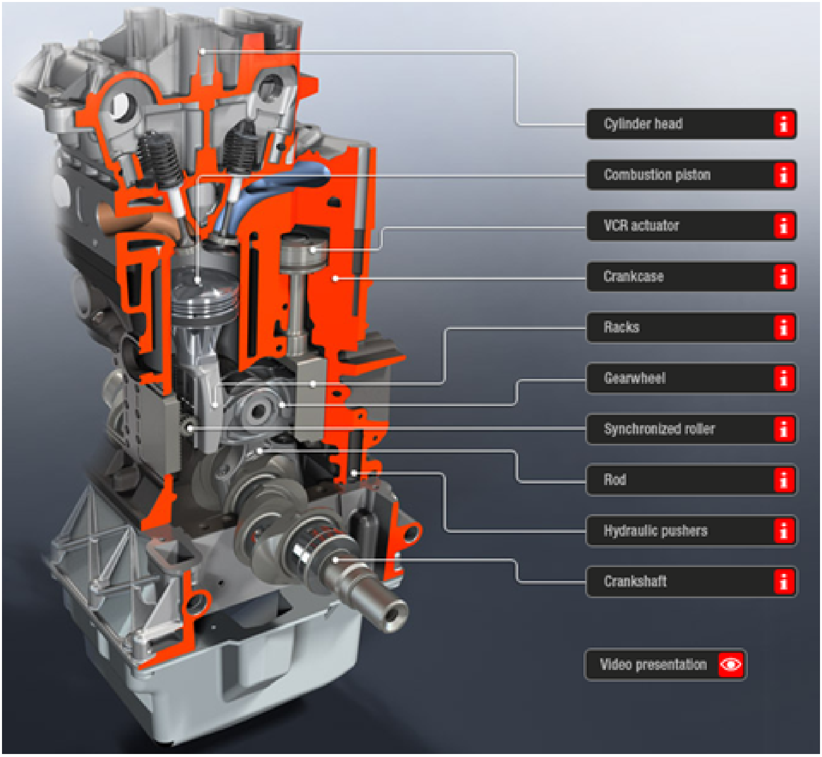


Figure 19: Concept of MCE-5 VCRi engine. The engine is comprised by several geared mechanisms that are able to change the compression ratio. (MCE-5, 2015)

[2]The working principle of the VCRi engine is not easy to explain. It is recommended for the reader to visit MCE-5 website for further information (http://mce-5.com/english/index.html)

Table 3: Characteristics from the MCE-5 VCRi Engine. (MCE-5, 2015)

Max. Power	215 HP
Max. Torque	420 Nm
Number of Cylinders	4
Engine displacement	1.5 l
Compression Ratio Range	6,5:1 to 15:1
Engine Consumption	Up to 30% less

3.3.5 FEV two-stage VCR Engine

FEV is a German engineering company, which works both in the consulting and the development sectors. Among its products, there is a VCR concept that applies an eccentric link between the connecting rod and the piston pin.

According to the FEV website, the VCR engine is a solution to improve fuel consumption in spark ignition engines, to enable downsizing beyond today's limits, to decrease particulate emissions in diesel engines and to minimize friction losses (FEV, 2015).

Fig. 20 shows the concept designed by FEV. Actually, their product is a connecting-rod which is able to promote the variation of compression ratio. The connecting rod has an eccentric bearing which varies the position of the piston pin, changing the engine TDC and thus, the compression ratio. The referred eccentric link is actuated by two hydraulic pistons which are also integrated inside the connecting rod structure. Unlike the other concepts, the FEV product offers a two-stage VCR and not a continuously variable compression ratio within a range.

Also according to the comapany website, FEV has be operating a Lotus Elise MK1 demonstrator vehicle. The referred vehicle features a 1.8 l engine downsized to 1.65 l, a 6-speed manual transmission and a VCR connecting-rod with CR stages of 8.8:1 and 12:1 (FEV, 2015).

Figure 20: Concept of FEV two-stage VCR connecting rod. The compression ratio actuation is made only by the connecting rod, which contains the eccentric link and the hydraulic pistons to change the position of the piston pin. (FEV, 2015)

3.4 PATENT SURVEY

Neither Section 3.3 nor Section 3.2 could provide a proper overview about the VCR technology. The manufacturers and/or developers do not give much information about their products and the existing classifications are confusing and are not common among the authors.

Moreover, the market analysis is not able to identify all existing designs in VCR technology, since several concepts are protected by patents and not necessarily revealed by the developers. Thus, in order to have a proper perspective about the VCR engines and to settle the discrepancies in the previous classification, it was decided to run a patent survey.

This patent survey was made according to the methodology exposed in Section 2.3 and the main results are exposed in this present section.

More than 1000 patents from 1974 to 2014 were analyzed and organized. Figure 21 shows a trend for the VCR research. Since 2000, the number of filed patents has been increasing significantly, suggesting a growing interest from automotive sector. From 2013 up to the present date, the numbers are still incomplete since some patents applications are still under confidential status (HOELTGEBAUM; SIMONI; MARTINS, 2015) .

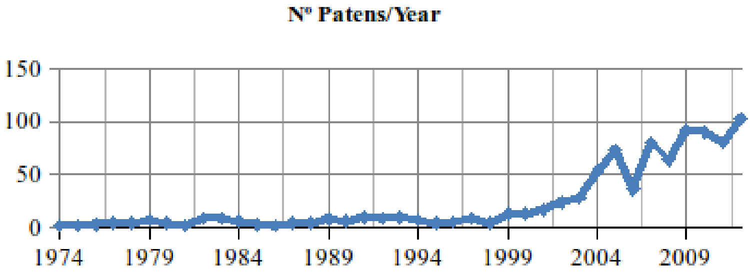


Figure 21: Results from the patent survey. Number of patents of VCR engines by year. Adapted from (HOELTGEBAUM; SIMONI; MARTINS, 2015)

Excluding from the survey all patents related to control, hydraulics and minor improvements of previous designs, a total of 127 different VCR engine designs remained[3]. Those 127 are listed in the second column of Table 4.

Taking the patent survey as a base, and comparing with the previous classifications, the VCR engines can be organized into seven classes, and one of these has three sub-classes, as presented at the first column of Table 4. The second column of Table 4 shows the number of cataloged patents for each class.

Table 5 makes a comparison between the proposed classification and the previous ones mentioned in Section 3.2.3. It is possible to notice that previous authors diverge on the classification of VCR engines. The apparently most complete classification is from Radonjic (2010). Radonjic (2010) does not take into account the Class F VCR engines and presents, however, another class of VCR engines the so called ”two crankshaft phased piston engine”. This class was not considered by the patent survey since it suggests a complete different engine concept and it was not possible to find any known automotive manufacturer (or engine developer) patenting such engines .

On the other hand, Wos et al. (2012) was the only author to consider the geared mechanisms as a different class of VCR engines. Some authors consider this class of engines being part of Class D. In a mechanism-orientated point of view, geared mechanisms work on different screw systems, therefore it is wise to distinguish those classes in order to facilitate further analysis.

[3]If a patent was filed in more than one country, it was considered as one single concept

Table 4: Enhanced Classification of Variable Compression Engines. (HOELTGEBAUM; SIMONI; MARTINS, 2015)

Proposed Classification (based on the patent survey)	Qty
Class A: Moving Cylinder Head	17
Class B: Variable Piston Deck Height	21
Class C: Eccentric on Bearings C1 - Between Piston Pin and Connecting Rod C2 - Between Connecting Rod and Crankshaft C3 - Between Crankshaft and Engine Block	36 (9) (15) (12)
Class D: Multi-Link Mechanisms	20
Class E: Additional Cylinder in Combustion Chamber	22
Class F: Geared Mechanisms	5
Class G: Variable Connecting Rod Length	6
Total	127

Class C it is another point of discrepancy. Gupta (2012) takes into account just the Class C3 while Shaik, Moorthi and Rudramoorthy (2007), Nilsson (2007) and Wos et al. (2012) also include C2. Radonjic (2010) is the only to consider all subclasses of Class C VCR engines.

Table 5: The proposed classification of VCR engines is compared with the classifications of several authors.

Proposed Classification	Gupta	Shaik	Nilsson	Radonjic	Wos
Class A	√	√	√	√	√
Class B	√	√	√	√	√
Class C					
C1				√	
C2		√	√	√	√
C3	√	√	√	√	√
Class D	√	√	√	√	√
Class E	√	√	√	√	√
Class F					√
Class G				√	

The classes of VCR engines shown in Table 4 will be detailed in the next sections according to the mechanism theory point of view with the help of several tables. Those tables will outline patents, manufacturers, schematic and structural representations, mobility (M), number of loops (ν) and order of screw system (λ) for each class. In every table and every figure, the link numbers follows the same standard:

- Number 1 is the fixed link (engine block);
- Number 2 is the connecting rod;
- Number 3 is the crankshaft. Since it represents the core DOF, it is also depicted in yellow;
- Number 4 is the piston;
- Number 5 is the auxiliary link that is directly actuated to promote the variation of compression ratio. This link represents the reconfigurability DOF. For that reason it is also depicted in red.

3.4.1 Class A: Moving Cylinder Head

In order to change the compression ratio, the Class A VCR Engines varies the clearance volume in the combustion chamber by means of changing the height of the cylinder head. The representative example of this class is the SAAB SVC Engine, which was also presented in Section 3.3.1. Table 6 presents the engine mechanism characteristics according to its respective patent (DRANGEL; NILSSON; BERGSTEN, 1992).

Table 4 shows that Class A resulted in 17 different engine designs which can be summarized by three different kinematic chains, shown in Table 7. During the patent survey it was possible to notice that, apart from SAAB, other manufacturers patented Class A VCR engines such as Toyota, Daimler and VW.

Table 6: Class A VCR Engines - the compression ratio is varied by changing the height of cylinder head (6) (HOELTGEBAUM; SIMONI; MARTINS, 2015).

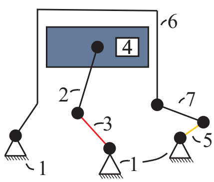
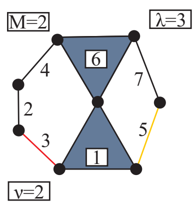
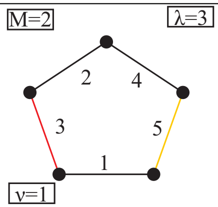
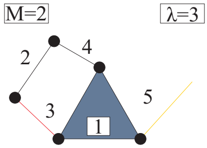
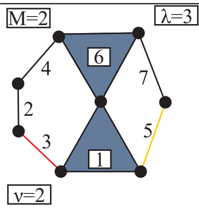
ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
SAAB	EP 560817 (1992)		

Table 7: Kinematic chains found in patent survey cataloged as Class A. (HOELTGEBAUM; SIMONI; MARTINS, 2015)



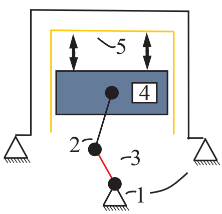
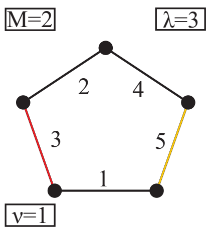




3.4.2 Class B: Variable Piston Deck Height

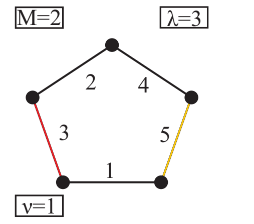
The Class B VCR Engine has a piston, which can vary its deck height. This concept usually applies two pistons in series. In Table 8, it is possible to notice that there is a secondary piston (5) outside the primary piston (4). It is important to emphasize that the outside piston (5) it is a part and it is actuated by the primary piston (4). In other words, it is possible to state that the assembly of the outside and primary piston form the part which is commonly known as piston in a fixed CR engine. The relative displacement between them will vary the compression ratio. Table 8 also presents one representative example of this class of engine patented by Honda (HIRANO, 2003).

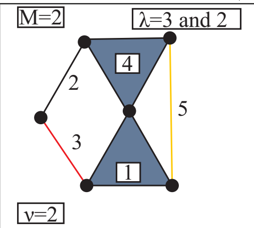
Table 8: Class B VCR Engines, it varies the compression ratio by changing the height of piston deck (5). (HOELTGEBAUM; SIMONI; MARTINS, 2015)

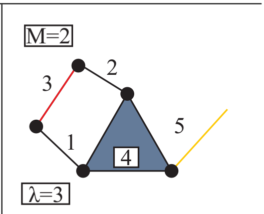
ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
Honda	US7066118 (2003)		

As Table 4 shows, the patent survey resulted in 21 different patents for Class B VCR engines. However, it is possible to find just three different kinematic chains presented in Table 9. PSA, Ford, Nissan, Daimler, Mahle, VW and BMW also patented Class B VCR engines.

Table 9: Kinematic chains found in patent survey cataloged as Class B. (HOELTGEBAUM; SIMONI; MARTINS, 2015)







3.4.3 Class C: Eccentric on Bearings

The Class C VCR engine applies eccentric links in order to change the position of determined links, varying the clearance volume and, thus, the compression ratio. The patent survey revealed that the Class C VCR engines can be divided into three subclasses, according to the position of the eccentric links:

C1: Eccentric link between piston pin and connecting rod (Table 10);

C2: Eccentric link between connecting rod and crankshaft (Table 12);

C3: Eccentric link between crankshaft and engine block. (Table 13).

Subclass C1: Eccentric link between piston pin and connecting rod.

Table 10 shows the representative example for Class C1 patented by Daimler (NOLTENMEYER, 1983). It is possible to notice the eccentric link (7) that reconfigure the position of piston (4) and thus, changes the compression ratio.

According to Table 4, C1 Class has a result of 9 different concepts. However, as Table 11 shows, it is possible to notice just two different kinematic chains for this class. Hyundai, Ford, Toyota, VW and Daimler are the most common manufacturers with patent applications for Class C1 VCR engines. Apart from these manufacturers, the FEV concept from Section 3.3.5 also belongs to this class.

Table 10: Class C1 VCR Engines. The compression ratio is set by applying an eccentric shaft (7) between the piston (4) and the connecting rod (2).(HOELTGEBAUM; SIMONI; MARTINS, 2015)

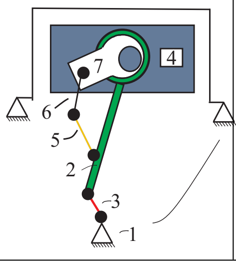
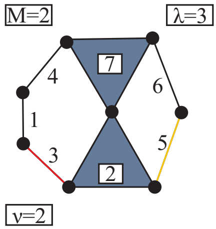
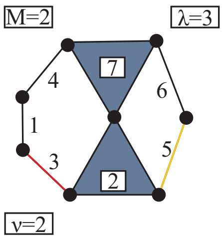
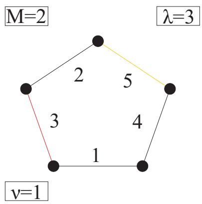
ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
Daimler	DE 3148193A1 (1983)		

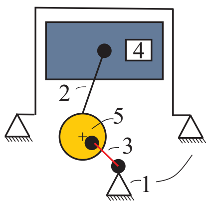
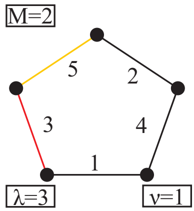
Table 11: Kinematic chains found in patent survey cataloged as Class C1.(HOELTGEBAUM; SIMONI; MARTINS, 2015)

Subclass C2: Eccentric link between connecting rod and crankshaft.

During the patent survey it was possible to find a single kinematic chain for C2 Class VCR engines exemplified by the Honda (SUGIMOTO; KADOTA; MORIYA, 1996) representative concept in Table 12. This concept modifies the position of the eccentric link (5) between the connecting rod (2) and crankshaft (3), which varies clearance volume and consequently changes the compression ratio. It is possible to notice VW, BMW, Ford and Mitsubishi, as lead assignees developing Class C2 VCR engines. The Gomecsys concept, shown in Section 3.3.3 also belongs to this class.

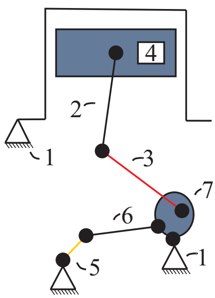
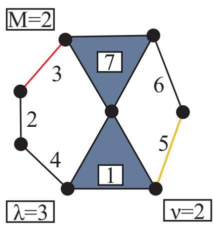
Table 12: Class C2 VCR Engines. The compression ratio is varied by means of an eccentric link (5) between the connecting rod (2) and the crankshaft (3). (HOELTGEBAUM; SIMONI; MARTINS, 2015)

ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
Honda	US 5562068 (1996)		

Subclass C3: Eccentric link between crankshaft and the engine block.

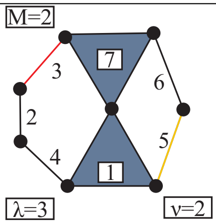
Table 13 shows the example for Class C3 patented by Hyundai (LEE; KONG; WOO, 2010). In this concept, the eccentric link (7) changes the position of the crankshaft (3) in relation to the engine block (1). This also varies the clearance volume and, thus the compression ratio.

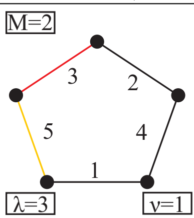
Table 13: Class C3 VCR Engines. The compression ratio is changed by applying an eccentric shaft (7) between the crankshaft (3) and engine block (1). (HOELTGEBAUM; SIMONI; MARTINS, 2015)

ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
Hyundai	US 20100326404 (2010)		

According to Table 4, the C3 Class resulted in 12 different concepts. However, as Table 14 shows, there are just two different kinematic chains for this class. Hyundai and SAAB are the common assignees for Class C3.

Table 14: Kinematic chains found in patent survey cataloged as Class C3.(HOELTGEBAUM; SIMONI; MARTINS, 2015)

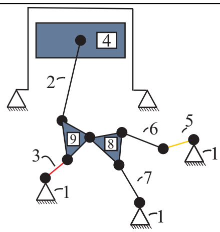
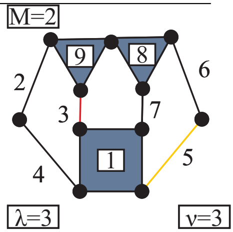




3.4.4 Class D: Multi-Link Mechanisms

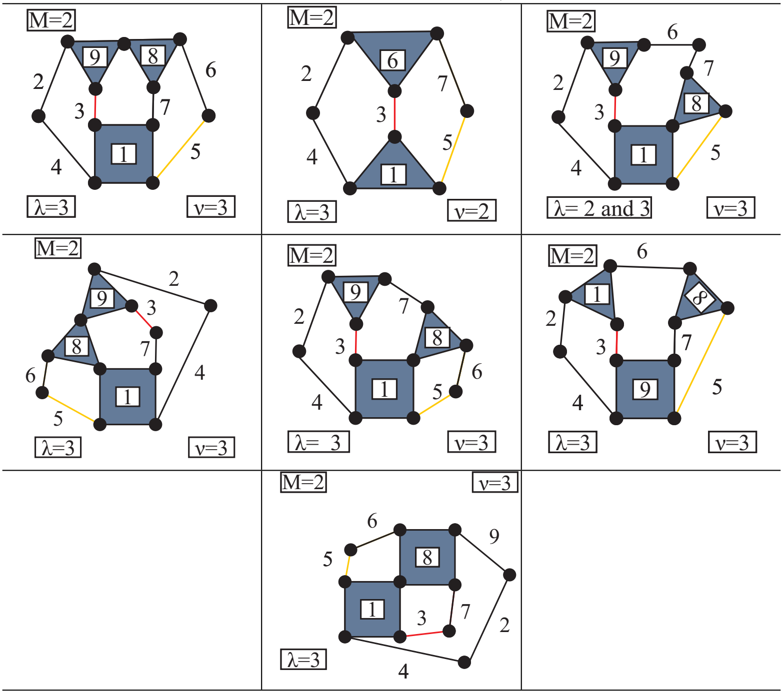
By applying a multi-link mechanism between the piston (4) and the crankshaft (3), the Class D VCR engine is able to change the compression ratio. This design is more complicated since it is the only case where the connecting rod (2) is not directly linked to the crank (3). Between the connecting rod (2) and the crankshaft (3) there is a whole mechanism that changes the compression ratio. Table 15 shows a representative patent from Hyundai (LEE; KONG; KIM, 2010). The Nissan concept from Section 3.3.2 also belongs to this class.

Table 15: Class D VCR Engines. The compression ratio is changed applying a multi-link mechanism between the connecting rod (2) and the crankshaft (3).(HOELTGEBAUM; SIMONI; MARTINS, 2015)

ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
Hyundai	US 2010000487 (2010)		

According to Table 4, the Class D VCR engines resulted in 20 different concepts. In addition, it was possible to notice 7 different kinematic chains from Daimler, Hyundai, Renault, Honda, Nissan, PSA and Ford. All kinematic chains are presented in Table 16.

Table 16: Kinematic chains found in patent survey cataloged as Class D. (HOELTGEBAUM; SIMONI; MARTINS, 2015)



3.4.5 Class E: Additional Cylinder in the Combustion Chamber

The Class E VCR Engine applies an additional cylinder (7) in the combustion chamber. This cylinder varies the combustion chamber volume, and thus, the compression ratio. Table 17 shows the Hyundai (CHOI, 2014) representative patent of this class of engine. Notice that it is a different concept from Class B, in which the piston (4) is divided into two parts. In Class E, on the other hand, the secondary piston is applied at the engine block and has no linkages to the slider crank mechanism.

According to Table 4, the Class E VCR engines resulted in 22 different concepts. The main assignees developing Class E VCR engines are Hyundai, GM and Ford. Further, 4 different kinematic chains are presented in Table 18.

Table 17: Class E VCR Engines. The compression ratio is changed applying an additional cylinder (7) in the combustion chamber.(HOELTGEBAUM; SIMONI; MARTINS, 2015)

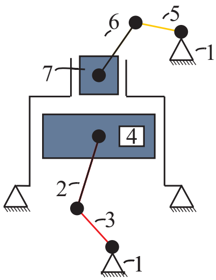
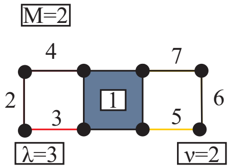
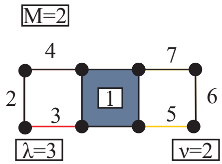
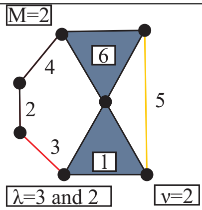
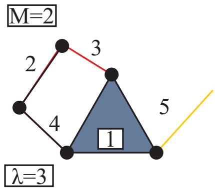
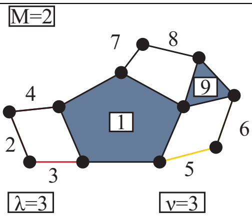
ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
Hyundai	US 2014165969 (2014)		

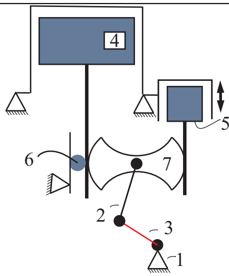
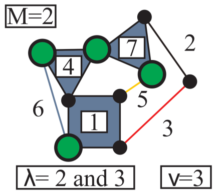
Table 18: Kinematic chains found in patent survey cataloged as Class E.(HOELTGEBAUM; SIMONI; MARTINS, 2015)

3.4.6 Class F: Geared Mechanisms

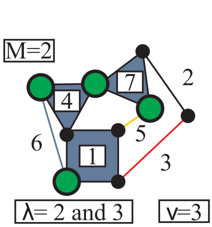
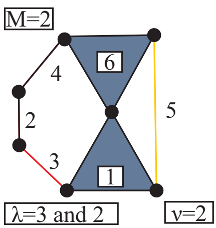
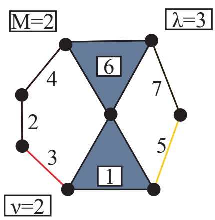
The Class F VCR Engine uses a complete different concept in engine design. The most representative example for this class of engine, shown in Table 19 is the MCE-5 (RABHI, 2010), which is an important engine developer researching VCR engines, also shown in Section 3.3.4. From the mechanism theory point of view, the MCE-5 (RABHI, 2010) concept runs on different screw systems because it mixes prismatic, revolute and geared joints. Since this concept is quite different from all the others, there are some differences in the schematic and structural representation. In the schematic representation, the blue circle (6) represents a geared roller. It allows the piston (4) to work properly within link (7). Anyway, it does not represent a revolute joint. The link (5) stands for a hydraulic piston that changes the orientation of link (7) and therefore changes the compression ratio. In the structural representation, the larger green circles represent all the geared joints.

Table 19: Class F VCR Engines. The compression ratio is changed by applying a geared mechanism between the piston (4) and the crankshaft (3).(HOELTGEBAUM; SIMONI; MARTINS, 2015)

ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
MCE-5	US 2010154740 (2007)		

According to Table 4, the Class F VCR engines is a very particular concept of VCR engine, since it resulted in 5 different designs. Even though, it is possible to find three different kinematic chains, as shows Table 20. However, none of them was filed by a known automotive manufacturer.

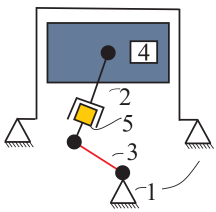
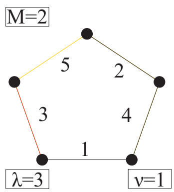
Table 20: Kinematic chains found in patent survey cataloged as Class F.(HOELTGEBAUM; SIMONI; MARTINS, 2015)

3.4.7 Class G: Variable Connecting Rod Length

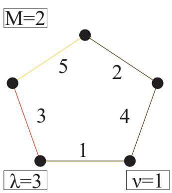
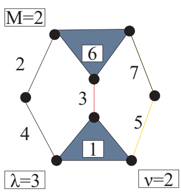
The Type G VCR engine divides the connecting rod (2) in two parts connected by a prismatic joint (2-5). This prismatic joint changes the length of the connecting and consequently alters the compression ratio. Table 21 shows a Ford (RAO; MADIN; IMAI, 2002) patent as the representative concept for this class of engine.

Table 21: Class G VCR Engines. The compression ratio is varied by applying a prismatic joint (2-5) in the connecting rod (2). (HOELTGEBAUM; SIMONI; MARTINS, 2015)

ASSIGNEE	PATENT (Year)	SCHEMATIC REP.	STRUCTURAL REP.
Ford	DE 10151516 (2002)		

According to Table 4, the Class G VCR engines resulted in 6 different concepts becoming a very particular concept of VCR engine. It was possible to find two different kinematic chains, as shown in Table 22. Even with few results, there are well known automotive manufacturers that developed Class G VCR engines such as Daimler and Ford.

Table 22: Kinematic chains found in patent survey cataloged as Class G. (HOELTGEBAUM; SIMONI; MARTINS, 2015)

The patent survey revealed important characteristics regarding the VCR engines field. Those results will help the definition of structural and functional requirements for the developments of such engines. The next section, though, will discuss about the reconfigurability of each class of VCR engines.

3.5 RECONFIGURABILITY OF VCR ENGINES

The research on Variable Compression Ratio engines contributed in the field of reconfigurable mechanisms. The reconfigurability has received special attention from the international scientific community of mechanisms and robots for its advantages when compared to the traditional ones (DAI; KONG; ZOPPI, 2009), (DAI; ZOPPI; KONG, 2012), (DING; KONG; DAI, 2015). The advances regarding reconfigurability are present in many areas such as reconfigurable mechanisms and robots, variable topology modeling, metamorphic mechanisms and robots, origami-inspired mechanisms and modular devices (DAI; KONG; ZOPPI, 2009), (DAI; ZOPPI; KONG, 2012), (DING; KONG; DAI, 2015).

Engines can be another interesting area regarding reconfigurability. As indicated before, a VCR engine can change its configuration during operation to meet fuel/consumption standards or power requirements. Therefore, according to Kuo, Dai and Yan (2009), VCR engines are reconfigurable mechanisms. According to Section 3.1, several engines concepts can be classified as reconfigurable mechanisms such as the Atkinson Cycle Engines, Homogeneous Charge Compression Ignition Engines, Variable Stroke Engines and Variable Compression Engines, for example. The latter is the focus of the present section.

A VCR engine has two degrees of freedom (please refer to Section 4.1.1 for more information):

- The core DOF - the conversion of the reciprocating piston movement into crankshaft rotary motion;
- The reconfigurability DOF - the control of the compression ratio.

The reconfigurability DOF is the DOF that allows the variation of the engine configuration to change the compression ratio. During the patent survey, it was possible to notice that the reconfigurability of VCR engines differed from class to class. Thereby, the reconfigurability in VCR engines is defined following the same classification indicated in Table 4. Consequently, there will be Classes A, B, C, D, E, F and G of Reconfigurability in VCR engines (HOELTGEBAUM; SIMONI; MARTINS, 2016).

For instance, the reconfigurability DOF of a Class A VCR engine is the DOF indicated in Table 6 and Table 7 by the yellow link (5) and it is responsible to vary the height of the cylinder head. SAAB concept uses a rotative DOF while some other patents use a prismatic DOF. In all cases, the reconfigurability DOF is connected to the engine block (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The yellow links (5) in Table 8 and Table 9 shows the reconfigurability DOF for the Class B VCR engine which is responsible to vary the piston deck height. Even with three different kinematic chains, the reconfigurability DOF was always prismatic and connected to the engine block (HOELTGEBAUM; SIMONI; MARTINS, 2016).

Class C has three sub-classes of reconfigurability DOF as indicated in the tables of Section 3.4.3 by the yellow links (5). These DOF's are responsible for varying the clearance volume in the combustion chamber. In all three sub-classes of Class C, by applying eccentrics on bearings the reconfigurability is achieved. Daimler patent (NOLTENMEYER, 1983) uses an eccentric between piston pin and connecting rod. Honda patent (SUGIMOTO; KADOTA; MORIYA, 1996) uses an eccentric between connecting rod and crankshaft, and, Hyundai patent (LEE; KONG; WOO, 2010) uses an eccentric between crankshaft and engine block. Neither Class C1 nor Class C2 have the reconfigurability DOF connected to the engine block while Class C3 is the only to have it (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The reconfigurability DOF of a Class D VCR engine is the DOF indicated in Table 15 and Table 16 by the yellow links (5). The reconfigurability DOF in this class is provided by a multi-link mechanism which usually has two or three loops as presented in Table 15 and 16. Hyundai patent (LEE; KONG; KIM, 2010) uses a rotative DOF, which is commonly the case for Class D VCR engines. However, there is a Nissan patent that applies a prismatic DOF. In six out of seven kinematic chains the reconfigurability DOF is connected to the engine block (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The reconfigurability DOF of a Class E VCR engine is the DOF indicated in Table 17 and Table 18 by the yellow links (5) and it is obtained through an additional cylinder in the combustion chamber. Hyundai patent (CHOI, 2014) uses a four bar mechanisms applying a rotative DOF. It is also common to find prismatic DOF. In all the cases the reconfigurability DOF is connected to the engine block (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The reconfigurability DOF of a Class F VCR engine is the DOF indicated in Table 19 and Table 20 by the yellow links (5) and it is obtained by the interaction of the whole geared mechanism. MCE-5 concept (RABHI, 2010) uses a prismatic DOF through a geared mechanism and the reconfigurability DOF is connected to the engine block. Usually this is the case for the other concepts in Class F (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The reconfigurability DOF of a Class G VCR engine is the DOF indicated in Table 21 and Table 22 by the yellow links (5) and it is responsible to vary the length of the connecting rod. By its definition, Ford patent (RAO; MADIN; IMAI, 2002) and the others uses a prismatic DOF. There are cases where the reconfigurability DOF is connected to the block and cases where it is not (HOELTGEBAUM; SIMONI; MARTINS, 2016).

Table 23 summarizes all information discussed above. The symbol ($\surd$) denotes that at least one case of determined property was found in each class. It is clear that the Class C engines do not have prismatic pairs as reconfigurability DOF. This class of engines applies eccentric bearings in order to promote the variation of Compression Ratio, thus it would be expected to have revolute reconfigurable DOF's. Also, Class C1 and C2 do not have ground connected reconfigurable DOF's. This is because they apply eccentric bearings between the piston pin and connecting rod, and between connecting rod and crankshaft. Thus it would be difficult to have ground connected reconfigurability DOF's to actuate such devices.

Table 23: Reconfigurability in VCR engines. (HOELTGEBAUM; SIMONI; MARTINS, 2016)

Reconfigurability DOF	Class								
	A	B	C1	C2	C3	D	E	F	G
Prismatic	$\surd$	$\surd$				$\surd$	$\surd$	$\surd$	$\surd$
Revolute	$\surd$		$\surd$	$\surd$	$\surd$	$\surd$	$\surd$		$\surd$
Ground Connected	$\surd$	$\surd$			$\surd$	$\surd$	$\surd$	$\surd$	$\surd$

3.6 CONCLUSIONS

This chapter used the methodologies from Chapter 2 in order to derive a state of the art overview about the VCR engines. As a result, a proper technology mapping was achieved and an enhanced classification of VCR engines was proposed. This classification was explained by means of representative examples of which were presented both the schematic and structural representations. Moreover, for the first time in the literature of mechanisms it was defined the reconfigurability of VCR engines.

Chapter 4 will also use the information discussed in Chapter 3 in order to derive the structural and functional requirements for the development of VCR engines.

4 DEVELOPMENT OF VARIABLE COMPRESSION RATIO ENGINES

During Chapter 3 the existing designs regarding VCR engines were presented comprising the first step of the design methodology exposed in Section 2.2.2. Those existing designs resulted in several kinematic chains which need to be analyzed in order to identify the design requirements for developing innovative VCR engines.

According to the proposed mechanism design methodology in Chapter 2, this chapter is focused on the definition of the design requirements which will be divided into structural and functional requirements. By means of definition, the structural requirements are related to the topology of the kinematic chain. In other words it means the definition of Mobility, Number of Loops and Screw System, for example. With the structural requirements it is possible to proceed with the enumeration.

On the other hand, the functional requirements are related to the selection of feasible kinematic chains. They are characteristics that normally represent the function of certain links, for example: the piston must be a binary link or the block must be the fixed link.

In addition to the structural and functional requirements it is important to explicit some other requirements there are fundamental for the decision-making process. Those requirements, condensed in the list below, are related to good engineering practices and usual industry philosophy and they will impact the mechanism configuration.

- **Complexity**: Engines are already a complex system. Therefore, it is not desirable to make the piston-to-crank mechanism even more complex. This will limit the number of loops of a kinematic chain and the number of linkages of certain links, for example. Moreover, it affects on the components design. A complex component might be more difficult to produce, less reliable and more expensive to purchase.

- **Balancing**: An engine is a dynamic system under high speeds and accelerations. Thus it is desirable to design a system which is rigid enough and not extremely difficult to balance. This will affect the number of floating links and the decisions of which links might be floating or not.

- **Piston function**: The engine pistons work under high temperatures, vibration, friction, side thrust, must avoid the blow-by and ensure an homogenous combustion, for example. Therefore, the decisions regarding those components must not compromise the functions they already perform

Following the definition of design requirements, an enumeration and selection of feasible kinematic chains will be presented. Then it will be discussed the potential for innovation regarding the VCR engines.

4.1 DESIGN REQUIREMENTS

The state of the art survey, presented in Chapter 3, was fundamental for the understanding of the VCR engines topic. It is clear that the technology is relevant for the automotive industry and there are plenty of designs to study in order to help the identification of the design requirements.

In addition, Freudenstein and Maki (1983) and Tsai (2000), also applied a design methodology to enumerate mechanisms for a Variable Stroke (VS) engine, which is another type reconfigurable. In this sense, it is desirable to relate the kinematic chains of the patent survey to the properties identified by Freudenstein and Maki (1983) and Tsai (2000), keeping always in mind that the design objectives are distinct in many aspects.

4.1.1 Structural Requirements

As stated before, the structural requirements are related to the topology of kinematic chains. The basic characteristics to start the enumeration will be defined in this moment. The discussion starts in Table 24, which presents a relationship between works of Freudenstein and Maki (1983),Tsai (2000) and the patent survey results. This information will be used as a guide to derive some requirements for the investigation of the potential for innovation in VCR technology (HOELTGEBAUM; SIMONI; MARTINS, 2016).

It is important to emphasize that Table 24 presents for the first time in literature structural characteristics for Variable Compression Ratio engines. Moreover, those requirements are defined regarding mechanism theory concepts, which leads to a more systematic synthesis process.

The first structural characteristic considered is mobility. The above cited authors develop their mechanisms for $M = 1$. Tsai (2000) explains that a VS engine should possess two degrees of freedom but, to simplify the problem, the degree of freedom associated with the control of stroke length was initially excluded. The variation of stroke length is later obtained by adding a reconfigurability DOF at a fixed pivot. According to Hoeltgebaum, Simoni and Martins (2016), the patent survey confirmed all mechanisms to

Table 24: Relation between the structural characteristics of Freudenstein and Maki (1983), Tsai (2000) and the patent survey - (HOELTGEBAUM; SIMONI; MARTINS, 2016)

Reconfigurable Engines		VS	VS	VCR
Structural Characteristics		Freudenstein and Maki (1983)	Tsai (2000)	Patent Survey
Mobility	$M = 1$	√	√	
	$M = 2$			√
Screw System	$\lambda = 2$			√
	$\lambda = 3$	√	√	√
Number of Loops	$\nu = 1$			√
	$\nu = 2$	√	√	√
	$\nu = 3$	√		√
Fractionation				√

have $M = 2$, which agrees with to Tsai (2000) comments on Chapter 8 of his book.

The second structural characteristic to be considered is screw system. In the existing designs, it was identified VCR engines working within two different screw systems, *i.e.*, planar ($\lambda = 3$) and geared mechanisms ($\lambda = 2$). Freudenstein and Maki (1983), Tsai (2000) and the Patent Survey agreed in applying planar kinematic chains to develop VCR and VS engines. However, the $\lambda = 2$ screw system was not considered by the referred authors. Class F VCR engines, specially MCE-5 concept, show the possibility of applying a two dimensional screw system for the VCR engines geared mechanisms (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The third structural characteristic to be discussed is the number of closed loops (ν) in the kinematic chain. Among the 127 different existing designs discovered by the patent survey, it was possible to find mechanisms with one, two or three closed loops (HOELTGEBAUM; SIMONI; MARTINS, 2016). Freudenstein and Maki (1983) and Tsai (2000) do not consider the single loop kinematic chains. Keep in mind that Freudenstein and Maki (1983) and Tsai (2000) enumerate for $M = 1$, which would lead to the slider crank mechanism if the single loop mechanism is considered.

In addition, Freudenstein and Maki (1983) suggest to run the enumeration for two and three loops, because the number of loops must be limited in order to minimize the number of additional links inside the engine and thus reduce the mechanism complexity.

The last structural characteristic is fractionation in kinematic chains.

Patent survey presented fractionated kinematic chains in Classes A, B and specially in E. Even though, the number of fractionated kinematic chains were not very representative (HOELTGEBAUM; SIMONI; MARTINS, 2016). Fractionated [1] kinematic chains are not commonly desirable on many projects and Freudenstein and Maki (1983) and Tsai (2000) did not even consider them in the synthesis process.

Up to now, this section discussed the structural characteristics found in the patent survey comparing them to previous works of Freudenstein and Maki (1983) and Tsai (2000). However, their main objective of this section is to translate those characteristics into design parameters, *i.e.* structural design parameters.

As stated beforehand, the structural parameters are related to the enumeration process. Thus, the parameters are the inputs for basic enumeration. According to (HOELTGEBAUM; SIMONI; MARTINS, 2016) the VCR engines mechanisms should be enumerated according to the following design parameters:

- Mobility (M): 2
- Number of Closed Loops (ν): up to 3
- Order of Screw System (λ): 3 (The gears screw system can be obtained by suitable contractions from planar kinematic chains[2])
- Non-fractionated kinematic chains. (The fractionated kinematic chains were not very representative in the whole patent survey).

4.1.2 Functional Requirements

The identification of functional characteristics is the third step in the design methodology presented in Section 2.2.3. The design team is responsible for the definition of such characteristics and this can be done either by technical specifications or by judgment, experience and ingenuity of the designer (DIMAROGONAS, 2001). However, in a mechanism development those characteristics are desirable to be objective and well defined, so the selection process (either by algorithm or by hand) becomes more effective.

The present section aim is to investigate the common functional characteristics found in the existing designs from patent survey and then, establish

[1] A complete description of fractionated kinematic chains can be found in Martins, Simoni and Carboni (2010).

[2] A complete work about screws systems can be found in Davidson and Hunt (2004), Kong and Gosselin (2007). More information on gears screw system can be found in Davies (1995).

a comparison with the design requirements stated by Freudenstein and Maki (1983) and Tsai (2000).

Analyzing those 127 existing designs discovered by the patent survey, it was possible to find some common characteristics that will help defining the functional requirements for a VCR engine development. Table 25 summarizes the common functional characteristics according to each class of VCR engines. Notice that those characteristics are related to mechanism theory, which will help defining the design requirements.

Table 25: Common functional characteristics found in the existing VCR designs from patent survey. - (HOELTGEBAUM; SIMONI; MARTINS, 2016)

Characteristics		Class								
		A	B	C1	C2	C3	D	E	F	G
1	Block is the higher order link	√	√		√	√	√	√	√	√
2	Connecting rod is binary	√	√		√	√	√	√	√	√
3	Piston is binary	√	√	√	√	√	√	√	√	√
4	Crankshaft, con. rod, piston and block form a four-bar loop							√		
5	Piston is connected to the block	√	√	√	√	√	√	√	√	√
6	Reconf. link is ground connected	√	√	√		√	√	√	√	√
7	Crankshaft is ground connected	√	√	√	√		√	√	√	√
8	Crankshaft is binary	√	√	√	√	√	√	√	√	√

The functional characteristic (1) shows that the engine block should be higher order link. It makes sense since it avoids excessive floating links which are not desirable for balancing and for the usually high accelerations inside the engine (HOELTGEBAUM; SIMONI; MARTINS, 2016). This characteristic is in agreement with Freudenstein and Maki (1983) and Tsai (2000). Freudenstein and Maki (1983) states that the ground link of all two loop structures should be ternary. In addition, all three loop structures which do not have at least one link with four joints are excluded from the search. For the VCR case, this exclusion cited by Freudenstein and Maki (1983) will not be considered in a first moment.

The characteristic (2) states that the connecting rod must be binary. This obligation is due to the fact that a connecting rod with more than two joints is likely to develop excessive side thrust and lead to high piston friction (FREUDENSTEIN; MAKI, 1983). Besides, for a near future application, it is desirable that the engine components should maintain the complexity they already have. More complex components would impact in different fabrication process, costs and reliability issues. In this sense, the binary piston characteristic (3) can be found in all classes, which makes sense according to what was explained beforehand (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The characteristic (4) shows that the crankshaft, connecting rod, piston and engine block are part of a four bar loop . It means that those components are in a loop with one DOF. This is not desirable since it does not allow a proper control of the compression ratio and its modification would be achieved by expense of changing the position and/or geometry of the whole slider-crank mechanism. Class E VCR engines is the only class having such characteristic. Keep in mind that this class changes the compression ratio by means of a secondary piston in the cylinder head. Thus, most of kinematic chains are fractionated which means that the actuation of the compression ratio is achieved externally to the slider crank mechanism (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The characteristic (5) states that the piston should be connected to the block. It is always desirable that the component responsible for the combustion, high temperatures and high friction to be ground connected in order to avoid excessive vibration, noise and friction (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The reconfigurability link should be ground connected (characteristic (6)), since it is not desirable to have a floating link responsible for the control of the compression ratio (HOELTGEBAUM; SIMONI; MARTINS, 2016). It would be difficult to actuate a link between the piston and the connecting rod, for example. When that happens, usually it is made by controlling the pressure of engine oil inside a determined component. Then, it gets difficult to perform the control loop. If the reconfigurability is ground connected *i.e.,* it is located in the engine block, control process is facilitated.

The characteristic (7) shows that the crankshaft should be ground connected. In fact, the crankshaft is the link that would be connected to the flywheel, gearbox and the whole drive-train itself. Thus, it is not desirable to have a floating crankshaft that could possibly induce vibration into the drive-train and not maintain a proper rigidity (HOELTGEBAUM; SIMONI; MARTINS, 2016).

The crankshaft should be binary is a characteristic (8) that may not be absolutely essential, but will avoid complicated cranks and the likelihood of high piston side thrust (FREUDENSTEIN; MAKI, 1983).

One can notice that the above discussed characteristics are totally related to mechanism theory and thus can be easily implemented as selection criteria for the number synthesis step. Therefore those characteristics are the functional design requirements for the development of feasible kinematic chains for VCR engines.

In addition, those characteristics can be translated into kinematic chain representation, so the reader can better understand what kind of structures are being considered during selection of kinematic chains. Fig 22, for instance, shows the characteristic (1) . It is clear that the engine block is the fixed link and it is the higher order link. Fig 22 depicts the engine block to be ternary or quaternary, however this requirement does not avoid it to have even more joints.

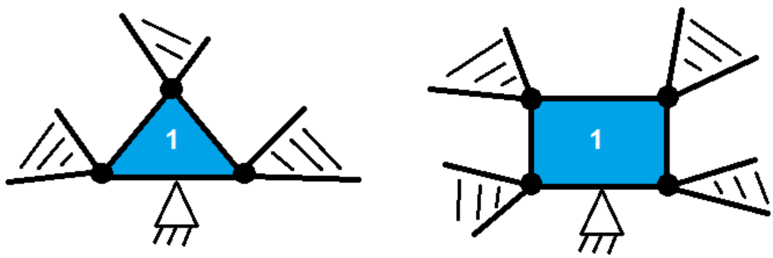


Figure 22: Kinematic chain representation of characteristic (1) - The engine block is the higher order link.

Characteristics (2), (3) and (5) state that both the connecting rod and the piston should be binary and that the piston must be connected to the engine block. Thus, Fig. 23 shows the translation into kinematic chain representation.

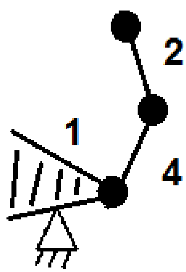


Figure 23: Kinematic chain representation of characteristics (2), (3) and (5) - Connecting rod and piston are binary links and the piston is connected to the block.

Characteristic (4) states that the crankshaft, connecting rod, piston and block cannot form a four-bar loops, otherwise a slider crank mechanism would be achieved. Characteristics (7) and (8) state that the crankshaft should be binary and ground connected. Fig. 24 shows on the left side that the characteristic (4) should not be considered. On the left, it shows the ground connected and binary crankshaft on a $M = 2$ loop.

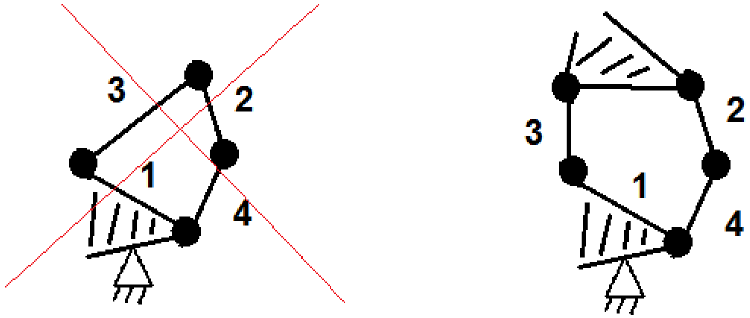


Figure 24: Kinematic chain representation of characteristics (4), (7) and (8) - The crankshaft, connecting rod, piston and block cannot form a four-bar loop. The crankshaft is binary and ground connected.

Evidently, those are not the only design requirements for a VCR engine development. It also should contain information about engine complexity, weight, cost and materials for example. Then a requirement analysis tool (QFD, for instance) would be necessary in order to define the most important design requirements and then judge the following design concepts.

However, one of the objectives of this work is to discuss the main design requirements that could lead to feasible kinematic chains for VCR engines. By achieving the feasible kinematic chains, it would be possible to add further design requirements related to a manufacturer reality, or to a restriction in cost or production line, for example.

4.2 ENUMERATION AND SELECTION OF KINEMATIC CHAINS

It is clear that the Variable Compression Ratio engines represent a growing field for development in the automotive industry. So, it is desirable to understand where one can find the better opportunities for innovation.

In order to do that, the methodology proposed in Section 2.2.3 will be used. The objective is to proceed with the enumeration of kinematic chains according to the design requirements discussed in Section 4.1.1 and Section

4.1.2.

This section will firstly present a number synthesis. All kinematic chains that fulfill the structural requirements are considered. Thus, those results are analyzed according to the functional characteristics in order to derive the feasible kinematic chains. The kinematic chains already patented in the existing designs will also be considered as non-feasible. At last, the potential for innovation in VCR engines field are discussed according to the classes of VCR engines and to the results of the number synthesis.

4.2.1 Number Synthesis for VCR engines

In order to create an atlas of all possible kinematic chains that might become a VCR engine a number synthesis must be done. This map is created according to the structural characteristics identified in 4.1.1 which concluded that the kinematic chains should have the following characteristics (HOELTGEBAUM; SIMONI; MARTINS, 2016):

- Mobility (M): 2
- Number of Closed Loops (ν): up to 3
- Order of Screw System (λ): 3 (planar)
- Non-fractionated kinematic chains

According to Pucheta, Ulrich and Cardona (2013) there are 39 non-fractionated kinematic chains that can meet those structural characteristics, as shows Figure 25.

Furthermore, when transforming the kinematic chains into mechanisms the number of opportunities increase. According to Simoni et al. (2011) the number of mechanisms for the 39 non-fractionated kinematic chains are the following:

- For $M = 2$, $\nu = 2$: There are 4 planar kinematic chains and 14 planar mechanisms possible;
- For $M = 2$, $\nu = 3$: There are 40 planar kinematic chains and 254 planar mechanisms possible;

Keep in mind that those possibilities will reduce because some kinematic chains will be eliminated from the atlas due to the functional characteristics. And since the objective is to investigate the potential for innovation in VCR engines field, the first kinematic chains to be excluded are those already

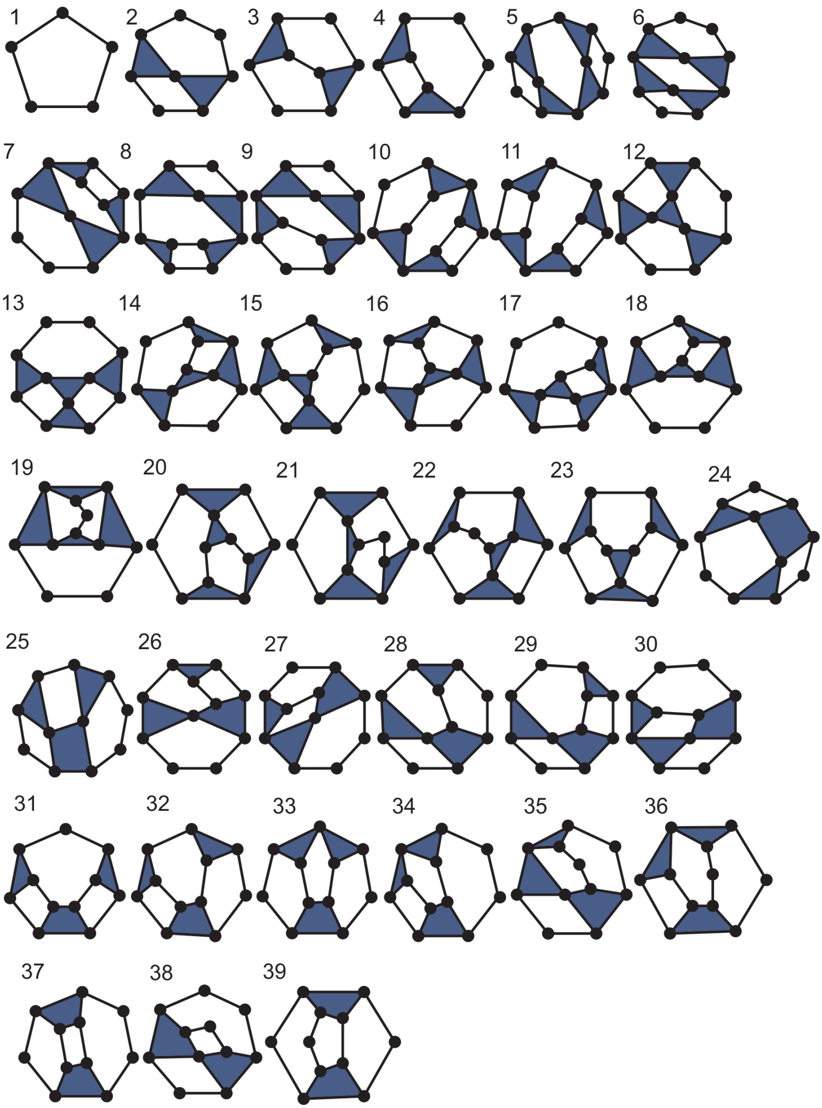


Figure 25: Kinematic chains that can meet the structural characteristics for VCR engines. (M = 2 ;ν = 1,2 and 3; λ = 3). Adapted from (PUCHETA; ULRICH; CARDONA, 2013).

found in the patent survey, which are represented in Figure 25 by numbers: 1, 2, 3, 28, 32, 33, 35 and 38.

The second approach is to apply the functional characteristics identified in Section 4.1.2, which are the following:

- The engine block is the higher order link;
- The connecting rod must be binary;
- The piston must be binary;
- The crankshaft must be binary;
- The crankshaft is ground connected;
- The reconfigurability link is ground connected;
- The crankshaft, connecting rod, piston and block must not be in a loop with $M = 1$;

By analyzing those characteristics the following kinematic chains from Figure 25 are excluded:

- 5, 6, 7, 8, 19, 21: It it not possible to have a binary crank;
- 11, 23: It is not possible to have a binary connecting rod;
- 31: It is not possible to the block be the higher order link;

In the end, 17 kinematic chains were excluded, remaining 22 for further developments. This 22 possibilities are the atlas of feasible kinematic chains and they are shown in Figure 26.

Those 22 results can also be analyzed in order to derive the number of mechanisms that each kinematic chain can generate. The functional requirements are very restrictive. Notice that they obligate the fixed link (engine block) to be the higher order, the piston must be binary and connected to the block, the crankshaft must be binary and connected to the block, for example. Those requirements induce certain structures into the kinematic chain so the number of mechanisms reduce considerably.

Considering the 22 results and performing a similar study presented by Simoni et al. (2011)it is possible to state the following:

- For $M = 2$, $\nu = 2$: There are 1 planar kinematic chain and 1 planar mechanism possible;
- For $M = 2$, $\nu = 3$: There are 21 planar kinematic chains and 34 planar mechanisms possible;

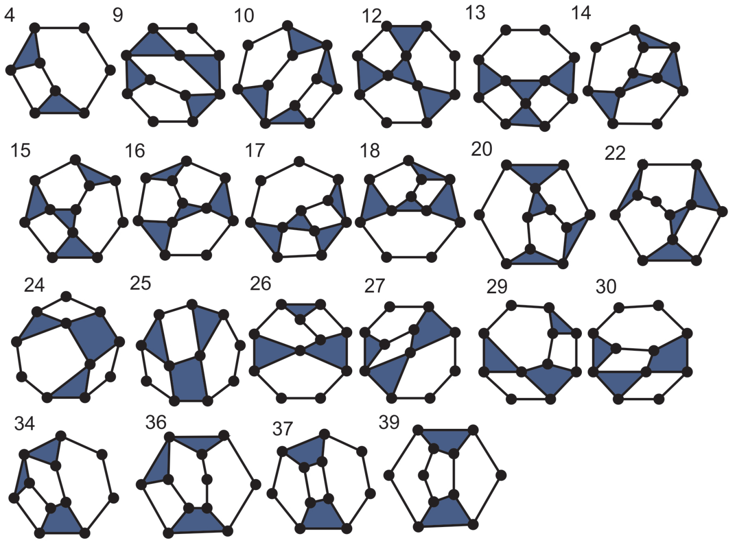


Figure 26: Atlas of feasible kinematic chains for VCR engines. Adapted from (PUCHETA; ULRICH; CARDONA, 2013).

4.2.2 Potential for Innovation in VCR engines

The patent survey presented in this research (Section 3.4) allowed the VCR engines to be classified into seven classes. Moreover, the number synthesis presented in 4.2.1 concluded that there are 22 novel kinematic chains and 35 mechanisms to be developed.

Therefore, it is desirable to understand which classes are prone to provide the best opportunities for the developments of VCR engines.

The kinematic chains of Classes B and G lead to quite simple structures which might be difficult to achieve improvements of the VCR engine from the point of view of the kinematic chains (HOELTGEBAUM; SIMONI; MARTINS, 2016). Moreover, the Class B changes the height of piston deck in order to achieve a VCR configuration. Thus, the control link is located at the piston, which is the part that is under higher pressures and temperatures. Class G, on the other hand, varies the length of connecting rod in order to achieve a VCR engine. Notice that the connecting rod is under higher accelerations, forces and transitions of movement. Thus two-piece connecting rod with a control link in between might lead to undesirable complexity for a near-future applications.

Class E VCR engines makes use of an additional cylinder in the combustion chamber in order to change the compression ratio. The kinematic chains of Class E are mostly fractionated which is not part of the design requirements. Moreover, additional cylinders in the combustion chamber are likely to induce unequal combustion process.

Class F VCR engines applies a non-planar screw systems (geared mechanism) in order to achieve a variable compression ratio. However, it presents a completely different engine concept. For an immediate application it represents an unnecessary complexity which might lead to uncertainties during the design phase.

Fractionated kinematic chains and non planar screw system were not mentioned by Freudenstein and Maki (1983) and Tsai (2000) but these properties were found in the patent survey and, consequently, might be incorporated as design requirements in a midterm future development. Simoni et al. (2011) point out that exist 5 planar fractionated kinematic chains and 34 fractionated mechanisms with mobility or $M = 2$, $\nu = 3$, which might lead to potential new designs specially in Class E VCR engines.

Therefore, the 22 kinematic chains are suitable for development of Class A, C and D since those are the classes that best fit structural and functional design requirements (HOELTGEBAUM; SIMONI; MARTINS, 2016).

It was previously stated that there are 22 kinematic chains and 35 mechanisms likely to originate innovative VCR engines. However, it is still possible that a certain number of these results become unfeasible even if they meet the defined design requirements. In order to be sure, further developments are necessary. For instance, the designer should proceed with a connectivity analysis so it is possible to understand the correct placement for the actuated joints. The type and dimensional synthesis also will help defining if a given embodiment is feasible or not.

Chapter 5 will provide some case studies, so the development process can be exemplified.

4.3 CONCLUSIONS

During this chapter it was possible to see the connections between the state of the art overview (3) with the design methodologies (Chapter 2) in order to define proper design requirements for VCR engines.

For the first time in the literature, it was presented design requirements (Structural and Functional) for Variable Compression Ratio engines while other authors presented only unfinished classifications, as seen in Chapter

3. Therefore, it was necessary to compare those requirements to Freudenstein and Maki (1983) and Tsai (2000) who developed other reconfigurable engines such as Variable Stroke engines.

This approach was fundamental for the discussion about the potential for innovation in the VCR engines field.

5 CASE STUDIES

In Section 4.2.1 it was stated that there are 22 kinematic chains and 35 mechanisms are likely to develop novel VCR engines. This present chapter will give three examples of a VCR engine development. The objective is to show how a kinematic chain can be transformed into an engine concept. In this present work, the dimensional synthesis, optimizations and simulations are not performed since those topics are not in the scope of this research.

But firstly, the development approach used in UFSC Robotics Lab is presented, so the reader can understand how the process of creation an engine concept occurs.

5.1 UFSC ROBOTICS LAB APPROACH

The UFSC Robotics Lab employs a systematic approach to mechanism development. First, during the state of the art survey, the existing designs are analyzed so the structural and functional characteristics can be defined. This is what Fig. 27 shows.

Fig. 27 presents an analysis of an engine from Honda (WATANABE; KONO; NAOE, 2005). Notice that first the main components are highlighted in the patent drawings. Then, the engine is redesigned removing the unnecessary parts and simplifying the main components. At last a kinematic chain is achieved and its characteristics can be derived.

When the existing designs are completely studied and the design requirements are defined, the next step is to perform the concept development. In other words, it is time to make the path from Fig. 27 in the opposite way. This is what Fig. 28 shows. Notice that first thing there are just design requirements. Then some partitions are added, a kinematic chain is achieved, a mechanism is defined until an engine concept is designed.

Evidently, the process does not stop here. With an engine concept defined, then it is necessary to perform the dimensional synthesis, start the CAD Modeling, simulations and start involving the other areas that are related to the field of invention.

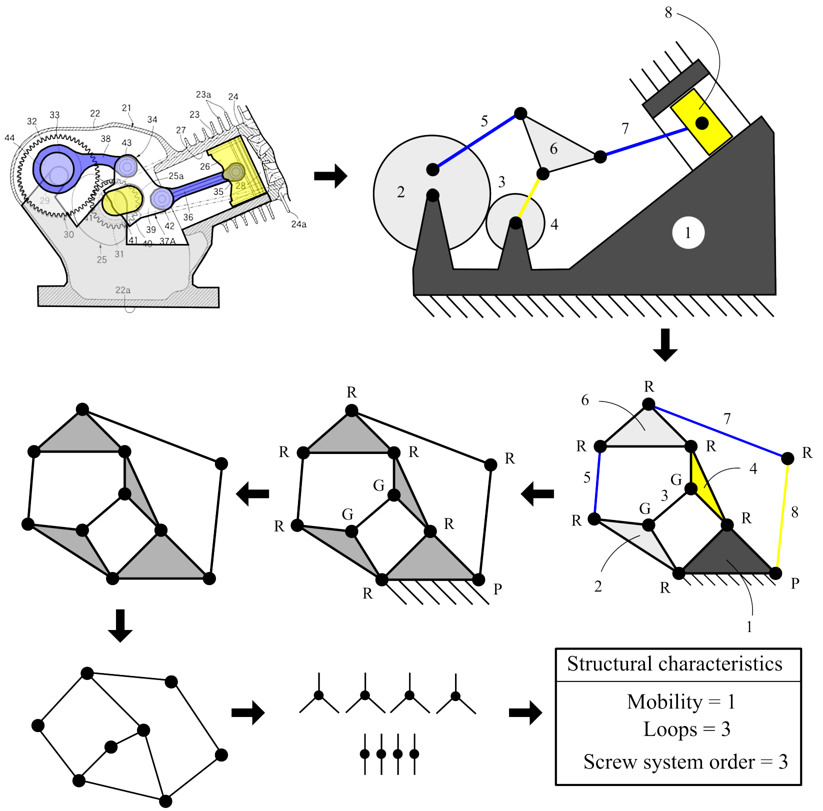


Figure 27: During the state of the art survey, the engine concept is transformed into kinematic chains.

This UFSC Robotics Lab systematic approach has been proved effective in several situations so far. The state of the art phase provides an unique overview about the researched topic and the development step is guided through defined methodology which helps the designer in creating several feasible concepts. Moreover, it also assists the designer in understanding which kinematic chains are no longer feasible.

Another advantage of this approach is the possibility of using it for several areas such as machines, engines, vehicle suspensions and medical devices for example.

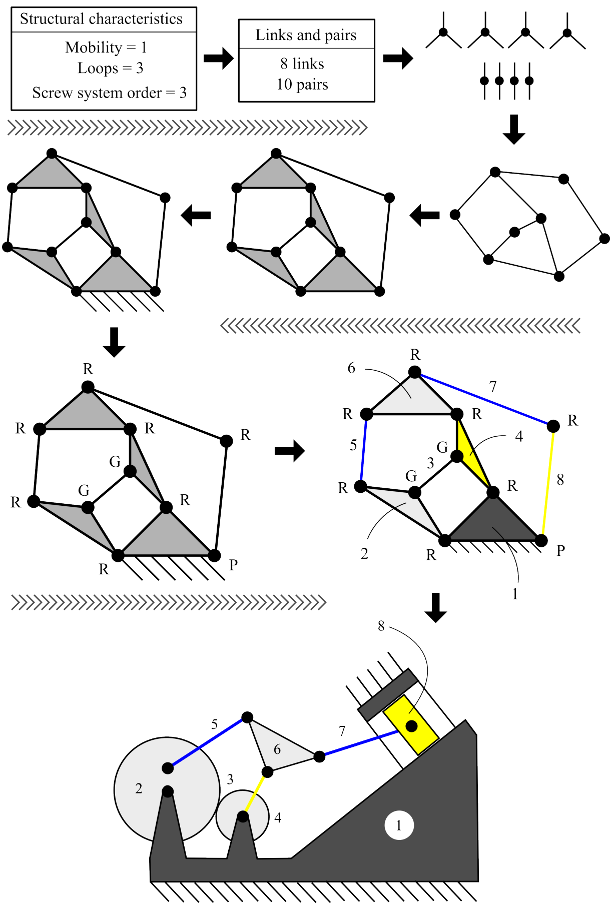


Figure 28: During the design phase, the design requirements are transformed into an engine concept.

The next sections provide three cases studies focused on the development of concepts of VCR engines. It is used kinematic chains from Section 4.2.1 with the same number denomination from Fig. 26.

In order to show that the approach can be used in several cases, it was selected kinematic chains with the following characteristics:

- Two closed loops;
- Three closed loops and the higher order link is ternary;
- Three closed loops and the higher order link is quaternary.

For all case studies, it was decided to develop a Class D VCR engine, since it was one of the most representative designs in the patent survey. Moreover, the patent survey showed that the Class D are the most trending classes, specially from 2010 to present date. The design process is also more intuitive within this class, so the reader can easily understand the design steps.

5.2 CASE STUDY 01 - KINEMATIC CHAIN 04

The first case study to be presented is related to the kinematic chain n^o 4 from Fig. 26. It is the only kinematic chain with two closed loops available.

Fig. 29 shows the design process. Notice that it exists just one allocation possibility for the engine block (1), connecting rod (2), crankshaft (3) and piston (4).

The engine block (1) must be the higher order link, in this case, a ternary link. This kinematic chain has two ternary links, but since it is symmetric, choosing one or another will result in the same mechanism.

The connecting rod (2) and the piston (4) must be binary and the latter must be also ground connected. Thus, those links must be allocated in a place where there are at least two binary links in sequence. In this case, there is just one possibility, as shows Fig. 29

The choice for the crankshaft (3) and the reconfigurability link (5) is already defined, since there is exactly two ground connected links available.

With the engine parts placed, it is possible to start sketching an engine concept. Notice that the both actuation (crankshaft motion and VCR control) are located in a four-bar loop. This means that the $M = 1$ loop has a redundant actuation which makes this kinematic chain unfeasible for VCR engines.

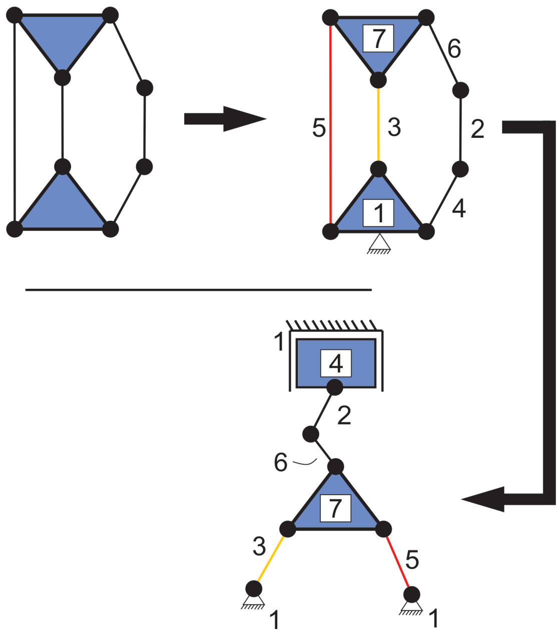


Figure 29: Kinematic Chain n^o 4. This kinematic chain fulfilled all design requirements but, unfortunately it is not feasible as a VCR engine mechanism.

5.3 CASE STUDY 02 - KINEMATIC CHAIN 16

This present case study is about kinematic chain n^o 16 from Fig. 26. It has three closed loops and it is formed by just ternary and binary links, as shows Fig 30 .

The engine block (1) must be a ternary link and this kinematic chain offers three different possibilities. In order to decide in which link the engine block (1) must be located, it is necessary to investigate the other requirements.

Notice that the connecting rod (2) and piston (4) must be binary. Thus a sequence of at least two binary links are necessary. The piston (4) must also be ground connected. These requirements restrict the engine block (1) to be the one connected to a sequence of two binary links.

With this decision, the crankshaft (3) is already defined since there is available just one binary link connected to the block. In addition, the reconfigurability link (5) would be a ternary.

The development of an engine with the characteristics described above are shown in Fig. 30

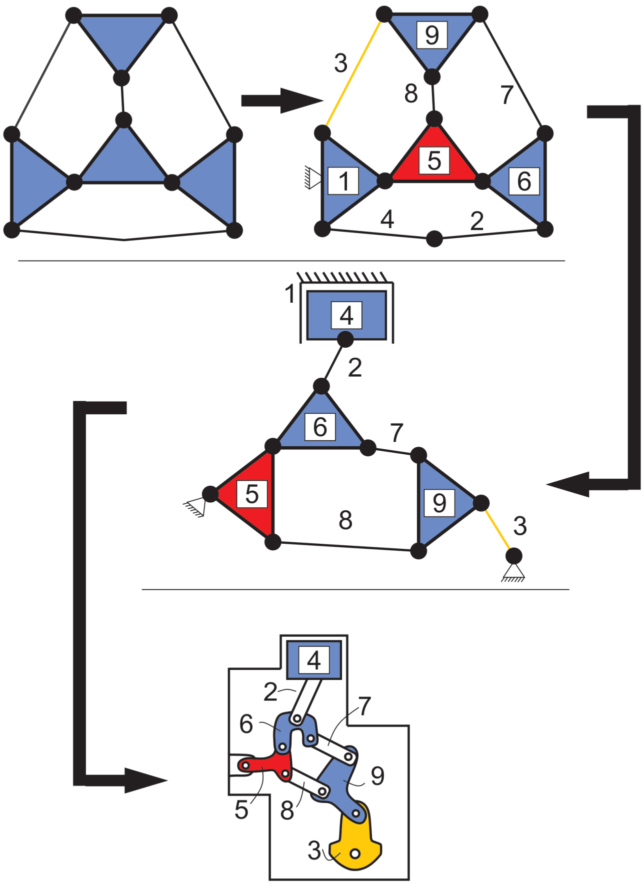


Figure 30: Kinematic Chain n^o 16.

5.4 CASE STUDY 03 - KINEMATIC CHAIN 34

The present case study is based on the kinematic chain n^o 34. It also has three closed loops, but in this case the higher order link is quaternary, which automatically defines the engine block (1), as shows Fig. 31.

The definition of the connecting rod (2) and piston (4) follows the same standard as presented in the previous cases. It is necessary a sequence of binary links, being one connected to the block (1). Thus, the referred links are already defined.

For the crankshaft (3) and reconfigurability link (5), there were a few options. Fig. 31 shows one of these possibilities, which does not mean that the presented sketch is better or worse than the other non-designed concepts.

In this case, the reconfigurability DOF is prismatic.

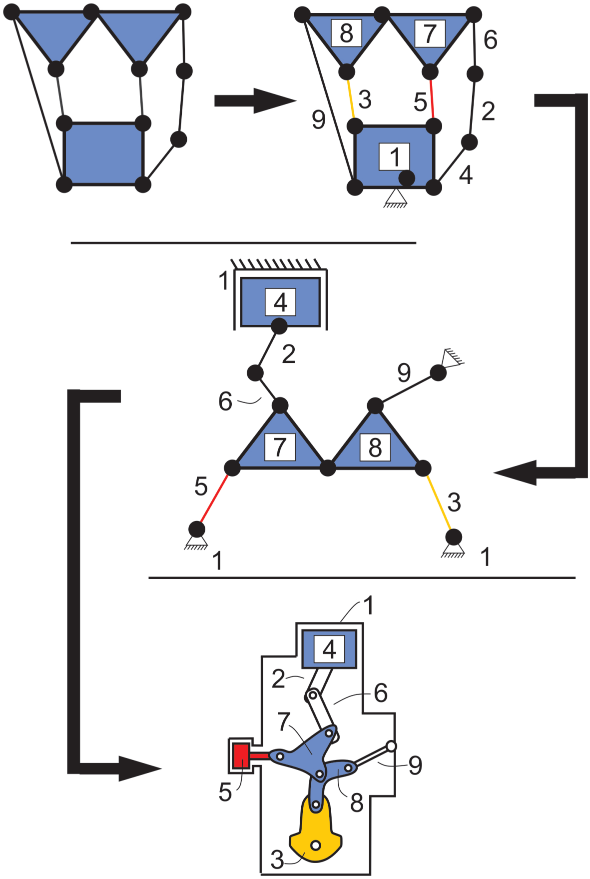


Figure 31: Kinematic Chain n^o 34.

6 CONCLUSIONS

This research dealt with reconfigurable engines, in particular to VCR engines. The VCR engines are good examples of reconfigurable mechanisms since it is possible to change the compression ratio during operation to meet emissions/fuel consumption standards or high power output requirements.

In order to understand this type of engine, several methodologies were reviewed such as product design methodology and mechanism design methodology. In addition, a patent survey methodology was proposed, since it was an important tool for the state of the art survey. A proper patent search methodology was fundamental for the understanding and further developments regarding the VCR engines.

A state of the art survey was conducted and presented results from literature (simulation, tests and previous classifications), market (products and press releases) and patent information. In this case, a patent survey was made and more than 1000 patents were analyzed. From all these patents, 127 different patents that deal with engine mechanisms were found, the remaining patents focused on control, hydraulics and improvements of previous designs. All those 127 patents were cataloged and classified into seven classes and three subclasses, which originated an enhanced classification of VCR engine presented in Table 4.

Some representative patents were presented and the main kinematic characteristics from all classes of VCR engines were discussed. In addition, the degrees of freedom associated with the variation of compression ratio were identified. The patent survey helped to identify all patent kinematic chains able to perform VCR engines. This information was used to indicate discuss the reconfigurability of VCR engines, which was made for the first time in the literature.

This research was guided by a design methodology to achieve atlas of potential kinematic chains to design innovative VCR engines. Most of VCR engines were designed by creativity and knowledge of the inventors, but Freudenstein and Maki (1983) and Tsai (2000) applied a design methodology to develop a Variable Stroke engine, which is another type of reconfigurable engine. Both references helped this present research in understanding the main structural and functional characteristics of all classes of VCR engines, leading the design of VCR engines to a new level.

An atlas of feasible kinematic chains for VCR engines was presented. The research concluded that there are 22 new kinematic chains to be studied in order to derive novel VCR engines. Also with the help of the patent survey it was possible to discuss the potential for innovation in the VCR engines field. At the and classes A,C and D have the most promising opportunities in order to develop the VCR engines.

Moreover, some case studies were performed in order to exemplify the process of mechanism development. The first case study happened to be unfeasible since the two degrees of freedom were located at a four bar loops. The other two case studies are feasible and further developments are necessary to continue the research.

It is important to state, that the design requirements were defined by a mechanism theory point of view. For the next steps, it would be desirable to include engine-oriented background so the requirements could be validated and more information could be added to the research. Then a proper type and dimensional synthesis could be performed, leading to novel VCR engines.

In addition, this research should continue into the reconfigurable engines topic. The Atkinson Cycle Engines and the HCCI engines might represent an interesting topic for further developments as well.

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