Full Customisation, Quick Performance Estimation and Optimisation of Parametric Snowboard Design

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Abstract

Current snowboard design relies heavily on riding experience and personal riding style of the board designers along with feedback from professional snowboard riders. Snowboard companies are spending huge amounts of money and time on this unproductive trial and error method of design. As a result, consumers’ choices are limited to the fixed sizes, shapes and structural designs offered by snowboard companies. At the same time, choosing a suitable snowboard by reading feedback and reviews from different sources can also be very time consuming.

Snowboard enthusiasts seek an optimal board design that will suit them as best as possible. Due to the limited off-the-shelf designs provided by snowboard companies, the “Do-It-Yourself” approach is the only solution for an optimal design. Sophisticated snowboard design requires a certain level of engineering Computer Aided Design (CAD) drawing and mathematical skill, including complex structural analysis of fabric composites and core materials; and bending and torsional stiffness distribution estimation. Therefore, an advanced design platform is desirable to enable users without engineering backgrounds to design and fully customise their own snowboard.

This research is aimed at providing snowboard riders and designers an optimisation and customisation tool for snowboard design. Rather than maximising the performance parameters of a board in every aspect, the optimisation tool provides a solution to optimise the feel of the board to best fit individual use. This greatly reduces the time and cost for riders and even snowboard manufacturers to design a new board and avoid the inefficient trial and error method. Current research employed Sequential Quadratic Programming (SQP) method and Multiple Objective Simulated Annealing (MOSA) to perform the optimisation tasks and to verify the solutions with each other. The optimisation tasks were implemented through Matlab® and modeFRONTIER®. Based on the results of three case studies, it was found that both optimisation solvers generated similar results on the snowboard performances with different design parameters.
The research results were validated with the assistance of two snowboard experts. A Freestyle board and an All-Mountain board were chosen and tested on snow. The experts reviewed and rated the performances/feel of the snowboards based on their riding experience. The obtained data were used to compare with the results generated from the model that developed in this research. The area of validation included thickness distribution estimation, stiffness distribution estimation, snowboard performance prediction and snowboard design optimisation.

This research also developed an advanced interactive parametric design platform combining two different programming languages, Visual Basic (VB) and Virtual Reality Modelling Language (VRML) with the support of Cortona Automation and JavaScript. It allows user to fully customise and personalise a snowboard in a 3D virtual environment without any engineering CAD drawing skills, mathematical modelling skills and arduous structural calculations. This design platform offers instant feedback on the snowboard performance based on the on-snow performance prediction model obtained from the RMIT snowboard research group.

The parametric snowboard design platform contains a user-friendly graphical user interface (GUI) for users to design and personalise their own board by simply altering the geometry and appearance of the virtual board and therefore parametric model. Furthermore, it offers professional riders, snowboard enthusiasts or experienced snowboard designers to “fine tune” the snowboard’s performance and structural behaviour manually by modifying core materials properties and design parameters of the fabric composite layers of the board. By doing so, an optimal snowboard design can be created so that performance best suits individual use.
Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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Last but not least, I would like to thank my partner Jody Chan and her family for the kindness and support over the years.
List of Publications

Publications related to snowboard design


Publications related to optimisation


Publications related to virtual reality modelling


Lee K.W. and Trivailo P.M. (2008), Advanced Interactive Visualisation and Simulation of Spacecraft Formation using Virtual Reality, -59th International Astronautical Congress 2008

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<td>$[a], [b], [d]$</td>
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<tr>
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\text{Heel width}
\text{Shovel width}
\text{Equivalent to heel and shovel width of a twin board}
\text{Design parameters matrix}
\text{k}^{\text{th}} \text{ element of vector } x
\text{Solution point}
\text{The position of the board edge at position } x \text{ on positive side}
\text{The position of the board edge at position } x \text{ on negative side}
\text{Coordinate position}
\text{Position of ellipse centre}
\text{Contact point of vertical shovel radius curve and camber curve}
\text{Contact point of vertical heel radius curve and camber curve}
\text{Position of heel transition curve}
\text{Position of shovel transition curve}
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\text{Estimate of the Lagrange multipliers}
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\text{Vertical shovel angle}
\text{Heel transition angle for side-cut}
\text{Shovel transition angle for side-cut}
\text{Heel transition angle}
\text{Shovel transition angle}
\text{Mass density at the point } r
\text{Heel camber angle}
\text{Shovel camber angle}
\text{Sidewall construction angle}
\text{Transition point position constant}
\text{Transition shape constant}
Chapter 1
Introduction

1.1 Motivation and Background

The first known snowboard was created by Sherman Poppen in the 1965. It shared the same concept and mechanics of surfing and skateboarding. It was named as “snurfer”, meaning surfing on the snow. Snowboarding is a relatively new winter sport compared to skiing. It started becoming more popular in the 1980s but was banned by some ski resorts. Two decades later, it officially became part of the Winter Olympic Sport in 1998. Snowboarding has now become one of the most popular winter sports in the world [1].

The popularity of this sport can be expressed in terms of the amount of books and publications related to snowboarding. Google claimed to have over 20 million digital books scanned and stored in their database in 2012 [27]. Google Books Ngram Viewer was developed as a research tool showing the change in the usage of specific words in books and publications over time. The result in Figure 1-1 shows that the trend of using “snowboarding” has increased dramatically since the 1980s.

![Figure 1-1 – Google Ngram Viewer Result of snowboarding](image)

Figure 1-1 – Google Ngram Viewer Result of snowboarding
Its popularity is still increasing nowadays. It is said that snowboarding is the fastest growing winter sport in the US [1]. The increasing popularity of snowboarding triggered rapid growth in the snowboarding equipment industry. It reached $487 million in 2008 [34].

Snowboarding is not restricted to hobby and recreation but also professional sport. Innovative design and advanced technology has been developed allowing snowboard companies to improve the performance of snowboards. However, current snowboard design methods rely mainly on riding experience and style of the board designer along with feedback from professional riders. Snowboard companies are spending huge amounts of money and time on this inefficient “trial and error” method of design [53]. As a result, consumers’ choices are limited to the fixed sizes, shapes and designs provided by snowboard companies. There is considerable interest in an advanced design platform allowing snowboard enthusiasts to fully customise and personalise their own snowboard.

Snowboard enthusiasts seek an optimal board design that will suit them as best as possible. Due to the limited off-the-shelf designs provided, the “Do-It-Yourself” approach is the only solution for an optimal design. However, sophisticated snowboard design requires a certain level of engineering CAD drawing and mathematical calculation skill, including complex structural analysis of fabric composites and core materials; and bending and torsional stiffness distribution estimation. Therefore, an advanced design platform is desirable to enable users to design and fully customise their own snowboard instead of being limited to off-the-shelf designs.
1.2 SportzEdge Research Program

RMIT University has had a long involvement in the Australian sports industry. Through dedicated research on advanced sporting technology and design, RMIT has made a great contribution to sports engineering in Australia. One of the most successful examples has been the joint research of the Olympic Superbike with the Australian Institute of Sport (AIS) sport research team in 1996. The innovative carbon fibre–polymer composite monocoque design helped athletes to reach world championships and break world records within the first four years of its development [56][57].

To further enhance the sport industry in Australia, the Sports Engineering and Technology (SportzEdge) research program was established at RMIT. It aims to facilitate the mass customisation, design optimisation, rapid prototyping and manufacturing of a wide range of personalised sports equipment such as snowboards, tennis racquets, apparel and footwear.

One of the key research areas of the SportzEdge research program is the parametric design of sports equipment for full customisation, rapid prototyping and manufacturing. In keeping with the thematic research at this program, this thesis presents research into the development of an advanced interactive virtual snowboard design platform for full customisation and rapid prototyping, quick on-snow performance estimation and snowboard design optimisation.
1.3 Research Questions

This thesis aims to address the following research questions:

- How to allow snowboard riders and enthusiasts to fully customise and design their own snowboard without having engineering CAD drawing skills and knowledge of complex structural analysis?
- How to reduce the amount time and money spend on the traditional “trial and error” snowboard design process by using a quick on-snow performance prediction model?
- How to quickly estimate the bending and torsional stiffness distribution of a customised design snowboard?
- How to optimise the on-snow performance of a snowboard that best suit for individual use?
1.4 Objectives

The primary objective of this research is to develop an advanced interactive design platform that allows snowboard enthusiasts without any engineering CAD drawing skills, knowledge of mathematical modelling and complex structural analysis to fully customise and personalise their own snowboards in a virtual environment.

This research also aims to formulate a set of equations and methods to search for optimal snowboard designs that best fit the user’s expectation on particular performance parameters whilst the solution satisfies all the design constraints. It greatly reduces the time and cost for snowboard enthusiasts and snowboard manufacturers to design a customised board avoiding the unproductive trial and error method.

An important task of this research is to develop a complete parametric snowboard model, which is a mathematical model that contains relationships between all the geometric parameters, material properties, weight and physical design constraints of the board. As part of the parametric modelling, a continuous thickness distribution model has been developed based on the measured data from three different riding style snowboards. In addition, this project aims to integrate the developed parametric model with a snowboard performance estimation model into the design platform to provide rapid on-snow performance prediction for snowboard design.

Finally, the research integrated and modified the existing sandwich structural model enabling estimation of the continuous stiffness distribution along the snowboard. It allows professional riders or experienced snowboard designers to “fine tune” the snowboard’s performance by manually choosing the core materials and adjusting the design parameters of the fabric composite layers of the board.
1.5 Methods

In order to achieve the objectives, the parametric snowboard design platform should

- be able to visualise the complete parametric snowboard model in a 3D virtual environment
- contain a user-friendly graphical user interface for users to fully customise and personalise a snowboard
- be able to estimate the bending and torsional stiffness distribution of the customised snowboard with composition sandwich structure
- provide quick performance prediction of the customised snowboard
- be able to search for an optimal design solution that best fit the user’s target performance

In order to develop the parametric model, the snowboard geometry is fully defined by using the ASTM standard terminology [2] together with some of the description defined by Clifton [11]. Extra custom design parameters are also created to complete the final model in this research. The model is fully defined by a total number of 37 design parameters where 28 design parameters are used to define the geometry, 8 parameters for the material properties and one parameter for its weight. A systematic analysis of the relationships between all these design parameters is performed and categorised into three groups, carefully mapping them to avoid any design conflicts. Within each group is formed a list of design constraints which are used for design optimisation.

The geometry of the snowboard model is visualised in a CAD-like environment using Virtual Reality Modelling Language (VRML). The VRML model is embedded into the custom developed graphical user interface through the open licence plug-in Cortona3D viewer. With the support of JavaScript and VRML Automation, the design platform provides more interactive control for the user to customise and design their own snowboard without the need for CAD drawing skills. It also allows the users to preview the final product of design in real-time without the necessity to use CAD.
licenced packages. The same technique has been successfully utilised for other research and publications by the author [30] [31][35].

Materials and structural property have great influence on snowboard performance. This design platform allows users to manually “fine tune” the materials’ properties of laminates including the top sheet, core and base as well as the design parameters of the upper and lower fabric composite layers of the board illustrated in Figure 1-2. This research has developed a continuous stiffness distribution estimation model based on the fundamental theory of fabric composite analysis and 2-D textile composites developed by Hashin [24], Byun [9] and Clifton et al [11][12][13].

Figure 1-2 - General Snowboard Composite Sandwich Structure [51]
Snowboard design optimisation is one of the main features of the design platform. The author has formulated a set of equations and methods to search for optimal snowboard design that best fit the user’s expectation on particular performance parameters whilst the solution satisfies all of the design constraints. The design platform greatly reduces the time and cost for riders or even snowboard manufacturers to design a new board avoiding the traditional trial and error method. The SQP optimisation technique and MOSA optimisation method were utilised in this design platform to optimise snowboard performance for individual use.

The results of this research are validated with the support of two snowboard experts. They are the head coach of BC Snowboard Association in Canada and a senior snowboard instructor of a snowboard training centre in Japan. Two different riding style snowboards were selected by the experts for validation purposes: a freestyle board and an All-Mountain board. Following a series of field test on snow, the experts reviewed and rated the performances/feel of the snowboards based on their riding experience. The initial board dimensions and structural materials were also obtained from snowboard manufacturers or from direct measurement by the experts. These data were recorded for custom design forms and used to compare with the results generated by the parametric snowboard model as well as the design optimisation model.
1.6 Chapter Overview

Chapter 2: Literature Review

This chapter provides an overview of the development of snowboard technology. A comprehensive literature review of snowboard design and research has been performed. As snowboarding is a relatively new winter sport compared to skiing, engineering research of the snowboard was limited until it became more popular in the 1990s. Following the footsteps of research of ski, early research focused on determining and estimating the primary mechanical properties of the board such as bending and torsional stiffness as well as the natural frequencies of free vibration from laboratory tests. Recent research has included Finite Element Method (FEM) modelling of snowboard structures; on-snow performance prediction model development; the effect on material properties to the dynamic behaviour of snowboard manoeuvres.

The literature review also covers the definition of the snowboard design parameters which are based on the ASTM standard terminology with some modifications and custom parameters. This is followed by a general overview of the modern snowboard composite sandwich structure and the materials used in the laminate layers. This chapter also presents the theory and process of the performance prediction model in the previous research. Finally, the capability of some of the snowboard design customisation and design software available in the market are also discussed.

Chapter 3: Parametric Design and Modelling

This chapter explains how the geometry, structural design and board materials could affect the overall performance and characteristics of a snowboard. The preferred shapes and some dimensions of the snowboard are determined by the rider’s body weight and height as well as the riding style and personal preferences. However, this is only used a guideline for general riders. Snowboard enthusiasts and professional always seek for an optimal board that suit their riding styles and performance as best as possible.
This chapter also presents the concept and development of using parametric modelling on snowboard design and customisation. Parametric design is a method of linking the board dimensions and design variables to geometry such that when a particular parameter changes, the related design variables also change under predefined design constraints. The amount of changes to the related design variables is determined from the parametric equations. The relationships between all these parameters are analysed and presented in a map. As part of the parametric modelling, a thickness distribution model has been developed based on the measured data from three different riding style boards. The thickness distribution is simulated by connecting two hyperbolic tangent functions.

**Chapter 4: Snowboard Design and Optimisation**

This chapter is dedicated to the development of snowboard design and optimisation. The performance prediction model developed by Clifton [11] is utilised in a reverse manner in this research. Instead of entering snowboard geometry to generate predicted performance, the current study enables a user search for an optimal snowboard design solution based on the personal preference performance.

The optimisation task is formulated by using Least Squares Methods. The goal is to minimise the difference between user target performance and the model predicted performance while satisfying all the design constraints. This chapter also presents the implementation of SQP and MOSA optimisation methods to obtain the optimal design solutions through Matlab® and modeFRONTIER® respectively. Three case studies are conducted in this research. The results and findings are reported at the end of the chapter.
Chapter 5: Results and Validation

This chapter presents the methods and process of validating the research results in this study. The validation is performed with the assistance of two snowboard experts. The data collected from a series of on-snow field tests are used to compare with the results generated by the parametric snowboard model as well as the design optimisation methods. The three main results included thickness distribution; stiffness distribution; snowboard performance prediction and design optimisation for each of the two riding style snowboards and these are presented and analysed in this chapter.

Chapter 6: Parametric Snowboard Design Platform

This chapter presents the architecture and development of the parametric snowboard design platform. It is a complete application package integrating all the studies and work performed in this research. It includes a complete snowboard parametric model, VRML model visualisation, snowboard design customisation, stiffness distribution estimation, performance prediction, and design optimisation. We introduce the use of VRML to visualise the developed parametric snowboard model in a virtual environment. The VRML model is embedded into a user-friendly graphical user interface (GUI) allowing users to fully customise, design, and personalise their own snowboard easily by changing the geometry parameters and appearance of the virtual model.

Chapter 7: Conclusions and Recommendations

The final chapter summarises the main results, findings and research work performed in this research. In addition, the author provides recommendations and directions for future research to extend development of parametric modelling as well as design customisation and optimisation.
Chapter 2

Literature Review

2.1 Snowboard Design and Research

The earliest snowboard design was very different to the modern snowboard. The first snowboard was developed in 1965. They were called “snurfer” which shared the concept and mechanics of surfing and skateboarding. It was described as a crossover between a plywood sled and a skateboard deck [1]. Since both sides of the board are straight, unlike the curved side-cut of modern snowboards, the agility and manoeuvrability are very limited. In general, a board with a deeper side-cut will make smaller and tighter turns, whereas a board with a shallower side-cut will make larger turns. Therefore, a rope was attached to the front tip of the board to offer some control to the rider. Instead of the modern snowboard bindings, the “snurfer” has several steel tacks punched though the board to hold the rider’s feet in place [1].

Since snowboarding was still considered as a general recreational activity in the 1980s, scientific or technical snowboard research was very rare until the 1990s. Early snowboard research was conducted by Sakata and Kawai [44]. This study was
focused on the dynamic bending and torsional analysis of snowboards. The experiment was setup using a urethane sheet under a snowboard to represent the snow surface. Laser displacement sensors were utilised to measure the vertical deformation of the centre line along the test board. The study was able to estimate the deformation and reaction forces from the snow’s surface onto the snowboard using numerical approach. However, the mechanical properties of each structural layer were not considered separately. A year later, Sakata et al. [45] performed experimental tests to determine the natural frequencies of free vibration of a symmetrical (directional twin) snowboard with and without an elastic foundation and tried to estimate the results by applying a numerical approach of an inhomogeneous orthotropic plate vibration model to the snowboard. Five considered mode shapes on both ends of the board were investigated. It was found that the lower natural frequencies are more strongly affected by the elastic foundation, which represented the snow surface, than the higher natural frequencies.

Kawai et al. [25] aimed to evaluate the forces acting on the snowboard from the rider’s control through the binding with repeated snowboarding manoeuvre actions. The experiment was set up utilising a 4cm thick urethane sheet to represent the snow surface. Eight load cells were used to measure input forces whilst six laser sensors were installed to measure the displacement during the test. They applied the numerical approach from the previous studies [44][45] and accurately predicted the acting forces on the snowboard with minor error compared to the experimental data.

Glenne et al [21] and Foss [18] investigated the vibration and motion of a snowboard based on previous experience and studies on skis [20][22]. The research indicated that the vibration of snowboards and skis was severe enough to affect the control and balance of the rider at high speed turning on hard snow. The vibration of snowboards and skis excited by the snow surface imposed a speed limit action due to increased difficulty in control. They managed to reduce the vibration by installing a viscoelastic standoff damper on the skis. The frequency response function (FRF) maps of a fiberglass/wood ski were plotted for comparison of the before and after installation of a viscoelastic standoff damper. It was concluded that the amplitude of the highest
response of torsional acceleration was reduced by approximately 50% by the damper. As a result, the damper was effective to improve the control and balance of the rider at high speed turning especially on hard snow.

Buffinton et al. [6] attempted to correlates the vague qualitative descriptions of snowboard performance with the quantitative measures of board characteristics represented by modal frequencies and damping ratios. A total number of eight snowboards from two manufacturers were put through laboratory tests. Since the experiment focused on the free vibration of a snowboard and the amount of deformation of the board during the tests was small, a simple beam method was used to determine the effective stiffness of the board. Natural frequencies and damping ratios of the first three bending modes and first two torsion modes were measured in the dynamic test by mounting accelerometers on the board at nine different locations. The experimental data were analysed by a custom written Matlab® program. They constructed five simplified finite element snowboard models, assuming uniform mass density and transversely isotropic stiffness, with the Pro/ENGINEER software package while finite element analyses were performed with Pro/MECHANICA. A field test of three snowboards was also conducted to obtain strain and acceleration data for typical snowboard manoeuvres. Results from the study showed that beginner boards, also categorised as “soft”, generally have lower natural frequencies and larger damping ratios than the “stiff” boards designed for advanced riders. Also, “high-quality” boards, designed for advanced and professional riders, have higher natural frequencies than "medium-quality" boards while both boards retained high damping ratios. However, the study only considered natural frequency and damping ratio as the main parameters affecting the snowboard performance. Other important factors such as snowboard geometry and the mechanical properties of the complex composite sandwich structure were not considered.

Buckingham and Blackford [5] measured four basic dimensions and masses of four different snowboards and performed static testing to determine the overall stiffness and torsional stiffness properties of the boards. The boards were then categorised into soft, medium and stiff. A number of on-slope tests were then conducted on an
artificial dry ski slope instead of snow surface. The artificial dry ski slope was made of “dendix”. It is a material commonly used to mimic snowboard surface. The “dendix” provides consistent surface properties for better comparison of “feel” of different boards. A qualitative assessment of the snowboards was made by riders grading the boards from 1 to 10 with 10 being the best. Another on-slope test was performed with ployvinylidene fluoride (PVDF) sensors installed on a single snowboard which was tested by riders with different riding experience. It was found that the snowboard technique can be determined and visualised from the frequency spectra data output from the PVDF sensors. Riders from early learning stage to beginner level tend to have higher voltage output and lower frequency than intermediate and advanced riders. The higher voltage output means that beginners were putting more afford to correct and balance their body position during the ride. Lower frequency outputs also showed that beginner riders had slower response to the feedback from the snowboard than the advanced riders. This system can be used to track the change of a rider’s technique and performance over time, demonstrating its potential as a snowboarding training tool.

Biancolini et al. [3] employed the Finite Element Method (FEM) to analyse the stability of a sandwich structural type snowboard. Bending stiffness, torsional stiffness as well as natural frequencies were determined from the FEM model and compared with published experimental data. In the study, a performance stability index S, which was originally designed for skis and proposed by De Cecco [16], was utilised to quantify the distribution of force interaction between snowboard and snow. The second-order moment of force distribution was expressed as:

\[ S = \frac{\sum_{i=1}^{N} (x_m - x_i)^2 f_i}{F_{tot}} \]

where  
f_i is the force distribution  
\( F_{tot} \) is the total force  
\( x_i \) is the distance of the fixed nodes “i” from the yz plane that contains the origin of the global coordinate system  
\( x_m \) is the centre of mass of the forces and \( F_{tot} \) is the applied load
Brennan et al. [7][8] developed a computer code called Snowboard-MECH to determine the bending and torsional stiffness along the snowboard length using simple thin beam theory [26] while the flex and twist were estimated by finite element methods (FEM) using thin beam/plate theory [15]. The computer code was further enhanced by Clifton et al. [12] and utilised in the current study to estimate the stiffness distribution of a composite sandwich structural snowboard. The dimensions, material properties, and cross-section layup construction were measured from two different snowboards and used as the input parameters to the code. The results were validated by laboratory test data. Another computer code known as Snowboard-TURN further supported the original code to predict the speeds, roll angles, and run times of a prearranged S-shape course with three slopes of 16.4, 4.75, and 17.0 degrees downhill. A field test was performed using a GPS system and cameras to track the travel path of the snowboard rider in real time. Position data and run time were recorded which exhibited a reasonably close result to the model prediction. The development in the study can be used to evaluate the turning and speed performance of different snowboards. Although the study only considers speed and roll angle as the snowboard performance, the two developed computer codes predicting the board stiffness and downhill run time are considered to be useful tools for preliminary snowboard design. The computer codes reduce the number of prototypes and field tests during the design process. However, it is limited to downhill speed riding without consideration of other riding style that required performing tricks and stabilisation such as Freeride, Freestyle and All-Mounting.

The snowboard research group at RMIT University has performed several studies regarding snowboard design and mechanical properties. Clifton et al. [12] developed a mathematical model to estimate the bending stiffness and torsional stiffness of a composite sandwich construction board. This prediction model allows any composite sandwich structure with up to ten common fabric configurations to be estimated. Three rectangular shaped sample boards with 2x2 bi-axial weave fabric configurations were used for validating the developed model. It has been proven that the model accurately predict the bending and torsional stiffness with under 4% error. The current
research utilised the same technique with some modification to generate the continuous stiffness distribution estimation for the custom designed snowboard.

Clifton et al. [12][14] set up an experiment to investigate the effect of temperature change on snowboard performance due to the change induced on stiffness properties. Three different riding style snowboards were examined by a load-defection test at temperature of 22°C, 4°C and -17°C in the laboratory. The results show that the overall stiffness increased with a decrease in temperature from 22°C to 4°C. It is because the elastic modulus of the fibreglass skins, wood core, UHMWPE base layer and ABS topsheet also increased with decreasing temperature. However, the stiffness gain was negligible when temperature decreased from 4°C to -17°C. The constant stiffness behaviour at lower temperature implied that the on-snow performance of a snowboard would not be greatly affected by the change of stiffness on general snow surface temperature. However, the stiffness gain behaviour would affect the results of some laboratory tests at room temperature especially for the research that focuses on snowboard vibration analysis.

Subic et al. [52] investigated the importance of bending and torsional stiffness as well as camber characteristics of snowboards for their performance under different riding styles. Three snowboards were tested and a statistical analysis was performed to assess any correlation between the objective parameters, such as geometry parameters and material properties, and the subjective performance parameters.
The subjective performance parameters are described in Table 2-1.

Table 2-1 – Performance Parameters Description [52]

<table>
<thead>
<tr>
<th>Performance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>How stable the rider feels on the board.</td>
</tr>
<tr>
<td>Feedback</td>
<td>The amount of stress felt on the rider's body including the effects of board chatter</td>
</tr>
<tr>
<td>Speed</td>
<td>The gliding speed of the board compared to other boards of similar length</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The precision of board movement in response to rider input</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>The tolerance of the board to errors from the rider</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>The level of grip exhibited during turns</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>How easily the board responds to rider inputs</td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>How easily the board flows from edge to edge</td>
</tr>
<tr>
<td>Board Liveliness</td>
<td>The level of 'pop' or spring in the board when performing a jump</td>
</tr>
</tbody>
</table>

It was found that all subjective performance parameters had positive associations with the body stiffness and camber except “forgiveness” which could be improved by increasing the flexibility of the board and adopting a lower camber in the design.

Furthermore, Subic et al. [54] designed and developed a dynamic experimental installation to simulate manoeuvres such as turn, jump, press and slide on different snowboarding terrains. Two pneumatic cylinders and three adjustable pressure airbags were controlled by a custom Program Logic Controller (PLC) which could be modified to replicate rider foot movement and snowboarding terrain. Stain gauges were installed to determine the load on the snowboard during the simulation for each set manoeuvre. The experimental installation could be used for research that requires reproducible and consistent dynamic tests of snowboard in a controlled environment. The data generated from the stain gauges could be used to evaluate the performance of different snowboards on varies simulated terrains and ride conditions. This
installation is considered to be a useful tool for performance comparisons and benchmarking of snowboards.

Together with the RMIT snowboard research group, Lee et al. [29] performed study on snowboard design optimisation. The research developed methods to optimise snowboard design utilising the snowboard performance prediction model from Subic et al [52] in reverse manner. An importance parameter was introduced to formulate the overall performance of the snowboard using a simple summation approach. The overall performance was maximised subject to three groups of design constraints:

- performance parameter constraints define the boundaries of the performance parameters of a snowboard to prevent under or over design for certain riding styles.
- user-defined geometry constraints restrict the snowboard dimensions, such as the overall length and width of the board, based on user’s preferences.
- physical design constraints represent the mathematical relationship between each of the design parameters.

Further detail of the design constraints is presented in Chapter 4.3.1 in this thesis. The optimal parametric solution was then determined by the sequential quadratic programming (SQP) method which solved for suitable snowboard design variables to achieve optimum performance. Further detail of the SQP optimisation is presented in Chapter 4.4.

Santoro et al. [46] investigated the use of natural fibre composite as the core material of the snowboard. The study aimed to design, optimise and manufacture an environmental friendly snowboard based on the consideration of cost. A total number of 9 design parameters were used to define the snowboard geometry. The objective of the optimisation task was to maximising the stiffness of the test board while minimising the overall weight by changing the snowboard geometry. The design parameters were constrained to lie in the range within a 5% difference from the original board design. The deflection of the model was simulated by using simple equilibrium beam analysis while the overall weight was formulated with the
assistance of AutoCAD estimating the average density of the board. Three deflection case studies were conducted. The results showed that the optimised board was slightly heavier than the original board but it was capable of withstands higher maximum allowable load with a lower deflection. Although stiffer and lighter snowboards are usually categorised as high performance and high quality board [6], they are not the only design parameters that affect the characteristics and on-snow performance of the board. The effect of snowboard geometries should be considered.
2.2 Snowboard Design Parameters

The latest documentation of the standard terminology of snowboard and snowboarding F1107-04 was published by ASTM International [2] in 2004. It covered terms used to describe the geometry of snowboards including the related hardware such as bindings and boots used on snowboards. The current study focuses on the geometry of the board utilising the ASTM standard terminology [2] together with some definitions created by Clifton [11]. However, some modifications and extra design parameters are introduced in this study to complete the parametric model.

The major dimensions and design parameters of the snowboard model are defined below and graphically illustrated in Figure 2-2 to Figure 2-5 respectively.

**Board lengths**

- Projected length \((L_P)\) - the length of the projection of the snowboard, measured between the snowboard tip and the snowboard tail with the snowboard unweighted on a plane surface. (Figure 2-3)

- Chord length - (LTS) the straight-line distance between the snowboard tail and the snowboard tip with the snowboard pressed flat to a plane surface to take out the camber. The difference between chord length \((L_T)\) and projected length \((L_P)\) is negligible. Here it is assumed to have the same value as the projected length to reduce computational cost.

- Contact length \((L_C)\) - the difference between the projected length and the sum of heel and shovel lengths. (Figure 2-3)
Shovel design parameters

- Shovel length ($L_s$) - The projected length of the forward turn-up, measured from the tip to the contact point where an 0.1-mm feeler gage intersects the running surface with the snowboard unweighted on a plane surface. (Figure 2-3)
- Tip height ($H_s$) - The height of the underside of the tip from a plane surface with the snowboard unweighted. (Figure 2-3)
- Shovel width ($W_s$) - The horizontal (XY-plane) perpendicular distance between two vertical parallel planes, placed on either edge of the snowboard shoulder, parallel to the longitudinal centreline of the snowboard. (Figure 2-2)
- Shovel radius ($R_s$) - The horizontal (XY-plane) average radius of the curved portion of the snowboard shovel (Figure 2-2)
- Shovel curvature radius ($r_s$) - The vertical (XZ-plane) radius of the curved portion of the snowboard shovel. (Figure 2-4)

Heel design parameters

- Tail length ($L_h$) - The projected length of the tail turn-up, measured from the snowboard tail to the contact point where an 0.1-mm feeler gage intersects the running surface of the snowboard resting unweighted on a plane surface. (Figure 2-3)
- Tail height ($H_h$) - The height of the underside of the tail from a plane surface with the snowboard unweighted. (Figure 2-3)
- Heel width ($W_h$) - The horizontal (XY-plane) perpendicular distance between two vertical parallel planes, placed on either edge of the snowboard heel, parallel to the longitudinal centreline of the snowboard. (Figure 2-2)
- Heel radius ($R_h$) - The horizontal (XY-plane) average radius of the curved portion of the snowboard heel. (Figure 2-2)
- Heel curvature radius ($r_h$) - The vertical (XZ-plane) radius of the curved portion of the snowboard heel. (Figure 2-4)
Body design parameters

- Waist width \( (b_m) \) - The width at the narrowest point of the snowboard body between the heel and the shoulder. (Figure 2-2)
- Side-cut radius \( (R_{sc}) \) - The radius of the line describing the curved portion of the snowboard contour. (Figure 2-4)
- Free bottom camber \( (H_f) \) - the height of the running surface from a vertical plane surface measured at the highest point, with the snowboard held laterally on edge, free from the effect of the snowboard weight. (Figure 2-3)
- Camber curvature radius \( (r_f) \) - The vertical (XZ-plane) radius of the curved portion of the snowboard body. (Figure 2-4)
- Asymmetrical offset \( (O_s, O_h) \) — the distance along the longitudinal axis that each side of an asymmetrical shape is offset from the other side. Offset may be different at the shoulder and heel. (Figure 2-5)

Thickness distribution parameters

- Body thickness \( (T_b) \) - The distance between the upper and lower surface of the snowboard measured from the centre of the board between the two contact points. (Figure 2-4)
- Shovel thickness \( (T_s) \) - The distance between the upper and lower surface of the snowboard measured in the middle between the shovel contact point and the tip. (Figure 2-4)
- Heel thickness \( (T_h) \) - The distance between the upper and lower surface of the snowboard measured in the middle between the heel contact point and the tip. (Figure 2-4)

The following graphs illustrate the design parameters of the snowboard model used in this research.
Figure 2-2 – Top View of a Symmetric Snowboard Model

Figure 2-3 – Side View of a Snowboard Model

Figure 2-4 – Side View of a Snowboard Model (Thickness)
Figure 2-5 – Top View of an Asymmetrical Snowboard
2.3 Snowboard Composite Sandwich Structure

The modern snowboard structure is generally constructed of a composite sandwich structure which consists of five layers with the addition of sidewalls and steel edges. The basic structure of a modern snowboard is shown in Figure 2-6 below.

![Modern Snowboard Structure](image)

The core material in the middle of the board is usually a laminated hardwood such as birch wood, beech wood and poplar wood. These hardwood laminates have high strength to weight ratio whilst the same time providing sufficient flex to the board. Hardwood also has good vibration absorption properties and is easily manufactured into the desirable shape by a CNC machine. Other materials such as Kevlar, carbon, hollow aluminium honeycomb and PVC (poly-vinyl chloride) foam are also commonly used resulting in different properties for the board.

Sandwiching the core material are two layers of composite reinforcement material, such as fibreglass, adding strength and stiffness. These are generally arranged in either a bi-axial configuration (weaved in 90 degrees to each other) or tri-axial configuration (weaved in -45, 0 and 45 degrees together). These layers are fixed to the core material by resin and contribute to the overall strength and stiffness of the board. Current research has developed a continuous stiffness distribution estimation model combining the thickness distribution model with the fundamental theory of fabric composite analysis and 2-D textile composites developed by Hashin [24], Byun [9],
and Clifton [11][12][13] as well as the classical laminate theory approach used by Brennan [7][8]. This structural model enables professional riders and experienced snowboard designer to estimate the bending and torsional stiffness distribution along the snowboard by manually choosing the core properties and adjusting the design parameters of the two bi-axial fabric composite layers of the board.

The base of the board is the surface that directly contacts the snow, artificial riding terrain or the surface of obstacles such as handrails. It is usually made of P-Tex, also known as ultra-high-molecular-weight polyethylene (UHMWPE), which is a kind of thermoplastic plastic. UHMWPE is suitable as the snowboard base because of its high toughness, high impact strength and low coefficient of friction characteristics. The durability of the material is dependent on the molecular weight number. The higher the number, the more durable the material [9].

The topsheet is used to protect the inner structure of the board. It also covers and protects the graphics on the upper surface from scratching. It can be made of different materials including nylon, wood, fibreglass and composites. ABS, also known as Poly-acrylonitrile-butadiene-styrene, is commonly used as the topsheet material. In addition to the layers, a thin steel edge is inserted in between the base material and lower fibreglass layer. This steel edge allows the board to grip the snow surface by penetrating into snow. Finally, the sidewall is usually made of ABS plastic. It provides shock absorption and protection to the internal structure.

The overall stiffness of the board plays an important role in the on-snow performance and affects the characteristics of the snowboard. Softer boards are slower and less responsive but more forgiving which is suitable for a beginner. However, it may lack liveliness and pop. Softer boards tend to have trouble holding a smooth turn during high speed carves. [58] As a result, most of the advanced and high quality snowboards are stiffer than beginner and learner boards [6].
2.4 Snowboard Performance Prediction

This section presents the development of the snowboard performance prediction model utilised in this research for snowboard design optimisation. The prediction model was originally developed by the RMIT Snowboard Research Group [11][12][52] and aimed to fully characterise the “feel” of snowboards for the main riding styles. Subjective performance data was gathered via a series of online surveys from 115 total respondents; in depth focus group interviews of 9 snowboard experts and a series of on-snow field tests by 8 local snowboard instructors [52].

The data was analysed using a quality function deployment (QFD) method to fully identify customer requirements for snowboarders and common riding styles. This process resulted in 9 performance parameters being defined and their importance to each style determined. The final list of performance parameters utilised is shown in the table below which was mentioned in Chapter 2.1.

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<td>The level of 'pop' or spring in the board when performing a jump</td>
</tr>
</tbody>
</table>
A correlation model was formulated in order to link the objective and subjective parameters, thus providing an on-snow performance prediction for any snowboard design. Discrete objective and subjective data were collected for three high performance test boards [52]. The objective data was collected in the laboratory using simple measurements and static bending and torsion tests, or obtained from published data sheets. Conversely, the subjective data rating of the on-snow performance of the boards was obtained through on-snow testing by professional snowboard instructors. After riding a pre-defined slalom course and performing several basic tricks, they were interviewed as to the levels of each performance parameter present in each test snowboard on a 1-10 scale.

The Spearman ranked correlation coefficients between the objective and subjective data collected from the tests were used as the basis of the performance prediction model, which was formulated in Eq 2-1 [11].

\[
P_n = \sum_{n=1}^{N} R_n C_{n,i}
\]

Eq 2-1

where

- \( P_n \) is the normalised \( n^{th} \) subjective performance parameter rating from 1-10.
- \( R_n \) is the \( n^{th} \) relative scaling factor for each objective parameter.
- \( C_{n,i} \) is the \( i^{th} \) correlation coefficient between the subjective and objective parameter.

\( N \) is the total number of objective design parameters.
The relative scaling factor $R_n$ for each objective design parameter can be expressed as follow [11].

$$R_n = \frac{I_{FR} + I_{FS}}{2} \times \frac{D_n^{input}}{D_n^{max}}$$  \hspace{1cm} \text{Eq 2-2}

where

- $I_{FR}$ is the Freeride QFD importance weight
- $I_{FS}$ is the Freestyle QFD importance weight
- $D_n^{input}$ is the input design value for the objective parameter
- $D_n^{max}$ is the maximum objective parameter value from the test board data

According to Clifton [11], the stiffness and camber values of $D_n^{max}$ were taken from the -17°C objective data set to ensure the performance prediction is centred on parameters sampled at on-snow temperatures. The summation product of the relative scaling factor $R_n$ and correlation coefficient $C_{n,i}$ was then normalised against the test snowboard objective and subjective data to ensure performance ratings fit a scale between 1 and 10.
2.5 Computer-Aided Design of Snowboard

There are numerous Computer-Aided Design (CAD)/Computer-Aided Manufacturing (CAM) software packages available in the market. The most widely used design and modelling software packages included AutoCAD, CATIA, SolidWorks and ProEngineering. All of them are capable of creating a detailed 3D snowboard model with defined dimensions and material properties. Snowboard design companies convert the snowboard design specification into CAD drawings [33]. The model would then be exported into CAD/CAM software format for manufacturing. A prototype would then be produced and then subjected to a number of field tests in order to evaluate its on-snow performance or feel. Feedback from riders can then be considered and improvements made accordingly. A significant amount of time and expense would be spent on improvement and new board design to satisfy their customers’ needs.

From the consumers’ point of view, the choice and options for purchasing snowboards are very limited as the shape and size of the boards are designed by the snowboard companies but not the riders themselves. Therefore, a DIY snowboard design and customisation tool becomes very useful for the snowboard enthusiast and professional rider who is always searching for the best board to enhance their riding experience. Even beginner riders deserve to have a personalised board to improve their snowboarding learning curve and to reduce the risk of injury from picking the wrong board.

To the best of the candidate’s knowledge, there are only two software packages dedicated to snowboard design and customisation available in the market. The first one is Boardcrafter Design™ [4] developed by EnthuzNet. It allows a user to design their snowboard in a two-dimensional display CAD-like environment.
As can be seen in the screenshot from the package depicted in Figure 2-7, the software outlines the snowboard model with:

- a top view showing the width distribution and shovel/heel shapes of the bottom sheet and the binding position
- a cross-section side view which outlines the camber curve and shovel/heel height and length

![Figure 2-7 – Boardcrafter Design(TM) screenshot [4]](image)

Boardcrafter Design™ was designed for snowboard and ski builders to be able to design a board without having CAD modelling skills. In addition, the software allows 1:1 ratio template printing as well as cut guidelines helping the user to cut off the snowboard templates accurately [4]. This software has mainly focused on board geometry without consideration of structural analysis and material properties of the board. Performance and mechanical properties of the design can only be evaluated after the board is manufactured.
The design software package is known as snoCAD-X [48] which was developed by Dan Graf. Similar to Boardcrafter Design, snoCAD-X also presents the ski or snowboard model in two-dimensional plane with a top view and a side view respectively, (see Figure 2-8).

`snoCAD-X` [48] has more advanced control on shaping the snowboard model than does Boardcrafter Design. In addition, entering the basic dimensions of the board, a software also provides various design nodes which can be dragged with the mouse cursor to alter the shape and size of the particular part of the model. Although the feature of design nodes increases the flexibility of shaping the board design, it was found that sharp angles, inappropriate edges and inconsistent shapes could be produced in the snowboard model due to the lack of physical parameter constraints. This makes some of the snowboard design impractical.

Lee et al. [31] developed a design platform allowing the user to customise the snowboard design by simply altering the geometric parameters and material properties of the board with a user-centred Graphical User Interface (GUI). The program produced is able to visualise the final product in a three-dimensional virtual environment whilst providing a quick on-snow performance estimation of the
personalised board. The application was developed to support the full gambit of customisation controls. It demonstrated the utility of parametric design and performance estimation of the customised snowboard using a virtual reality platform supported by Virtual Reality Modelling Language (VRML).

McIntosh et al. [35] proposed a new approach for the development of a virtual engineering design platform based on Lee et al. [30][31][32] research model. Instead of developing a standalone program for individual use, this platform focused on multidisciplinary, collaborative, mass distributed and cross platform design using open source simulation and modelling technology. The CAD/CAM research platform was developed with the support of the Delta3D simulation engine and named RMIT Adaptable Platform for Interactive Distributed Design, Customisation and Optimisation (rapidDCO). Rather than the original VB/VRML approach, the new GUI was built using the cross-platform application framework Qt whilst 3D graphics were rendered with OpenSceneGraph on top of OpenGL. Figure 2-9 depicts a screenshot of rapidDCO in operation. The work utilised the snowboard model from the author Lee et al. [31] as a study.

![Figure 2-9 – rapidDCO screenshot [35]](image)
Throughout the literature review, there has been limited research in snowboard design and performance optimisation that focus on individual use. The majority of research only considered the board stiffness, damping, weight and natural frequency as the indication of snowboard performance without consideration of the effect of snowboard geometry and different riding styles. This thesis aims to formulate a set of equations and methods to search for optimal snowboard designs that best fit the user’s expectation on particular performance parameters whilst the solution satisfies all the design constraints. It greatly reduces the time and cost for snowboard enthusiasts and snowboard manufacturers to design a customised board avoiding the unproductive trial and error method.

Without performance prediction and optimisation functionality, the current snowboard design programmes require user to have certain engineering in order to design and customise a snowboard in a proper way. Therefore, this research address this issue by developing an advanced interactive design platform that allows snowboard enthusiasts without any engineering CAD drawing skills, knowledge of mathematical modelling and complex structural analysis to fully customise and personalise their own snowboards in a virtual environment.
Chapter 3
Parametric Design and Modelling

3.1 Introduction

Woodbury [61] wrote:

“Design is change. Parametric modelling represents change.”

Traditional CAD modelling requires exact specifications and precise dimensions of geometry. Changes can be very difficult to introduce once the model is created [47]. Therefore, traditional CAD systems were found not to be suitable for conceptual design which involves frequent changes of dimensions, specifications and constraints. Therefore, parametric design was introduced to modern CAD systems which allows designers to modify an existing model by changing design parameters with certain constraints such as tangency and parallelism [28][39][43].

As a result of the increasing research and new algorithms developed in both research laboratories and companies, parametric modelling technology has become well incorporated into various CAD systems such as SolidWorks, CATIA, ProEngineer and AutoCAD. These CD systems are widely used in the field of engineering, product design and by the manufacturing industry. Parametric design initiated substantial changes to architecture from the year 2000 [61].

Followed by the description of how the geometry affects the overall performance and characteristic board of a snowboard. This chapter introduces the concept of parametric design to snowboard design and customisation. Parametric snowboard design is a method of linking the board dimensions and design variables to geometry such that when a particular parameter changes, the related design variables also change under predefined design constraints. The amount of change to the related design variables is
determined from the parametric equations. These equations define the relationship between the design parameters and physical snowboard design constraints.

### 3.2 Snowboard Geometry

#### 3.2.1 Snowboard Shape

The shape of snowboards can be categorised into three main groups.

- Directional
- True twin
- Directional twin

Directional snowboards are designed to be ridden in one direction and mainly downhill. They are suitable for Freeride style with a longer and softer shovel to increase stability and assist floating on deep snow and powder. To compensate the lack of agility due to larger side-cut radius, directional board usually have stiffer and shorter heel to provide better manoeuvrability.

True twin snowboards have a symmetric geometry and structure. They have exactly the same shape for the shovel and heel, making the board perform the same in forward and backward directions. The symmetrical design allows riders to have better balance when performing tricks and jumps. Therefore, true twin boards are popular choice for Freestyle riding.

Directional twin snowboards are designed in between directional and true twin snowboard to provide all round performance. They have longer shovel and shorter heel like the shape of directional snowboard with symmetrical flex pattern as true twin snowboard.
3.2.2 Board Lengths

In general, longer boards are more stable than shorter boards especially at high speed because they have higher moment of inertia and generally larger side-cut radius. Therefore, they are easier to learn on and suitable for the beginner. However, longer boards are harder to turn and less responsive. The moment of inertia can be expressed by Eq 3-1 below. The value depends on the mass and the distance from the rotating axis. Moreover, the torque required to turn the board is also increased because the contact points, which have the highest frictional force between the board and terrain, are further away from the board centre.

\[ I = \int_V \rho(r)r^2dV \]  
Eq 3-1

Where  \( r \) is radius vector of a point of the body from the rotating axis
\( \rho(r) \) is the mass density at the point \( r \)
\( V \) represent the integration of body in terms of volume

The overall length of a snowboard is mainly dependent on the rider’s weight, height and riding style. Some snowboard companies and online resources provide guidelines for the rider to choose a suitable snowboard length based on the rider’s weight only [10].
The chart in Table 3-1 suggests that a heavier rider should choose a longer board. Another common method is to choose a board whose length is the distance between the rider’s chin and nose. The length is then further refined by the rider’s weight [38].

![Table 3-1 – Snowboard Length Guide](image)

Riding style also plays a role in choosing the board length. Freestyle requires a snowboard with higher agility that is easier to perform tricks on a terrain park. Therefore, a Freestyle rider should choose a shorter board. On the other hand, a longer board can provide higher stability for the Freeride style. An all-Mountain board is more versatile and requires all-round performance. The length is somewhere between a Freestyle and Freeride board. Finally, off-piste uses the longest board for high speed and stability.
3.2.3 Body Shape

The side-cut and camber have a significant contribution to the performance of a snowboard. The side-cut radius mainly affects the ability to turn the board. A smaller side-cut radius, resulting in a deep side-cut, makes the snowboard easier to turn at sharper angles and is more suited to the Freestyle style. A Shallow side-cut allows the rider to make longer turns with better edge grip and control, making this type of board popular for All-mountain and Freeride styles of snowboarding.

A positive camber gives more pop and a lively feel to the snowboard and facilitates jumping between turns. The shape of the camber is designed to push the ends of the snowboard into the snow, making the entire edge of the board come in contact with the snow in order to provide better edge grip during a turn [36]. Snowboards with negative camber are called “rocker boards”. The mechanics of a rocker board are very different to the traditional snowboard design and so this style of board is not considered in this research.

3.2.4 Board Widths

There are three main width dimensions of a snowboard. They are shovel width, heel width and waist width. The combination of the widths and contact length affect the body shape and side-cut radius which is discussed in the previous section. A slimmer board has less contact surface area which reduces friction between the lower surface and the snow. This makes slimmer board to travel faster, and easier to turn combine with the smaller moment of inertia. On the other hand, a wide board is slower in general, but more stable and easier for landing.

The recommended widths of a snowboard are usually determined by the size of rider’s feet. A rider with bigger feet should choose a wider board to avoid the toe and heel of the boot digging down to the snow and creating unnecessary drag [36].
3.2.5 Shovel and Heel Shape

Snowboards with a longer, higher and wider shovel are generally good for powdered and deep snow. A softer shovel also provides better capability to float which means the rider can travel smoother on deep snow. On the other hand, a shorter, lower and stiffer heel will enhance the response on turning. The dimensions of the shovel and heel shape depend on the riding style, the chosen waist width and the desired side-cut radius.

3.2.6 Thickness Distribution

The thickness distribution directly affects the stiffness distribution of the board. In general, snowboard bodies are thicker than the shovel and heel for several reasons. Depending on the position of the snowboard bindings and the height of camber, the boots and the snow surface create a continuous bending force to the region around the centre of the board. Also, the waist width at the centre of the board is always narrower than the shovel and heel width due to the side-cut curve design for higher manoeuvrability. Moreover, the moment of inertia depends on the mass and distance from the rotating axis as expressed in Eq 3-1. Reducing the overall mass at the shovel and heel of a board can effectively reduce the moment of inertia and therefore improve the agility and turn ability of the board.

3.2.7 Overall Weight

The same moment of inertia theory in Eq 3-1 can be applied to the overall weight of the snowboard. Lighter boards are easier to turn due to the reduction of moment of inertia. This also allows rider to perform more tricks and flips in the air. As a result, snowboard professionals are seeking light weight and high strength material such as fibre composite materials for constructing their snowboard.
3.3 Parametric Modelling

The core objective of parametric modelling is to determine relationship between all of the design parameters of a snowboard. The relationship flow chart is presented in Figure 3-1 below. It consists of source nodes, internal nodes, sink nodes and links (arrows). Each node contains a design parameter. The nodes are joined by links from tail (predecessor) to head (successor) nodes.

A source node represents user input which has no dependent properties and therefore no predecessor nodes. A sink node represents a parameter that is determined from its predecessor nodes and has no successor nodes. Finally, an internal node is a transition node that is neither a source nor a sink.

![Diagram of Parametric snowboard modelling flow chart]

**Figure 3-1 – Parametric snowboard modelling flow chart**
It should be noted that all of the design parameters in Figure 3-1 are based on the dimensions of the lower surface of the snowboard. Therefore, the body thickness $T_b$, shovel thickness $T_s$ and heel thickness $T_h$ are independent of the lower surface design parameters. However, lower surface design parameters do affect the thickness distribution of the board and thus the calculation of the upper surface. Also, the asymmetrical offset parameters $O_s$ and $O_h$ are independently applied after the snowboard model is completed.

### 3.3.1 Snowboard Shovel and Heel Modelling

The parametric modelling starts from the lower surface of a symmetric snowboard while the width may be different at the shoulder and heel. It is divided into five parts including the snowboard heel and shovel; the snowboard body with side-cut and camber curve; and two transition curves. The first part shown in Figure 3-2 covers the snowboard heel which is governed by heel length $L_h$ and heel width $W_h$. The heel shape is created by a quarter-ellipse starting from the tail end to the heel. The same method is applied to the snowboard shovel to model the elliptical shape along the tip to the shoulder using shovel length $L_s$ and shovel width $W_s$.

#### 3.3.1.1 Horizontal Shovel and Heel Curve Modelling

![Figure 3-2 – Top View of a Lower surface snowboard heel](image-url)
The general parametric form of an ellipse can be expressed in terms of a traced coordinates by the \((X(t), Y(t))\) on a XY-plane.

\[
X(t) = X_C + a\cos(t)\sin(\varphi) - b\sin(t)\cos(\varphi) \quad \text{Eq 3-2}
\]
\[
Y(t) = Y_C + a\cos(t)\cos(\varphi) + b\sin(t)\sin(\varphi) \quad \text{Eq 3-3}
\]

Where \((X_C, Y_C)\) is the centre of the ellipse, \(t\) is a variable from 0 to \(2\pi\), \(\varphi\) is the angle between the X-axis and the major axis of the ellipse.

In our case, the major axis of the ellipse is along the X-axis which implies that \(\varphi = 0\) whilst the centre of ellipse \((X_C, Y_C)\) is at \((-\frac{L_c}{2}, 0)\).

Therefore, the elliptical curve of the snowboard heel can be expressed as:

\[
X_h(\theta_h) = \frac{-L_c}{2} - L_h\cos(\theta_h) \quad \text{Eq 3-4}
\]
\[
Y_h(\theta_h) = \frac{W_c}{2}\sin(\theta_h) \quad \text{Eq 3-5}
\]

where \(\frac{\pi}{2} \leq \theta_h \leq \pi\)

Similarly, the elliptical curve of the snowboard shovel can be determined as follow:

\[
X_s(\theta_s) = \frac{L_c}{2} + L_s\cos(\theta_s) \quad \text{Eq 3-6}
\]
\[
Y_s(\theta_s) = \frac{W_s}{2}\sin(\theta_s) \quad \text{Eq 3-7}
\]

where \(0 \leq \theta_s \leq \frac{\pi}{2}\)
3.3.1.2 Vertical Shovel and Heel Curve Modelling

Before defining the equations for the vertical heel and shovel shapes, the radius of both heel \( r_h \) and shovel curves \( r_s \) have to be determined. Figure 3-3 below shows a side view of the lower surface of a snowboard heel model.

![Figure 3-3 – Lower surface snowboard heel side view](image)

The vertical heel and shovel curves are shaped by upward circular curves using heel length \( L_h \) and height \( H_h \) as well as shovel length \( L_s \) and height \( H_s \). The relationship can be determined by using Pythagoras’s Theorem.

\[
L_h^2 + (r_h - H_h)^2 = r_h^2 \\
\text{Eq 3-8}
\]

Therefore,

\[
r_h = \frac{L_h^2 + H_h^2}{2H_h} \\
\text{Eq 3-9}
\]

Similarly, the radius of curvature for the snowboard heel side can be determined.

\[
r_s = \frac{L_s^2 + H_s^2}{2H_s} \\
\text{Eq 3-10}
\]
Since both the vertical curves are created by upward circular curves, they can be expressed as a path traced by coordinates \((X(t), Z(t))\) on the XZ-plane.

\[
X(t) = X_c + r \cos(t) \quad \text{Eq 3-11}
\]
\[
Z(t) = Z_c + r \sin(t) \quad \text{Eq 3-12}
\]

where \((X_c, Z)\) is the centre of circle

\(t\) is a variable which in general varies from 0 to \(\alpha_h\).

Therefore, the equations for the heel curve on a XZ-plane can be expressed by:

\[
X_h(\alpha_h) = -\frac{L_c}{2} + r_h \cos(\alpha_h) \quad \text{Eq 3-13}
\]
\[
Z_h(\alpha_h) = r_h \sin(\alpha_h) \quad \text{Eq 3-14}
\]

where \(\pi + \cos^{-1}\left(\frac{L_h}{r_h}\right) \leq \alpha_h \leq \frac{3\pi}{2}\)

Similarly, the equations for shovel curve can be expressed by:

\[
X_s(\alpha_s) = \frac{L_c}{2} + r_s \cos(\alpha_s) \quad \text{Eq 3-15}
\]
\[
Z_s(\alpha_s) = r_s \sin(\alpha_s) \quad \text{Eq 3-16}
\]

Where \(\frac{3\pi}{2} \leq \alpha_s \leq \frac{3\pi}{2} + \cos^{-1}\left(\frac{L_s}{r_s}\right)\)
3.3.2 Snowboard Body Modelling

The lower surface body curve is governed by two important design parameters, side-cut radius $R_{sc}$ and free bottom camber $H_f$, which have a significant impact on snowboard performance.

3.3.2.1 Side-cut Curve Modelling

A side-cut curve is a circular arc drawn between the heel and shovel transition curve with the centre of the circle at $(X_{sc}, Y_{sc})$ and a side-cut radius $R_{sc}$ where the radius is determined by the contact length $L_c$, waist width $b_m$, shovel width $W_s$ and heel width $W_h$ shown in Figure 3-4.

![Figure 3-4 – Lower surface snowboard side-cut radius top View](image)

Considering a symmetric twin board with the same heel and shovel width, we have

$$L_1 = L_2 = \frac{L_c}{2} \quad \text{Eq 3-17}$$

and declare:

$$W_{hs} = W_h = W_s \quad \text{Eq 3-18}$$
Applying Pythagoras’s Theorem to the right triangle, we obtain

\[
\left( \frac{L_c}{2} \right)^2 + \left( \frac{b_m}{2} + R_{sc} \right)^2 = \left( \frac{W_{hs}}{2} + R_{sc} \right)^2 \tag{Eq 3-19}
\]

By solving the equation above, the side-cut radius \( R_{sc} \) can be expressed as

\[
R_{sc} = \frac{L_c^2 + b_m^2 - W_{hs}^2}{4(W_{hs} - b_m)} \tag{Eq 3-20}
\]

Since the board is symmetric with the same heel and shovel width, the X and Y coordinate of the centre of the side-cut circular curve can be determined as:

\[
X_{sc} = 0 \tag{Eq 3-21}
\]
\[
Y_{sc} = R_{sc} + \frac{b_m}{2} \tag{Eq 3-22}
\]

For a non-offset symmetric directional board with different heel and shovel width \( (W_h \neq W_s) \), we can generate the following equations by considering the relationship between distances along the board.

\[
\left( \frac{W_h}{2} + R_{sc} \right)^2 - \left( \frac{b_m}{2} + R_{sc} \right)^2 = L_1^2 \tag{Eq 3-23}
\]
\[
\left( \frac{W_s}{2} + R_{sc} \right)^2 - \left( \frac{b_m}{2} + R_{sc} \right)^2 = L_2^2 \tag{Eq 3-24}
\]
\[
L_1 + L_2 = L_c \tag{Eq 3-25}
\]

Expanding both Eq 3-19 and Eq 3-20 above, we have

\[
\left( \frac{W_h}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2 + R_{sc}(W_h - b_m) = L_1^2 \tag{Eq 3-26}
\]
\[
\left( \frac{W_s}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2 + R_{sc}(W_s - b_m) = L_2^2 \tag{Eq 3-27}
\]
Rearrange Eq 3-25 and squaring both sides, we obtain

\[ L_2^2 = (L_c - L_1)^2 \]  

Eq 3-28

Substitute \( L_2^2 \) from Eq 3-27 to Eq 3-28, results

\[ \left( \frac{W_s}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2 + R_{sc}(W_s - b_m) = (L_c - L_1)^2 \]  

Eq 3-29

Expanding Eq 3-29 and substituting \( L_1 \) from Eq 3-26 into Eq 3-29, we then obtain

\[
\left( \frac{W_s}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2 + R_{sc}(W_s - b_m)
= L_c^2 - 2L_c \sqrt{\left( \frac{W_h}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2 + R_{sc}(W_h - b_m)}
\]

Eq 3-30

\[
+ \left( \frac{W_h}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2 + R_{sc}(W_h - b_m)
\]

Rearranging Eq 3-30 above, we now obtain:

\[
R_{sc}(W_s - W_h) + \left( \frac{W_s}{2} \right)^2 - \left( \frac{W_h}{2} \right)^2 - L_c^2
= 2L_c \sqrt{\left( \frac{W_h}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2 + R_{sc}(W_h - b_m)}
\]

Eq 3-31

Introducing the following common constants:

\[
A = W_s - W_h
\]

\[
B = \left( \frac{W_s}{2} \right)^2 - \left( \frac{W_h}{2} \right)^2 - L_c^2
\]

\[
C = \left( \frac{W_h}{2} \right)^2 - \left( \frac{b_m}{2} \right)^2
\]

\[
D = W_h - b_m
\]
Eq 3-31 can then be simplified as follows:

\[ AR_{sc} + B = 2L_c\sqrt{C + DR_{sc}} \]  \hspace{1cm} \text{Eq 3-32}

Squaring both sides and rearranging Eq 3-32.

\[ AR_{sc}^2 + (2AB - 4L_c^2D)R_{sc} + B^2 - 4L_c^2C = 0 \]  \hspace{1cm} \text{Eq 3-33}

The side-cut radius can be determined by solving the quadratic equation of Eq3-32, so that:

\[ R_{sc} = \frac{-(2AB - 4L_c^2D) \pm \sqrt{(2AB - 4L_c^2D)^2 - 4A^2(B^2 - 4L_c^2C)}}{2A^2} \]  \hspace{1cm} \text{Eq 3-34}

The centre of the side-cut circular curve \((X_{sc}, Y_{sc})\) can be expressed by:

\[ X_{sc} = \sqrt{\left(\frac{W_h}{2} + R_{sc}\right)^2 + \left(\frac{b_m}{2} + R_{sc}\right)^2} - \frac{L_c}{2} \]  \hspace{1cm} \text{Eq 3-35}

\[ Y_{sc} = R_{sc} + \frac{b_m}{2} \]  \hspace{1cm} \text{Eq 3-36}

Therefore, the equation for the side-cut curve on a XY-plane will be

\[ X_{sc}(\beta) = X_{sc} + R_{sc}\cos(\beta) \]  \hspace{1cm} \text{Eq 3-37}

\[ Y_{sc}(\beta) = Y_{sc} + R_{sc}\sin(\beta) \]  \hspace{1cm} \text{Eq 3-38}

Where \( \pi + \beta_h \leq \beta \leq 2\pi - \beta_s \)

The angles \( \beta_h \) and \( \beta_s \) can be determined as follow:

\[ \beta_h = \sin^{-1}\left(\frac{R_{sc}}{R_{sc} + \frac{W_h}{2}}\right) \]  \hspace{1cm} \text{Eq 3-39}

\[ \beta_s = \sin^{-1}\left(\frac{R_{sc}}{R_{sc} + \frac{W_s}{2}}\right) \]  \hspace{1cm} \text{Eq 3-40}
3.3.2.2 Camber Curve Modelling

Figure 3-5 shows a side view of the snowboard camber curve. It is created by intersecting the free bottom camber and is parallel to both vertical shovel and heel curves.

Consider the distance between the centre of camber curve \((x_f, z_f)\) and both circles’ centres from the shovel curve radius \(r_s\) and heel curve radius \(r_h\), the equations depicted below can be obtained:

\[
(X_f - X_h)^2 + (Z_f - Z_h)^2 = (r_h + r_f)^2 \quad \text{Eq 3-41}
\]

\[
(X_f - X_r)^2 + (Z_f - Z_s)^2 = (r_s + r_f)^2 \quad \text{Eq 3-42}
\]

The vertical distance between the camber height \(H_f\) and the centre of camber curve \((x_f, z_f)\) can be expressed by:

\[
H_f - Z_f = r_f \quad \text{Eq 3-43}
\]

The XZ-coordinates of the centre of the camber curve as well as the radius can be determined by solving the three sequential equations above to obtain:
\[
X_f = \frac{L_c^2 - 2r_s H_f + 2r_h H_f}{2L_c} - \frac{L_c}{2} \quad \text{Eq 3-44}
\]
\[
Z_f = H_f - r_f \quad \text{Eq 3-45}
\]
\[
\gamma_f = \left(\frac{X_f + L_c}{2}\right)^2 - 2r_h H_f + H_f^2
\]

\[
2H_f \quad \text{Eq 3-46}
\]

Therefore, the equation for the side-cut curve in the XZ-plane will be

\[
X_f(\gamma) = X_f + rf\cos(\gamma) \quad \text{Eq 3-47}
\]
\[
Z_f(\gamma) = Y_f + rf\sin(\gamma) \quad \text{Eq 3-48}
\]

Where \( \gamma_s \leq \gamma \leq \pi - \gamma_h \)

In order to determine the angles \( \gamma_h \) and \( \gamma_s \), the x-coordinate of the contact point between the vertical heel/shovel curves and camber curves need to be determined.

From Figure 3-5, we compare the ratio between \( r_h \) and \( r_f \) with \( x_h, x_f \), to obtain:

\[
\frac{X_{hc} - X_h}{X_f - X_{hc}} = \frac{r_h}{r_f} \quad \text{Eq 3-49}
\]

Applying the same method to the shovel side, we have

\[
X_{hc} = \frac{r_h X_f + r_f X_h}{r_h + r_f} \quad \text{Eq 3-50}
\]
\[
X_{sc} = \frac{r_s X_f + r_f X_s}{r_s + r_f} \quad \text{Eq 3-51}
\]

The two contact points are used for the smooth transition from heel tail to shovel tip through the camber curvature. As a result, the angles \( \gamma_h \) and \( \gamma_s \) can be determined by:

\[
\gamma_h = \cos^{-1}\left(\frac{X_{hc}}{r_h}\right) \quad \text{Eq 3-52}
\]
\[
\gamma_s = \sin^{-1}\left(\frac{X_{sc}}{r_s}\right) \quad \text{Eq 3-53}
\]
3.3.3 Modelling of Transition Curves

Instead of continuing the elliptical shovel/heel to the side-cut, two transition curves are introduced to connect the snowboard body to both heel and shovel together smoothly without producing unwanted corners or spikes. Since, the transition curves are based only on heel width \( W_h \) and shovel width \( W_s \) respectively, the side-cut radius and the shovel/heel length can be customised independently without conflict.

The transition curves are created by circular arcs with a diameter of the snowboard’s width. The heel transition curve can be expressed by:

\[
X_{ht}(\beta) = -\frac{L_c}{2} + \frac{W_h}{2} \cos(\beta) \quad \text{Eq 3-54}
\]

\[
Y_{ht}(\beta) = W_h \sin(\beta) \quad \text{Eq 3-55}
\]

Where \( \beta_h \leq \beta \leq \frac{\pi}{2} \)

Similarly, the equations for shovel transition curve will be:

\[
X_{st}(\beta) = \frac{L_c}{2} + \frac{W_s}{2} \cos(\beta) \quad \text{Eq 3-56}
\]

\[
Y_{st}(\beta) = W_s \sin(\beta) \quad \text{Eq 3-57}
\]

Where \( \frac{\pi}{2} \leq \beta \leq \frac{\pi}{2} + \beta_s \)
3.3.4 Lower Surface Snowboard Model

The symmetric lower surface snowboard model is completed by mirroring the finished curves in the previous section across the XZ-plane. The three-dimensional view of a completed lower surface snowboard model is shown in Figure 3-7. The thick solid line represents the first half of the model and the dotted line represents the mirrored model of the first half.

Figure 3-7 – Three-dimensional view of a completed lower surface snowboard model
3.3.5 Upper Surface Modelling

The upper surface modelling is created based on the completed lower surface in the previous section through the addition of a thickness distribution along the board and the type of sidewall design along the edge.

3.3.5.1 Thickness Distribution model

The thickness distributions of three different style (Freeride, Freestyle and All-Mountain) boards were measured at the RMIT laboratory [11] and the results are shown in Figure 3-8 below. All testing boards had a higher body thickness (9mm to 12mm) than their heel/shovel thickness (3mm to 6mm) due to the fact that snowboard bodies are often subjected to progressively higher bending and torsional stress and consequently would need to be thickened. On the other hand, thinner shovel and heel makes the snowboard lighter and easier to turn. It was found that the thickness of different style boards displayed a similar distribution pattern. The pattern is mainly governed by three parameters including body thickness $T_b$, heel thickness $T_h$ and shovel thickness $T_s$.

![Figure 3-8 – Thickness distribution of three different style boards [11]](image-url)
By observation, the thickness distribution can be replicated by connecting two hyperbolic tangent functions. A positive \( \tanh \) function replicates the pattern from the tail along to the body centre while a negative \( \tanh \) function replicates the pattern from the body centre to the tip.

- \( \delta \) represents the distribution slope from the snowboard heel/shovel to the body
- \( \emptyset \) represents the position where the thickness transits from the snowboard heel/shovel to the body

The magnitude of the \( \tanh \) functions are multiplied by \( \frac{T_b - T_h}{2} \) and \( -\frac{T_b - T_s}{2} \) to represent the difference between the body thickness and the heel/shovel thickness. At the same time, \( \frac{T_b + T_h}{2} \) and \( \frac{T_b + T_s}{2} \) are added to the functions respectively to represent the middle line between the thicknesses, making the minimum value become the heel/shovel thickness and maximum value become the body thickness.

We also denoted the series of XYZ Cartesian coordinates of the lower and upper surface as:

\[
[X_l] = [X_1, X_2, ..., X_n], \quad [X_u] = [X_1, X_2, ..., X_n]
\]
\[
[Y_l] = [Y_1, Y_2, ..., Y_n], \quad [Y_u] = [Y_1, Y_2, ..., Y_n]
\]
\[
[Z_l] = [Z_1, Z_2, ..., Z_n], \quad [Z_u] = [Z_1, Z_2, ..., Z_n]
\]

where \( n \) is the total number of nodes along the board in the x-direction.

The thickness distribution along the centreline of the snowboard is expressed by:

\[
[T] = [T_1, T_2, ..., T_n]
\]

where \( n \) is the total number of nodes along the board in the x-direction.

Therefore the thickness distribution can be modelled by the two equations as follows:
On the heel side of the board, we have:

\[
[T]_h = \frac{T_b - T_h}{2} \tanh \left( \frac{\delta}{T_h} (|X|_h + \phi L_c) \right) + \frac{T_b + T_h}{2}
\]

Eq 3-58

On the shovel side of the board, we have:

\[
[T]_s = -\frac{T_b - T_s}{2} \tanh \left( \frac{\delta}{T_s} (|X|_s + \phi L_c) \right) + \frac{T_b + T_s}{2}
\]

Eq 3-59

It is noted that the position of the transition points are dependent on the contact length of the board. The longer the contact length, the further the transition point towards the tip/tail. Therefore, \( \phi L_c \) represents how far the transition point is from the contact point. The slope of the thickness transition curve is also affected by heel/shovel length. A longer heel/shovel length makes the curve flatter and thus the constant is expressed by \( \delta \) multiplied by the inverse of the heel/shovel thickness.

Comparisons between the model prediction and the measurements of the three different boards are depicted in Figure 3-9 to Figure 3-11.

![Figure 3-9](image-url)

**Figure 3-9 – Comparison between thickness distribution model and measured data of Freeride board,**

\[
\delta = 0.05, \phi = 0.40
\]
Figure 3-10 – Comparison between thickness distribution model and measured data of Freestyle board, $\delta = 0.06$, $\varphi = 0.40$

Figure 3-11 – Comparison between thickness distribution model and measured data of All-Mountain board, $\delta = 0.03$, $\varphi = 0.43$
It is shown that both the thickness distribution of Freestyle and Freeride style board are well estimated with a maximum error of 8.2% and 5.2% at -600mm and 450mm distances from the snowboard centre respectively. However, the distribution of the All-Mountain board is slightly different to the others where the thickness of the tail and tip are not flat. This leads to an increase in the error to values of 9.3% at the tail and 10.8% at the tip while the error at the highest point is 7.6% at -250mm distance from the board centre. The parameter $\phi$ ranges from 0.4 to 0.43 while the parameter $\delta$ ranges from 0.03 to 0.05.

Since snowboard thickness is measured by the distance between two parallel surfaces along the board but not in Z direction, the thickness direction and position of the upper surface can be calculated based on the contact length and curve radius as follows:

On the heel side of the board,

$$[X_u]_h = \left[ X_t - \frac{(L_c + X_t)T}{r_h} \right]_h$$  \hspace{1cm} \text{Eq 3-60}

$$[Z_u]_h = \left[ Z_t - \frac{(r_h + Z_t)T}{r_h} \right]_h$$  \hspace{1cm} \text{Eq 3-61}

along the centre body of the board,

$$[X_u]_b = \left[ X_t + \frac{(X_f - X_t)T}{r_f} \right]_b$$  \hspace{1cm} \text{Eq 3-62}

$$[Z_u]_b = \left[ Z_t + \frac{(r_f - Z_t)T}{r_f} \right]_b$$  \hspace{1cm} \text{Eq 3-63}
On the shovel side of the board,

\[
[X_u]_s = \left[ X_l - \frac{(L_c - X_l)}{r_s} \right]_s \quad \text{Eq 3-64}
\]

\[
[Z_u]_s = \left[ Z_l - \frac{(r_s - Z_l)T}{r_s} \right]_s \quad \text{Eq 3-65}
\]

Figure 3-12 shows the side view of a completed snowboard model taking into account the thickness distribution.

Figure 3-12 – Side view of the snowboard model showing the thickness distribution
3.3.5.2 Sidewall Construction

There are mainly three types of sidewall design. There are ABS sidewall constructions, Cap constructions and Half-Cap constructions. Figure 3-13 shows a cross sectional view of these designs at the snowboard waist position at the centre of the board. Since the effect of sidewall on the snowboard performance is relatively minor compared to the main geometry, the shape of the sidewall model is simplified to reduce computational cost in this study.

![Figure 3-13 – Cross section view of snowboard waist with three different types of sidewall](image)

The sidewall design only affects the calculation along the centre body of the board. Therefore, the upper surface position of the shovel and heel remains the same where \( X_l(i) \leq -\frac{L_c}{2} \) or \( X_l(i) \geq \frac{L_c}{2} \).

\[
[Y_u]_s = [Y_l]_s \quad \text{Eq 3-66}
\]

\[
[Y_u]_h = [Y_l]_h \quad \text{Eq 3-67}
\]
For the body between the two contact points where $X_l(i) > \frac{L_c}{2}$ and $X_l(i) < \frac{L_c}{2}$, the equations are shown below. The shape of the upper surface for the ABS sidewall construction is the same as the lower surface except for the thickness.

$$[Y_u]_b = [Y_l]_b$$  \hspace{1cm} \text{Eq 3-68}

The shape of the Cap construction depends on the angle $\varphi_{sw}$ which can be expressed by

$$[Y_u]_b = \left[ Y_l - \frac{T}{2} \tan \left( \theta_{sw} \cos \left( \frac{\pi X_l}{L_c} \right) \right) \right]_b$$  \hspace{1cm} \text{Eq 3-69}

Finally, the shape of the Half-Cap construction is defined by

$$[Y_u]_b = \left[ Y_l - T \tan \left( \theta_{sw} \cos \left( \frac{\pi X_l}{L_c} \right) \right) \right]_b$$  \hspace{1cm} \text{Eq 3-70}
3.3.6 Offset

Mechanically, there are some differences between heel side turns and toe side turns. In general, a rider has better control on the toe side by tipping the board at different angles. However, heel side turn can yield more power due to the fact that the reaction force is directly transferred to the body. Asymmetric snowboards are designed to balance the turning capability on the heel side and toe side of the board by having a deeper side-cut on the heel side. Although the current research only focuses on the performance and design of symmetrical snowboards, the snowboard design platform is capable to create parametric model of an asymmetric board.

Figure 3-14 below shows the top view of the shovel side of an asymmetric positive offset snowboard. It is divided into four regions. For each region, the board shape is either squeezed or extended along the board based on the amount and direction of the offset as well as the position of the board.

For region 1 where \( Y \geq 0 \) and \( 0 \leq X \leq \frac{L_c}{2} \)

\[
X_{os} = X_S \left( 1 + \frac{O_s}{L_c} \right)
\]

Eq 3-71
For region 2 where $Y \geq 0$ and $X > \frac{L_c}{2}$

$$[X_{os}] = \left[X_S + \frac{O_s}{2L_s} \left(L_s + \frac{L_c}{2} - X_S\right)\right]$$  \hspace{1cm} \text{Eq 3-72}

For region 3 where $Y < 0$ and $0 \leq X \leq \frac{L_c}{2}$

$$[X_{os}] = \left[X_S \left(1 - \frac{O_s}{L_c}\right)\right]$$  \hspace{1cm} \text{Eq 3-73}

For region 4 where $Y < 0$ and $X > \frac{L_c}{2}$

$$[X_{os}] = \left[X_S - \frac{O_s}{2L_s} \left(L_s + \frac{L_c}{2} - X_S\right)\right]$$  \hspace{1cm} \text{Eq 3-74}

The same approach is applied to the heel side offset. When $Y \geq 0$ and $-\frac{L_c}{2} \leq X < 0$

$$[X_{oh}] = \left[X_h \left(1 - \frac{O_h}{L_c}\right)\right]$$  \hspace{1cm} \text{Eq 3-75}

When $Y \geq 0$ and $X < -\frac{L_c}{2}$

$$[X_h] = \left[X_h + \frac{O_h}{2L_h} \left(L_h + \frac{L_c}{2} + X_h\right)\right]$$  \hspace{1cm} \text{Eq 3-76}

When $Y < 0$ and $-\frac{L_c}{2} \leq X < 0$

$$[X_{oh}] = \left[X_h \left(1 + \frac{O_h}{L_c}\right)\right]$$  \hspace{1cm} \text{Eq 3-77}

When $Y < 0$ and $X < -\frac{L_c}{2}$

$$[X_{oh}] = \left[X_h - \frac{O_h}{2L_h} \left(L_h + \frac{L_c}{2} + X_h\right)\right]$$  \hspace{1cm} \text{Eq 3-78}
3.4 Conclusions

In this chapter, we introduced the concept of parametric design to snowboard design and customisation. The geometry of a snowboard was fully defined by the standard terminology of snowboard and snowboarding F1107-04 from the ASTM International document [2] together with some definition created by Clifton [11]. In order to complete the model, some modifications and additional custom design parameters were introduced.

Parametric snowboard design was a method of linking the snowboard dimensions and design variables to geometry such that when a particular parameter changes, all the related design variables also change accordingly under predefined design constraints. The relationships between all the design parameters of the snowboard are interconnected. These relationships are categorised into three groups, consisting of source nodes, internal nodes and sink nodes, to avoid any design conflicts. A systematic analysis has been performed and presented in a data flow map.

The parametric model is divided into different sections and regions on different planes. Each of the sections is modelled separately and connected together with transition curves. Most of the dimensions are used to create the lower surface of the snowboard except the three thickness parameters. The model is completed with the upper surface based on the thickness distribution and the sidewall construction. The parametric model also provides offset design as an advanced option. The number of changes to the related design variables is determined from a series of parametric equations which also govern the physical snowboard design constraints.

As part of the modelling, a thickness distribution model has been developed based on the measured data from three different riding style boards. The thickness distribution can be simulated by connecting two hyperbolic tangent functions. Two custom parameters, δ and Ø were introduced to complete the model. The former represents the distribution slope from the snowboard heel/shovel to the body. The latter represents the position where the thickness transits from the snowboard heel/shovel to the body.
Results from the comparison between the model and the measured data shows that both the thickness distribution of Freestyle and Freeride style board are well estimated with a maximum error of 8.2% and 5.2% at -600mm and 450mm distance from the snowboard centre respectively. The distribution of the All-Mountain board is slightly different to the others where the thicknesses of the tail and tip are not flat. The error leads to a different of 9.3% at the tail and 10.8% at the tip between the actually measured and estimated model. The parameter $\phi$ ranges from 0.4 to 0.43 while the parameter $\delta$ ranges from 0.03 to 0.05.
Chapter 4
Snowboard Design and Optimisation

4.1 Introduction

Current snowboard design relies heavily on review and feedback from professional riders and snowboard designers. Snowboard companies are spending huge amounts of money and time on the “trial and error” method of design. Snowboard companies can only offer a limited number of off-the-shelf designs. For snowboard enthusiasts that seek an optimal board design the “Do-It-Yourself” method seems to be the only solution. However, this approach requires a certain level of engineering CAD drawing skills and knowledge of snowboard structure and material properties. There is a need for a snowboard design method that allows users to optimise a custom board to best fit their individual use.

This chapter is dedicated to the development of snowboard design optimisation. The performance prediction model, developed by Clifton [11], is utilised in a reverse manner. The goal is to minimise the different between user target performance and the model predicted performance while satisfying all the design constraints using Least Squares Methods. Instead of entering snowboard geometry to generate predicted performance, the current study enables users to search for an optimal snowboard design solution based on the personal performance preference of a user.

This chapter also presents the implementation of SQP technique and MOSA optimisation methods obtaining the optimal design solutions for three case studies. The results and findings are reported at the end of the chapter.
4.2 Snowboard Stiffness Estimation

Snowboard stiffness plays an important role in snowboard performance. The original sandwich structural model was developed using the classic thin plate/laminate theory which was used on the computational model formulated by Brennan [7][8]. The 2-D textile composites structural model developed by Hashin [24], Byun [9] has been incorporated into the sandwich structural classic thin plate/laminate theory by Clifton et al. [13]. The research constructed three flat rectangular shaped, sandwich composite sample boards to validate the mathematical model. It was found that the model accurately predicted the bending stiffness of the sample boards with less than 2% error while the majority of the torsional stiffness estimation had errors between 2-4%. Clifton [11] further extended the research to consider the calculation of composite skin layer properties for various fabric configurations. However, the shape and the thickness of a snowboard are not regular. The board stiffness needs to be determined by discretising the sandwich structure board into small rectangular elements. As a result, this research combines the thickness distribution model and the pre-existing sandwich structural model, developed by Clifton [11][12][13], to estimate the continuous snowboard stiffness.

Figure 4-1 shows the cross-section of one half of a snowboard sandwich structure.
The equations for classical laminate theory of thin plate can be expressed as follows.

\[
\begin{bmatrix}
[N] \\
[M]
\end{bmatrix} = 
\begin{bmatrix}
[A] & [B]
\end{bmatrix}
\begin{bmatrix}
[\varepsilon^0]
\end{bmatrix}
\]

Eq 4-1

where \( [N] = \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} \) represents forces in the x and y directions,

\( [M] = \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} \) represents moments in the x and y directions,

\( [\varepsilon^0] = \begin{bmatrix} \varepsilon^0_x \\ \varepsilon^0_y \\ \gamma_{xy} \end{bmatrix} \) represents strains in the x and y directions,

\( [k] = \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix} \) represents curvatures in the x and y directions.

The laminate stiffness matrices are determined from the layer stiffness matrices shown below.

\[
[A] = \sum_{i=1}^{n} (h_{i+1} - h_i) [Q_i]
\]

Eq 4-2

\[
[B] = \frac{1}{2} \sum_{i=1}^{n} (h_{i+1}^2 - h_i^2) [Q_i]
\]

Eq 4-3

\[
[D] = \frac{1}{3} \sum_{i=1}^{n} (h_{i+1}^3 - h_i^3) [Q_i]
\]

Eq 4-4

where \( h \) is the datum height illustrate in Figure 4-2

\([Q_i]\) the \( i^{th} \) layer stiffness matrix

\( n \) is the number of layers.
Figure 4-2 shows the laminated layer heights measure from the datum line.

![Figure 4-2 – Laminate layer heights from datum line](image)

The total thickness at a particular location of the board is expressed as follows.

\[ T(x) = t_t + t_{uc} + t_c(x) + t_{lc} + t_b \]  \hspace{1cm} \text{Eq 4-5}

where

- \( T(x) \) is the total thickness of the board at position \( x \)
- \( t_t \) is the topsheet thickness
- \( t_{uc} \) is the upper composite layer thickness
- \( t_c(x) \) is the core thickness at position \( x \)
- \( t_{lc} \) is the lower composite layer thickness
- \( t_b \) is the base thickness

Recall the thickness distribution model, the total thickness can be replaced by the two \( \tanh \) functions Eq 3-57 and Eq 3-58.

\[
[T]_h = \frac{T_b - T_h}{2} \tanh \left( \frac{\delta}{T_h} ([X]_h + \phi L_c) \right) + \frac{T_b + T_h}{2} \]  \hspace{1cm} \text{Eq 3-57}

\[
[T]_s = -\frac{T_b - T_s}{2} \tanh \left( \frac{\delta}{T_s} ([X]_s + \phi L_c) \right) + \frac{T_b + T_s}{2} \]  \hspace{1cm} \text{Eq 3-58}
The thickness of the core material is a function of the model subtracting the other four thickness constants which can be expressed in matrix form below by rearranging the Eq 4-5.

\[
[t_c]_h = [T]_h - [t_t] - [t_{uc}] - [t_{lc}] - [t_b] \quad \text{Eq 4-6}
\]

\[
[t_c]_s = [T]_s - [t_t] - [t_{uc}] - [t_{lc}] - [t_b] \quad \text{Eq 4-7}
\]

The compliance matrix of the sandwich composite structure is then calculated by the inverse of matrices.

\[
\begin{bmatrix}
[a] & [b] \\
[b] & [d]
\end{bmatrix} = 
\begin{bmatrix}
[A] & [B] \\
[B] & [D]
\end{bmatrix}^{-1} \quad \text{Eq 4-8}
\]

Where

\[
[a] = \begin{bmatrix}
a_{11} & a_{12} & a_{16} \\
a_{12} & a_{22} & a_{26} \\
a_{16} & a_{26} & a_{66}
\end{bmatrix}
\]

\[
[b] = \begin{bmatrix}
b_{11} & b_{12} & b_{16} \\
b_{12} & b_{22} & b_{26} \\
b_{16} & b_{26} & b_{66}
\end{bmatrix}
\]

\[
[d] = \begin{bmatrix}
d_{11} & d_{12} & d_{16} \\
d_{12} & d_{22} & d_{26} \\
d_{16} & d_{26} & d_{66}
\end{bmatrix}
\]

When the material properties of each layer are defined, the overall stiffness of the sandwich structure becomes a function of width and thickness.

\[
EI(x) = f(T(x), W(x)) = \frac{W(x)}{d_{11}} \quad \text{Eq 4-9}
\]

\[
GJ(x) = g(T(x), W(x)) = \frac{4W(x)}{d_{66}} \quad \text{Eq 4-10}
\]
For a symmetric board such as true twin and directional twin without offsets, the board width can be expressed as

\[ W(x) = 2y(x) \]  \hspace{1cm} \text{Eq 4-11} \\

where \( W(x) \) is the width of the board at position \( x \) \\
\( y(x) \) is the position of the board edge at position \( x \)

For an asymmetric board with offsets,

\[ W(x) = y^+(x) - y^-(x) \]  \hspace{1cm} \text{Eq 4-12} \\

where \( W(x) \) is width of the board at position \( x \) \\
\( y^+(x) \) is the position of the board edge at position \( x \) on positive side \\
\( y^-(x) \) is the position of the board edge at position \( x \) on negative side
4.3 Optimisation of Snowboard Performance

In view of multiple conflicting requirements for the individual, there is no “perfect” snowboard that can satisfy everyone. The highest quality and highest performance snowboard rated by a professional rider is not necessarily the best snowboard for a beginner rider. Advanced and high quality snowboards are generally stiffer than beginner and learner board because stiffer boards are more responsive and have better manoeuvrability. These stiffer boards allow advanced snowboarders to make sharper turns, ride at higher speed and perform more tricks. On the other hand, softer and longer boards are more stable and forgiving which makes them more suitable for a beginner.

The riding style and riders’ height and weight can also determine the shape of a snowboard which affects the overall characteristic and feel of the board. Therefore, the concept of optimal design does not mean to maximise the performance of a snowboard in all aspects. Instead, this research aims to best fit particular performance parameters of the snowboard for individual use while satisfying all the user-defined requirements and the design constraints.

Figure 4-3 shows the flow chart for snowboard design optimisation followed in this research. In a normal situation, user inputs a set of design parameters and generates a snowboard model via the parametric model. This model is used to estimate the on-snow performance of the custom board through a performance prediction model. In addition to the performance prediction, this research utilises the model in a reverse manner. The design platform allows a user to optimise the custom snowboard by simply entering user-defined design constraints, material properties and target performance parameters. The optimisation solvers generate a set of design parameters to best match with the user target performance depending on the design constraints and material properties.
4.3.1 Design Constraints

There are three types of design constraints that need to be considered for the optimisation task. These are discussed in the sub-sections below.

4.3.1.1 User-Defined Geometry Constraints

The user-defined geometry constraints are used to restrict the snowboard dimensions to reflect a user’s preferences. There is a direct relationship between the riders’ body characteristics and snowboard dimensions. As an example, although increasing the “contact length” of the snowboard leads to an increase in “Speed” and “Stability” performance, it is not practical to generate a board where the overall length is longer than the user’s height or shorter than two thirds of the body height. It is recommended that the board should stand between the rider’s chin and nose. The length is then refined by the rider’s weight. A heavier person should choose a longer board. Table 3-1 in the previous Chapter provides a general guide for a rider to choose a suitable board length.
As another example, the body thickness is normally between 8 to 10 mm for an 85kg rider which depends on the material used for the core and the composite laminate layers. It ensures the board has sufficient strength to support the rider during the course or performing a trick.

4.3.1.2 Physical Design Constraints

Physical design constraints are used to reinforce the relationships between design parameters. This relationship forms a series of equality and inequality constraints to the optimisation tasks. Some of the major constraints are listed below.

- The projected length is obtained from the contact length, heel length and shovel length
- The chord length is obtained from the projected length, heel height and shovel height
- The waist width is smaller than the shovel and heel width
- The side-cut radius is calculated from the contact length, waist width, heel width and shovel width
- The mass of the snowboard is obtained from the volume and density of the core material of the board
- The average shovel and heel radius are obtained from the heel/shovel length and width
- The camber height is always considered positive in the current research.

Moreover, physical design constraints can also be used to determine the overall board shape such as true twin and directional boards. As an example, the physical design constraints for a true twin board are listed below.

- The shovel length is equal to the heel length
- The shovel width is equal to the heel width
- The average shovel is equal to the heel radius
- The shovel and heel offsets are zero
4.3.1.3 Performance Parameter Constraints

Performance parameter constraints are used to define the boundaries of the performance parameters to prevent under or over design. As an example, a beginner rider prefers a board with high stability and forgiveness by sacrificing the feedback and liveliness. However, without appropriate constraint settings the optimisation solver may generate a snowboard with a long and wide board section that exhibits an unbalanced performance. The feedback and liveliness performance may be too low for the user’s preference. On the other hand, an advanced rider prefers a snowboard with higher manoeuvrability, accuracy and edge grip but without sacrificing too much of the speed and liveliness. Therefore, performance parameter constraints are important to prevent under or over design of a particular performance parameter.

4.3.2 Optimisation Methods

To optimise particular performance parameters for individual use, we have defined the objective function using Least Squares to represent the “residual” or “error” between the user’s target performances and the predicted performances from the model.

The Least Squares method is a standard approach to the approximate solution of over-determined systems where there are more equations than unknowns. A classic example of Least Squares application is data fitting. The goal is to find a line or curve that best fits a data set. In other words, the method searches for the optimal values of a model or equation to minimise the sum of the squared residuals. The residual is defined by the difference between an observed value and a value generated as the model.
In this research, the “residual” is defined by comparing different between the target performances and predicted performances.

\[ J = \sum_{n=1}^{N} (P_n - T_n)^2 \]  

Eq 4-13

where \( T_n \) is the user defined target performance of the \( n^{th} \) predicted performance parameter from 1-10.

\( P_n \) is the desired \( n^{th} \) subjective performance parameter, a function of design parameters vector rating from 1-10.

\( N \) is the number of performance parameter.

The aim is to minimise the objective function \( J \) by changing the design parameters matrix while satisfying all the equality and inequality design constraints.

\[
\min_{\chi} J = \min_{\chi} \sum_{n=1}^{N} (P_n - T_n)^2 \\
\text{Subject to } \begin{cases} 
  c_i(\chi) = 0, i = 1, \ldots, m_e \\
  c_j(\chi) \leq 0, j = m_e + 1, \ldots, m 
\end{cases}
\]

Eq 4-14

Where \( c_i(\chi) \) is a series of equality design constraints

\( c_j(\chi) \) is a series of inequality design constraints

\( e \) is a subscript represent the number of equality design constraints

\( m \) is the total number of design constraints

\( \chi \) is the design parameters matrix
4.4 Implementation of SQP Optimisation

In this research, the performance prediction model, the objective function and the design constraints were formulated and implemented into the Matlab® environment. Instead of entering design parameters and generating the on-snow performance, the objective function was minimised by changing the snowboard geometry. The optimal solution was then obtained by using the solver “minconf” function from the optimisation toolbox with the Sequential Quadratic Programming (SQP) Method.

Typical problems with linear objective functions and constraints can be solved using a Linear Programming (LP) technique. The Quadratic Programming (QP) method can be used to solve a quadratic objective function with linear constraints. However, Nonlinear Programming (NP) problems in which the objective function and constraints are nonlinear functions cannot be solved directly as can be done using the LP and QP methods. Non-linear programming requires an iterative sequence to form a direction of search at each major iteration. The so called Sequential Quadratic Programming (SQP) approach.

In order to search for an optimal solution for nonlinear constrained programming problem, it is necessary to satisfy the Karush-Kuhn-Tucker (KKT) conditions which can be expressed in Eq 4-15 below.

\[ \nabla f(x^*) + \sum_{i} \lambda_i \nabla c_i(x^*) = 0 \quad \text{Eq 4-15} \]

Subject to
\[
\begin{align*}
\lambda_i c_i(x^*) &= 0 \\
\lambda_i &\geq 0
\end{align*}
\]

where
\begin{itemize}
  \item $\nabla$ represents the gradient operator
  \item $\lambda_i$ is an estimate of the Lagrange multipliers
  \item $c_i$ represents the constraints
\end{itemize}
The equation represents a cancelation of the gradients between the objective function and the constraints at the solution point \( x^* \) where the Lagrange multipliers \( \lambda_i \) are required to balance the deviations in magnitude of both the objective function and constraint gradients.

SQP is an efficient and robust method for solving nonlinear optimisation programming problems. To implement SQP for optimisation, Matlab® approximates the Hessian \( H_k \) of the Lagrangian function at every major iteration by using quasi-Newton approximation which is shown in Eq 4-16.

\[
H_{k+1} = H_k + \frac{q_k q_k^T}{q_k^T s_k} - \frac{H_k^T s_k}{s_k^T H_k s_k} s_k H_k
\]

Eq 4-16

where \( s_k = x_{k+1} - x_k \)

\[
q_k = \left( \nabla f(x_{k+1}) + \sum_{i=1}^{m} \lambda_i \nabla c_i(x_{k+1}) \right) - \left( \nabla f(x_k) + \sum_{i=1}^{m} \lambda_i \nabla c_i(x_k) \right)
\]

The value \( s_k \) represents the difference between the new estimated design parameters and the old estimated design parameters for every major iteration where \( q_k \) is the difference of the KKT equation with substitution of vector \( x \).

The new Hessian approximation \( H_k \) is then used to generate a QP sub-problem which is defined in Eq 4-17 where the solution can provide a search direction for the optimal solution.

\[
\min_d \frac{1}{2} d^T H_k d + \nabla f(x_k)^T d \quad \text{Eq 4-17}
\]

Subject to

\[
\begin{align*}
\nabla c_i(x_k)^T d + c_i(x_k) &= 0 \\
\nabla c_i(x_k)^T d + c_i(x_k) &\leq 0
\end{align*}
\]

Where

\( d \) is the search direction
The solution of the sub-problem can be solved directly using the projection method which is a QP technique. However, it is necessary to search for a feasible point which satisfies all the constraints and conditions before generating the iterative sequence of points which converge to the optimal solution. Once the search direction is found, a new iterates can be formed. This process continues until the optimal solution is found or the iterations reach a pre-defined limit.
4.5 Implementation of MOSA Optimisation

modeFRONTIER® is a design platform built purposely for optimisation task. It is able to couple with other software packages such as CAD/CAE, FEA and CFD software. In this research, the performance prediction model is programmed into Microsoft Excel and coupled with modeFRONTIER®. The optimal solution is obtained by using a Multiple Objective Simulated Annealing (MOSA) optimisation methods.

Figure 4-4 on the next page is a screenshot showing the design optimisation flow chart of modeFRONTIER®. The top column represents the snowboard geometry inputs. These are linked to the Excel node which contains the performance prediction model. The DOE (Design of Experiment) node provides different design strategies and iterative techniques. Factorial DOE is used for the initial design in the current research. The MOSA (Multiple Objective Simulated Annealing) node represents the optimisation methods.

Simulated Annealing is a method designed to search for the globally optimal solution. According to Granville et al. [23], “the probability of finding the global optimal solution using the Simulated Annealing technique for a finite problem can theoretically approach one when the annealing schedule is extended to infinity.” In other words, the global solution can always be found when the number of iteration is unlimited. This implies that the accuracy of the approximation solution generated by Simulated Annealing depends on the number of iterations. In this study, the number of iterations of 1500 is used.

The outputs from the Excel node represent the nine subjective performance parameters. Each of the nodes is bounded by the performance parameter constraints defined by the user. Finally, the objective node contains the objective function defined in Eq 4-13. It is linked to the objective13 node for the optimisation calculation.
Figure 4-4 - design optimisation flow chart in the modeFRONTIER® environment
4.6 Case Studies

In this section, we explore three case studies on snowboard design optimisation. Two sets of results are generated by SQP and MOSA for each of the cases respectively. The same structural properties and design constraints are applied across the three case studies for comparison purposes. Due to the consideration of computational cost, the snowboard geometry optimisation is also restricted to twin board design. Moreover, the iteration setting of MOSA is set to the 1500 limit. The step size of the design parameters is also introduced to shorten the iteration process. Table 4-1 below shows an example of the geometry design constraints.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design parameters</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$</td>
<td>Projected Length</td>
<td>1500 mm</td>
<td>1700 mm</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Contact Length</td>
<td>1100 mm</td>
<td>1300 mm</td>
</tr>
<tr>
<td>$L_h$</td>
<td>Heel Length</td>
<td>175 mm</td>
<td>225 mm</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Shovel Length</td>
<td>175 mm</td>
<td>225 mm</td>
</tr>
<tr>
<td>$b_m$</td>
<td>Wrist Width</td>
<td>220 mm</td>
<td>280 mm</td>
</tr>
<tr>
<td>$W_h$</td>
<td>Heel Width</td>
<td>250 mm</td>
<td>350 mm</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Shovel Width</td>
<td>250 mm</td>
<td>350 mm</td>
</tr>
<tr>
<td>$H_f$</td>
<td>Camber Height</td>
<td>0 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>$H_t$</td>
<td>Tail Height</td>
<td>45 mm</td>
<td>65 mm</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Tip Height</td>
<td>45 mm</td>
<td>65 mm</td>
</tr>
<tr>
<td>$R_h$</td>
<td>Average Heel Radius</td>
<td>0</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Average Shovel Radius</td>
<td>0</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$R_{sc}$</td>
<td>Side-cut Radius</td>
<td>0</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$T_h$</td>
<td>Heel Thickness</td>
<td>3 mm</td>
<td>7 mm</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Body Thickness</td>
<td>8 mm</td>
<td>14 mm</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Shovel Thickness</td>
<td>3 mm</td>
<td>7 mm</td>
</tr>
</tbody>
</table>
4.6.1 Case Study 1

In the first case study, the author plans to design a typical Freeride style snowboard. The performance parameters are rated from 1 to 10. A typical Freeride snowboard requires high Edge Grip, Accuracy, Manoeuvrability, Stability and Transition Smoothness to perform different kinds of tricks but average Liveliness and Speed and relatively low Feedback, and Forgiveness. These ratings are used as the user target performances shown in Table 4-2 below.

Table 4-2 – Target Performance of Case Study 1

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Target Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>8</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>9</td>
</tr>
<tr>
<td>Feedback</td>
<td>6</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6</td>
</tr>
<tr>
<td>Liveliness</td>
<td>7</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>8</td>
</tr>
<tr>
<td>Speed</td>
<td>7</td>
</tr>
<tr>
<td>Stability</td>
<td>8</td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 4-5 on the next page shows a radar chart comparing the performances between the target performance (diamond marker with dotted line) and the two sets of optimal solution (Square marker for SQP and triangular maker for MOSA).
Results in Table 4-3 shows that the optimal solutions are very close to the target performances with a maximum of ±0.4 point different except the Feedback which is 1.3 lower than the target of 6.

Table 4-3– Snowboard Performance Results of Case Study 1

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Target Performance</th>
<th>SQP</th>
<th>MOSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>8</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>9</td>
<td>8.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Feedback</td>
<td>6</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6</td>
<td>5.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Liveliness</td>
<td>7</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>8</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Speed</td>
<td>7</td>
<td>7.1</td>
<td>7.1</td>
</tr>
<tr>
<td>Stability</td>
<td>8</td>
<td>8.1</td>
<td>8.1</td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>8</td>
<td>7.6</td>
<td>7.6</td>
</tr>
</tbody>
</table>
The optimisation solvers minimised the objective function to 2.202 with a 0.0006% difference which is shown in Table 4-4 and Figure 4-6.

Table 4-4 - SQP Optimisation of Case Study 1

<table>
<thead>
<tr>
<th>Iter</th>
<th>F-count</th>
<th>f(x)</th>
<th>Max constraint</th>
<th>Line search steplength</th>
<th>Directional derivative</th>
<th>First-order optimality</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27</td>
<td>1.77274</td>
<td>20.75</td>
<td></td>
<td></td>
<td></td>
<td>Infeasible start point</td>
</tr>
<tr>
<td>1</td>
<td>54</td>
<td>5.72181</td>
<td>0.2407</td>
<td>1</td>
<td>0.021</td>
<td>105</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>2</td>
<td>81</td>
<td>4.90598</td>
<td>5.609e-005</td>
<td>1</td>
<td>-1.56</td>
<td>231</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>3</td>
<td>108</td>
<td>3.00088</td>
<td>2.321e-005</td>
<td>1</td>
<td>-0.54</td>
<td>5.08</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>4</td>
<td>136</td>
<td>2.37330</td>
<td>0.106e-005</td>
<td>0.5</td>
<td>-0.486</td>
<td>33</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>5</td>
<td>163</td>
<td>2.6713</td>
<td>7.08e-005</td>
<td>1</td>
<td>-0.405</td>
<td>42.3</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>6</td>
<td>190</td>
<td>2.04653</td>
<td>5.031e-006</td>
<td>1</td>
<td>-0.237</td>
<td>14.5</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>7</td>
<td>217</td>
<td>2.09020</td>
<td>1.401e-005</td>
<td>1</td>
<td>-0.199</td>
<td>15.2</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>8</td>
<td>244</td>
<td>2.04390</td>
<td>1.411e-006</td>
<td>1</td>
<td>-0.0774</td>
<td>9.98</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>9</td>
<td>271</td>
<td>2.13713</td>
<td>0.0001678</td>
<td>1</td>
<td>-0.0334</td>
<td>94.4</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>10</td>
<td>298</td>
<td>2.13713</td>
<td>0.0001678</td>
<td>1</td>
<td>-0.0375</td>
<td>14.5</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>11</td>
<td>326</td>
<td>2.40240</td>
<td>0.00005735</td>
<td>0.5</td>
<td>-0.0391</td>
<td>47.2</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>12</td>
<td>354</td>
<td>2.36772</td>
<td>0.000052</td>
<td>0.5</td>
<td>-0.0393</td>
<td>56.8</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>13</td>
<td>381</td>
<td>2.25971</td>
<td>0.01156</td>
<td>1</td>
<td>-0.0323</td>
<td>45.4</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>14</td>
<td>408</td>
<td>2.21849</td>
<td>0.000126</td>
<td>1</td>
<td>-0.0316</td>
<td>42.8</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>15</td>
<td>435</td>
<td>2.20779</td>
<td>0.0067e-007</td>
<td>1</td>
<td>-0.163</td>
<td>10.4</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>16</td>
<td>462</td>
<td>2.20382</td>
<td>1.420e-008</td>
<td>1</td>
<td>-0.0209</td>
<td>0.0376</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>17</td>
<td>489</td>
<td>2.20382</td>
<td>1.420e-008</td>
<td>1</td>
<td>-0.00107</td>
<td>0.0746</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>18</td>
<td>516</td>
<td>2.20313</td>
<td>0.00003134</td>
<td>1</td>
<td>-0.00107</td>
<td>1.3</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>19</td>
<td>543</td>
<td>2.20302</td>
<td>3.722e-005</td>
<td>1</td>
<td>-0.000056</td>
<td>0.702</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>20</td>
<td>570</td>
<td>2.20156</td>
<td>6.014e-006</td>
<td>1</td>
<td>-0.000056</td>
<td>0.0597</td>
<td>Hessian modified</td>
</tr>
<tr>
<td>21</td>
<td>597</td>
<td>2.20155</td>
<td>2.975e-008</td>
<td>1</td>
<td>-0.0000352</td>
<td>0.0165</td>
<td>Hessian modified</td>
</tr>
</tbody>
</table>

Figure 4-6 – MOSA Optimisation of Case Study 1
Although the optimal performances generated by the solvers are identical, the snowboard geometry results are very different. This is because each of the snowboard design parameters has its own positive or negative contribution to particular performance parameters. If one of the design parameters is changed, it affects all the performance ratings in certain amount. As a result, other design parameters are needed to be adjusted to compensate the gain or loss of those particular performance parameters. It implies that there are multiple combinations of snowboard geometries that could generate snowboards with similar performance. For instance, MOSA tends to generate a longer board and compensates ability to turn by having a deeper side-cut. On the other hand, SQP suggests a shorter and slimmer board with slightly higher camber and less aggressive side-cut. Depending on the riders’ body and riding style, further user-defined constraints can be applied to guide the snowboard geometry to the final design product.

Table 4-5 – Snowboard Geometry Results of Case Study 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design parameters</th>
<th>SQP</th>
<th>MOSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$</td>
<td>Projected Length</td>
<td>1577 mm</td>
<td>1679 mm</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Contact Length</td>
<td>1185 mm</td>
<td>1265 mm</td>
</tr>
<tr>
<td>$L_h$</td>
<td>Heel Length</td>
<td>196 mm</td>
<td>207 mm</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Shovel Length</td>
<td>196 mm</td>
<td>207 mm</td>
</tr>
<tr>
<td>$b_m$</td>
<td>Wrist Width</td>
<td>255 mm</td>
<td>245 mm</td>
</tr>
<tr>
<td>$W_h$</td>
<td>Heel Width</td>
<td>303 mm</td>
<td>320 mm</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Shovel Width</td>
<td>303 mm</td>
<td>320 mm</td>
</tr>
<tr>
<td>$H_f$</td>
<td>Camber Height</td>
<td>12 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>$H_h$</td>
<td>Tail Height</td>
<td>65 mm</td>
<td>57 mm</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Tip Height</td>
<td>65 mm</td>
<td>57 mm</td>
</tr>
<tr>
<td>$R_{h}$</td>
<td>Average Heel Radius</td>
<td>250 mm</td>
<td>264 mm</td>
</tr>
<tr>
<td>$R_{s}$</td>
<td>Average Shovel Radius</td>
<td>250 mm</td>
<td>264 mm</td>
</tr>
<tr>
<td>$R_{sc}$</td>
<td>Side-cut Radius</td>
<td>7170 mm</td>
<td>5190 mm</td>
</tr>
<tr>
<td>$T_h$</td>
<td>Heel Thickness</td>
<td>4 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Body Thickness</td>
<td>14 mm</td>
<td>13 mm</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Shovel Thickness</td>
<td>4 mm</td>
<td>4 mm</td>
</tr>
</tbody>
</table>
4.6.2 Case Study 2

In the second case study, the author designs a high speed snowboard which has to be very stable and have good edge grip. Therefore, the target performances for this board will be high Speed, Stability, Edge Grip and Accuracy and average Manoeuvrability, Transition Smoothness and relatively low Liveliness, Forgiveness and Feedback. The Target performances parameters are show in Table 4-6 below.

Table 4-6 – Target Performance of Case Study 2

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Target Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>9</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>9</td>
</tr>
<tr>
<td>Feedback</td>
<td>5</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6</td>
</tr>
<tr>
<td>Liveliness</td>
<td>6</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>7</td>
</tr>
<tr>
<td>Speed</td>
<td>10</td>
</tr>
<tr>
<td>Stability</td>
<td>10</td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>7</td>
</tr>
</tbody>
</table>

The optimised results are shown in Figure 4-7 and Table 4-7 on the next page. Although the Speed and Stability performance do not reach to the value of 10, the optimal solutions closely follow the pattern of the target performances except for Transition Smoothness which is 2 points higher than the target of 7. Similar to case study 1, both methods minimised the objective function value to 8.590 which is almost identical to each other with a 0.0014% difference. The optimal solutions for snowboard performances are also identical.
Figure 4-7 – Performance Optimisation Result of Case Study 2

Table 4-7 – Snowboard Performance Result of Case Study 2

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Target Performance</th>
<th>SQP</th>
<th>MOSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>9</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>9</td>
<td>9.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Feedback</td>
<td>5</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Liveliness</td>
<td>6</td>
<td>6.6</td>
<td>6.6</td>
</tr>
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Table 4-8 - SQP Optimisation of Case Study 2

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<th>Infeasible start point</th>
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</table>

Figure 4-8 – MOSA Optimisation of Case Study 2
Table 4-9 below shows the geometry of the high speed snowboard optimisation of case study 2. As discussed in case study 1, the optimisation solvers intended to match the target performances by adjusting the design parameters. There are different combinations of design parameters to compensate each other to achieve similar performance. In this case, with almost the same contact lengths, SQP generates a 29mm longer board by increasing the length of the heel and the shovel. Combined with the shallow side-cut radius 14540mm, it creates a stable and high speed snowboard. On the other hand, MOSA creates a shorter board. It achieves the high speed by having a slimmer body and a lower the camber height which also helps stabilising the board.

Table 4-9 – Snowboard Geometry Result of Case Study 2

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design parameters</th>
<th>SQP</th>
<th>MOSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$</td>
<td>Projected Length</td>
<td>1579 mm</td>
<td>1550 mm</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Contact Length</td>
<td>1187 mm</td>
<td>1190 mm</td>
</tr>
<tr>
<td>$L_h$</td>
<td>Heel Length</td>
<td>196 mm</td>
<td>180 mm</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Shovel Length</td>
<td>196 mm</td>
<td>180 mm</td>
</tr>
<tr>
<td>$b_m$</td>
<td>Wrist Width</td>
<td>266 mm</td>
<td>238 mm</td>
</tr>
<tr>
<td>$W_h$</td>
<td>Heel Width</td>
<td>290 mm</td>
<td>275 mm</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Shovel Width</td>
<td>290 mm</td>
<td>275 mm</td>
</tr>
<tr>
<td>$H_f$</td>
<td>Camber Height</td>
<td>12 mm</td>
<td>7 mm</td>
</tr>
<tr>
<td>$H_t$</td>
<td>Tail Height</td>
<td>63 mm</td>
<td>56 mm</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Tip Height</td>
<td>63 mm</td>
<td>56 mm</td>
</tr>
<tr>
<td>$R_h$</td>
<td>Average Heel Radius</td>
<td>243 mm</td>
<td>228 mm</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Average Shovel Radius</td>
<td>243 mm</td>
<td>228 mm</td>
</tr>
<tr>
<td>$R_{sc}$</td>
<td>Side-cut Radius</td>
<td>14540 mm</td>
<td>9440 mm</td>
</tr>
<tr>
<td>$T_h$</td>
<td>Heel Thickness</td>
<td>4 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Body Thickness</td>
<td>14 mm</td>
<td>12 mm</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Shovel Thickness</td>
<td>4 mm</td>
<td>5 mm</td>
</tr>
</tbody>
</table>
4.6.3 Case Study 3

In the third case study, the author designs a snowboard with high manoeuvrability, low speed and stability. The target performance ratings for this board are high Manoeuvrability, Liveliness and Forgiveness; average Edge Grip and Accuracy and Feedback and Transition Smoothness; and low Speed and Stability.

Table 4-10 – Target Performance of Case Study 3

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<td>Accuracy</td>
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<tr>
<td>Edge Grip</td>
<td>7</td>
</tr>
<tr>
<td>Feedback</td>
<td>7</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>8</td>
</tr>
<tr>
<td>Liveliness</td>
<td>8</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>9</td>
</tr>
<tr>
<td>Speed</td>
<td>6</td>
</tr>
<tr>
<td>Stability</td>
<td>6</td>
</tr>
<tr>
<td>Transition Smoothness</td>
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</tbody>
</table>

The results are shown in Figure 4-9 and Table 4-11 on the next page. Most of the performances managed to match the targets with a maximum difference of ±0.5 point. However, the largest difference between the target performance and solutions are Manoeuvrability, Forgiveness and Feedback with 1.4, 1.3 and 2.1 points of margin which is higher than case studies 1 and 2.
Table 4-11 also shows the performance between the results of the optimisation methods are very close to each other within ±0.1 difference.

Table 4-11 – Snowboard Performance Result of Case Study 3

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Target Performance</th>
<th>SQP</th>
<th>MOSA</th>
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</thead>
<tbody>
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</tr>
<tr>
<td>Edge Grip</td>
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<td>6.7</td>
<td>6.8</td>
</tr>
<tr>
<td>Feedback</td>
<td>7</td>
<td>4.9</td>
<td>4.9</td>
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<tr>
<td>Forgiveness</td>
<td>8</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Liveliness</td>
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<td>7.6</td>
<td>7.6</td>
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<tr>
<td>Manoeuvrability</td>
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<tr>
<td>Speed</td>
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<td>Transition Smoothness</td>
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</table>
There are three main factors that affect the performance of the solution.

- The optimal designs are bounded by many design constraints
- There are direct relationships between performance parameters
- The performance parameters are also affected by the material properties

Therefore, the gap between the target and the solution can be reduced by adjusting the design constraints and stiffness properties of the board.

Table 4-12 and Figure 4-10 show that the values of the objective function generated by the solvers are slightly different, MOSA obtains 8.739 while SQP returned 8.723 which is 0.19% smaller. This implies that the snowboard designed by SQP optimisation is slightly closer to the target performance expected by the user than that of MOSA.

Table 4-12 - SQP Optimisation of Case Study 3

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<th>Max constraint</th>
<th>Line search steplength</th>
<th>Directional derivative</th>
<th>First-order optimality</th>
<th>Procedure</th>
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</table>
Table 4-13 on the next page shows the result of the optimal design for case study 3. Compared to the high speed board in case study 2, both the designs in this case have much deeper side-cuts which greatly contributes to the ability to turn and manoeuvre. On one hand, SQP creates a slimmer board (30-40mm narrower along the centre of the board). The higher tail and tip height also assists riders to turn and lower the overall speed. On the other hand, MOSA generates a much shorter board (63mm shorter) to reduce the moment of inertia to improve manoeuvrability. It also has deeper side-cuts and a stiffer body to assist with the ability to turn. The overall wider board also reduces the speed performance.
### Table 4-13 – Snowboard Geometry Result of Case Study 3

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design parameters</th>
<th>SQP</th>
<th>MOSA</th>
</tr>
</thead>
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<tr>
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<td>Projected Length</td>
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<td>1515 mm</td>
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<td>Contact Length</td>
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<td>Heel Length</td>
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<td>175 mm</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Shovel Length</td>
<td>196 mm</td>
<td>175 mm</td>
</tr>
<tr>
<td>$b_m$</td>
<td>Wrist Width</td>
<td>253 mm</td>
<td>280 mm</td>
</tr>
<tr>
<td>$W_h$</td>
<td>Heel Width</td>
<td>309 mm</td>
<td>350 mm</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Shovel Width</td>
<td>309 mm</td>
<td>350 mm</td>
</tr>
<tr>
<td>$H_f$</td>
<td>Camber Height</td>
<td>4 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>$H_h$</td>
<td>Tail Height</td>
<td>53 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Tip Height</td>
<td>53 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>$R_h$</td>
<td>Average Heel Radius</td>
<td>253 mm</td>
<td>263 mm</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Average Shovel Radius</td>
<td>253 mm</td>
<td>263 mm</td>
</tr>
<tr>
<td>$R_{sc}$</td>
<td>Side-cut Radius</td>
<td>6130 mm</td>
<td>4690 mm</td>
</tr>
<tr>
<td>$T_h$</td>
<td>Heel Thickness</td>
<td>7 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Body Thickness</td>
<td>8 mm</td>
<td>13 mm</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Shovel Thickness</td>
<td>7 mm</td>
<td>6 mm</td>
</tr>
</tbody>
</table>
4.7 Conclusions

In this chapter, we have presented the concept of snowboard design optimisation using the performance prediction model in reverse. Instead of entering snowboard geometry to predict snowboard performance, this study enabled users to search for an optimal snowboard design solution based on personal preferences of performance. These preferences included target performances, user-defined design constraints and material properties.

The objective function of the optimisation task was formulated by Least Squares Methods. It represents the “residual” or “error” between the user’s target performances and the predicted performances. The goal of the optimisation task was to minimise the objective function while satisfying all three types of design constraints. These constraints included user-defined geometry constraints, physical design constraints and performance parameters constraints.

Three case studies have been conducted in this research. The solutions were obtained from two different optimisation methods, SQP and MOSA, which were implemented through Matlab® and modeFRONTIER® respectively. It was found that the minimised objective functions obtained from the two methods were almost identical with a maximum difference of 0.019% in case study 3. The optimal performance solutions were also very close to each other with less than ±0.1 point of margin out of the performance rating of 10.

For a typical Freeride snowboard design in case study 1, both optimisation methods managed to match the target performances with a maximum different of ±0.4 point except the feedback performance which was is 1.3 lower than the target of 6. It had the smallest objective function of 2.02 of the three case studies, meaning the solutions were very close to the target performance. Case study 2 focused on a high speed snowboard design with an objective function of 8.590. Although the Speed and Stability performance did not reach 10, the optimal solutions closely followed the pattern of the target performances except the Transition Smoothness which was 2 points higher than the target of 7. A high manoeuvrability snowboard was designed
in Case study 3. Results showed that most of the performances were matched to the
targets within $\pm 0.5$ point. However, the largest difference for Manoeuvrability,
Forgiveness and Feedback went up to 1.4, 1.3 and 2.1 points of error which was
higher than the case studies 1 and 2. An objective function of 8.739 was achieved by
MOSA and 8.723 by SQP.

Although the objective function and optimal performance obtained from the two
solvers were almost identical, the final snowboard geometries were very different.
The solvers were able to search for different combinations of the snowboard design
under the same design constraints to achieve similar performance and characteristics.

In each of the three case studies, the SQP optimisation obtained better results, i.e.
slightly smaller objective function values in all cases, than MOSA. The optimisation
performance of MOSA depends on the number of iterations. Due to the consideration
of computational cost, the iteration count was limited to 1500. Moreover, the
geometric parameters contain steps which further limit the optimisation performance.
For instance, the minimum step for contact length is limited to 5mm while the step is
0.5mm for the thickness parameters.

There were several factors affecting the overall performance of the solution.

- The Optimal designs were bounded by design constraints
- There were direct relationships between performance parameters
- The performance parameters were affected by the material properties

Therefore, the gap between the target and the solution could be reduced by adjusting
the design constraints and stiffness properties of the board based on user’s height and
weight as well as the riding style.
Chapter 5

Results and Validation

5.1 Introduction

This chapter presents the method and process of validating the results in this research. Two snowboard experts were interviewed and invited to participate in the validation program. They are a head coach of snowboard association and BC Development Team in Canada; and a senior snowboard instructor of a snowboard centre at Falls Creek in Victoria Australia and Myoko Snowsports in Japan.

5.2 Method and Procedure

The snowboard experts received a set of documents which included:

- A PowerPoint summary of the current research which includes the objectives and development. It allowed the experts to get familiar with the project. (Appendix A.1)
- The procedure of the validation procedure. (Appendix A.2)
- Description of all the pre-defined performance parameters (Appendix A.3)
- Description and graphical illustration of all the custom snowboard design parameters defined in this research (Appendix A.4)
- Snowboard performance rating and measurement form (Appendix A.5)

After the snowboard experts fully understood the validation process, they were required to select a set of snowboards that suited their riding styles. The snowboards were then chosen for the validation with the following criteria:

- Snowboards are true twin boards or directional twin boards
- Snowboards are commercial products without modification or customisation
- Snowboards have zero or positive camber
- Snowboards have a sandwich composite structure
- The upper and lower laminate are constructed by Bi-axial Fiberglass

Two snowboards with different style were selected for validation. They are a Freestyle board and an All-Mountain board. These snowboards were tested on snow by the experts multiple times until they are comfortable and familiar with the boards.

After the on snow field tests, the experts reviewed and rated the performance and feel of the snowboards based on their riding experience. The board dimensions and structural material details were obtained from the snowboard manufacturer, direct measurement of the experts as well as published data from Clifton research [11]. These data were recorded in the snowboard performance rating and board dimension form which was provided in the document package.

The recorded data were used to compare and validate with the research results in four main areas. It included validation of the thickness distribution model, continuous snowboard stiffness estimation, snowboard performance prediction and design optimisation. The last two areas are closely related. They will be presented and discussed together.
5.3 Thickness Distribution

Figure 5-1 and Figure 5-2 below show the comparison between the thickness distribution model and measured data of the two test boards. The solid lines represent the estimation of the thickness distribution model.

![Freestyle Test Board Thickness Distribution](image1)

Figure 5-1 – Comparison between thickness distribution model and measured data of Freestyle test board, \( \delta = 0.03, \varnothing = 0.41 \)

![All-Mountain Test Board Thickness Distribution](image2)

Figure 5-2 – Comparison between thickness distribution model and measured data of All-Mountain test board, \( \delta = 0.04, \varnothing = 0.44 \)

The two custom parameters \( \delta \) and \( \varnothing \) are optimised to minimise the average estimation error. The parameter \( \delta \) represents the distribution slope from the snowboard heel/shovel to the body while the parameter \( \varnothing \) represents the position where the
thickness transitions from the snowboard heel/shovel to the body. It can be observed that the transition of the All-Mountain board thickness from end to centre is steeper than the Freestyle board. It leads to a higher $\delta$. On the other hand, the thickness of the All-Mountain board’s body extends further away from the centre than that of the Freestyle board. Thus, it has a higher $\varnothing$.

Figure 5-3 and Figure 5-4 below show the errors in percentage of the comparison. The majority of the errors of the Freestyle board are between $\pm 5\%$ except the point at 500mm forward from the board centre and two points at the heel end which have a maximum of 12% error. The estimation of the All-Mountain board has less error. All except one of the data points lies within $\pm 5\%$ error. The maximum error of 8.7% is found at 650mm backward from the board centre.

![Freestyle Test Board Thickness Distribution Error](image)

**Figure 5-3 – Freestyle Test Board Thickness Distribution Error**

![All-Mountain Test Board Thickness Distribution Error](image)

**Figure 5-4 – All-Mountain Test Board Thickness Distribution Error**
5.4 Stiffness Estimation

Figure 5-5 and Figure 5-6 compare the difference of bending stiffness between measured data and estimated date generated by the stiffness distribution model while
Figure 5-7 and Figure 5-8 compare the torsional stiffness of the two test boards.

It is found that the stiffness data tends to underestimate the stiffness of the snowboard body and overestimate the heel and shovel on both test boards. This is because sidewall construction of the board body is different at both ends as has been discussed. The current stiffness distribution model assumed the sidewall to be a 90° construction.
Figure 5-9 and Figure 5-10 show the errors in percentage of stiffness model for each of the test boards respectively. The estimation errors of the Freestyle board are within ±10% while the majority of errors for the All-Mountain board are less than 10% with a maximum 12% at both ends. It is found that both bending and torsional stiffness errors are very close to each other and have a similar pattern along both boards except the transition area between boards’ body and shovel/heel.

![Freestyle Test Board Stiffness Distribution Error](image)

**Figure 5-9 – Freestyle Test Board Stiffness Distribution Error**

![All-Mountain Test Board Stiffness Distribution Error](image)

**Figure 5-10 – All-Mountain Test Board Bending Stiffness Distribution Error**
5.5 Snowboard Performance Prediction and Design Optimisation

5.5.1 Freestyle Test Board

Figure 5-11 below show the comparison between three set of performances. The experts’ rating is obtained based on the riding experience of the snowboard experts after the on-snow field tests. The Prediction model represents the results generated from the snowboard performance prediction model with real measured data input. Optimisation represents the results generated from design optimisation model that coincides with the experts’ rating.

Figure 5-11 – Freestyle Test Board Performance Prediction and Design Optimisation
According to the experts’ rating, the Freestyle test board is characterised by a very high edge grip and relatively high accuracy, manoeuvrability, speed, stability and transition smoothness. It is average in liveliness and forgiveness, and lacks feedback. The prediction model has estimated a set of performance that is close to the experts’ rating. Most of the performance parameters have errors of within ±0.5 points. The edge grip and feedback errors are within ±1.5 points. The results of performance prediction and design optimisation are also presented in Table 5-1 below.

Table 5-1 – Snowboard Performance Result of Freestyle Test Board

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Target Performance</th>
<th>Performance Prediction</th>
<th>Optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>8</td>
<td>7.8</td>
<td>8.4</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>9</td>
<td>7.6</td>
<td>8.6</td>
</tr>
<tr>
<td>Feedback</td>
<td>3</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6</td>
<td>6.6</td>
<td>5.9</td>
</tr>
<tr>
<td>Liveliness</td>
<td>7</td>
<td>6.8</td>
<td>6.9</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>8</td>
<td>7.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Speed</td>
<td>8</td>
<td>7.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Stability</td>
<td>8</td>
<td>7.2</td>
<td>8.2</td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>8</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>Overall Performance</td>
<td>7.2</td>
<td>7.1</td>
<td>7.4</td>
</tr>
</tbody>
</table>

The design optimisation model is able to match the target performance with the experts’ performance ratings. The iterative process of the design optimisation is presented in Table 5-2 on the next page. It minimised the objective function down to 2.67. Most of the optimised results have errors less than ±0.4 points except for the feedback which has an error of 1.5.
Table 5-2 - SQP Optimisation of Freestyle Test board

<table>
<thead>
<tr>
<th>Iter</th>
<th>F-count</th>
<th>f(x)</th>
<th>Max constraint</th>
<th>Line search steplength</th>
<th>Directional derivative</th>
<th>First-order optimality</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27</td>
<td>3.44410</td>
<td>30.75</td>
<td></td>
<td></td>
<td>Infesible start point</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>64</td>
<td>10.8801</td>
<td>0.2508</td>
<td>1</td>
<td>-0.0212</td>
<td>722</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>81</td>
<td>6.47968</td>
<td>0.60023972</td>
<td>1</td>
<td>-0.05</td>
<td>1.33e-003</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>2.70975</td>
<td>0.909e-007</td>
<td>1</td>
<td>-0.45</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>117</td>
<td>2.67117</td>
<td>1.649e-005</td>
<td>0.15</td>
<td>-0.024</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>164</td>
<td>2.67023</td>
<td>1.015e-007</td>
<td>1</td>
<td>-0.0266</td>
<td>0.532</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>191</td>
<td>2.67028</td>
<td>1.856e-011</td>
<td>1</td>
<td>-0.00131</td>
<td>0.0203</td>
<td></td>
</tr>
</tbody>
</table>

Optimisation terminated: directional derivative predicts change in objective value less than options.TolFun and maximum constraint violation is less than options.TolCon.
No active inequalities.
Objective Function : 2.670

Table 5-3 below shows the snowboard dimensions generated by the optimisation model. It should be noted that the optimised board dimensions do not necessarily have to be the same or similar to the test board dimensions because the same set of performance conditions can be achieved by various combinations of board dimensions.

Table 5-3 – Snowboard Geometry Results of Freestyle Test Board

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design parameters</th>
<th>Board Dimension</th>
<th>Optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$</td>
<td>Projected Length</td>
<td>1547 mm</td>
<td>1577 mm</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Contact Length</td>
<td>1247 mm</td>
<td>1185 mm</td>
</tr>
<tr>
<td>$L_h$</td>
<td>Heel Length</td>
<td>150 mm</td>
<td>196 mm</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Shovel Length</td>
<td>150 mm</td>
<td>196 mm</td>
</tr>
<tr>
<td>$b_m$</td>
<td>Wrist Width</td>
<td>255 mm</td>
<td>254 mm</td>
</tr>
<tr>
<td>$W_h$</td>
<td>Heel Width</td>
<td>298 mm</td>
<td>307 mm</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Shovel Width</td>
<td>298 mm</td>
<td>307 mm</td>
</tr>
<tr>
<td>$H_f$</td>
<td>Camber Height</td>
<td>10 mm</td>
<td>7 mm</td>
</tr>
<tr>
<td>$H_h$</td>
<td>Tail Height</td>
<td>41 mm</td>
<td>56 mm</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Tip Height</td>
<td>42 mm</td>
<td>56 mm</td>
</tr>
<tr>
<td>$R_h$</td>
<td>Average Heel Radius</td>
<td>150 mm</td>
<td>175 mm</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Average Shovel Radius</td>
<td>150 mm</td>
<td>175 mm</td>
</tr>
<tr>
<td>$R_{sc}$</td>
<td>Side-cut Radius</td>
<td>7900 mm</td>
<td>6142 mm</td>
</tr>
<tr>
<td>$T_h$</td>
<td>Heel Thickness</td>
<td>5 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Body Thickness</td>
<td>10 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Shove Thickness</td>
<td>5 mm</td>
<td>4 mm</td>
</tr>
</tbody>
</table>
The optimised solution suggested a longer board with the combination of longer shovel and heel but a shorter contact length. The reduction of contact length would generally decrease the speed and increase manoeuvrability but it is balanced by lowering of the camber height. Similarly, increasing the shovel length and heel length would result in lower manoeuvrability but it is balanced by reducing the side-cut radius. As a result, the overall performance of the optimised board will be matched with the experts’ rating which can be used as target performance of snowboard designers or enthusiasts who want to customise their own board.

5.5.2 All-Mountain Test Board

The second test board is an All-Mountain snowboard. It has average all-round performance featuring a higher transition smoothness and lower feedback. The results of the performance prediction and design optimisation are shown in Figure 5-12 and Table 5-4.

![All-Mountain Test Board Performance Prediction and Design Optimisation](image)

Figure 5-12 – All-Mountain Test Board Performance Prediction and Design Optimisation
Table 5-4 – Snowboard Performance Result of All-Mountain Test Board

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Target Performance</th>
<th>Performance Prediction</th>
<th>Optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>7</td>
<td>7.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>6</td>
<td>7.3</td>
<td>6.8</td>
</tr>
<tr>
<td>Feedback</td>
<td>4</td>
<td>4.3</td>
<td>4.5</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6</td>
<td>6.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Liveliness</td>
<td>6</td>
<td>6.6</td>
<td>6.9</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>7</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Speed</td>
<td>7</td>
<td>8.1</td>
<td>7.3</td>
</tr>
<tr>
<td>Stability</td>
<td>7</td>
<td>6.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>8</td>
<td>8.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Overall</td>
<td>6.4</td>
<td>7.1</td>
<td>6.8</td>
</tr>
</tbody>
</table>

The prediction model is able to estimate the snowboard performance accurately within ±0.8 points except the results of edge grip and speed which are 1.3 and 1.1 higher than the experts’ rating respectively. It is found that the prediction model slightly overestimates the overall performance of the board.
The iterative process of the design optimisation for the All-Mountain test board is presented in Table 5-5.

Table 5-5 - SQP Optimisation of All-Mountain Test board

<table>
<thead>
<tr>
<th>Iter</th>
<th>F-count</th>
<th>f(x)</th>
<th>Max constraint</th>
<th>Line search</th>
<th>Directional</th>
<th>First-order</th>
<th>Infesable start point</th>
</tr>
</thead>
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<tr>
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</tr>
<tr>
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<td>6.278e-005</td>
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<td></td>
</tr>
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<td>-0.193</td>
<td>97.9</td>
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</tr>
<tr>
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<td>-0.102</td>
<td>95.6</td>
<td></td>
</tr>
<tr>
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<td>-0.405</td>
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Optimisation terminated: directional derivative predicts change in objective value less than options.TolFun and maximum constraint violation is less than options.TolCon.

Active inequalities (to within options.TolCon = 1e-008):

Lower Upper IneqLin IneqMonot

6 14
15
16
17
19
23
26

Objective Function: 3.210

The SQP optimisation solver minimised the objective function to 3.23 which is higher than the previous case. It means the optimised performance parameters of the Freestyle board are closer to the target performances than the All-Mountain board. It is found that most of the optimised results have errors less than ±0.6 points except the edge grip and forgiveness which have errors of 0.8 and 1.0 respectively.
Despite the higher objective function, Table 5-6 shows that the optimised board dimensions are relatively close to the All-Mountain test board as compared to the Freestyle board. The project length, contact length and three major widths are close to the original board. The major differences include smaller side-cut radius which is reduced from 8220mm to 6577mm to increase manoeuvrability. Longer shovel and heel length are used to increase stability and speed of the board and an overall thinner board balances the reduction of side-cut radius. As discussed in the previous section, the board dimensions compensate with each other to achieve similar performance.

Table 5-6 – Snowboard Geometry Results of All-Mountain Test Board

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</table>
5.6 Conclusions

In this chapter, the author has presented the method and procedure of validating the research results. A series of on-snow field tests of two selected snowboard were performed by two snowboard expert volunteers.

The comparison of board thickness shows that the thickness distribution model matches well with the measured data. The majority of errors on both test boards stay within ±5%. The 12% and 8.7% maximum errors are found at locations close to both ends of the Freestyle board and the All-Mountain board respectively.

The thickness distribution model is incorporated into the sandwich composite structural model [11] to estimate the continuous stiffness distribution along a snowboard. The result shows that the estimation errors of the Freestyle board are within ±10% while the majority of errors for the All-Mountain board are less than ±10% with a maximum error of 12% at both ends. It is also found that both bending and torsional stiffness errors are very close to each other and have a similar pattern along both boards except in the transition area between the boards’ body and shovel/heel.

The experts’ performance ratings on the test boards have been compared with the performance prediction model as well as the design optimisation model. Most of the performance prediction parameters have errors less than ±0.5 to ±0.8 points although some of the targets parameters, such as edge grip, feedback and speed for particular board, have errors of ±1.1 to ±1.5. It is also found that the prediction model slightly overestimates the overall performance of both test boards.
Chapter 6
Parametric Snowboard Design Platform

6.1 Introduction

There is a need for a user-centred design platform that solely focuses on customised snowboard design without engineering background and complex mathematical calculation. There are various 3D modelling programs and software packages available in the market. The most popular CAD/CAM engineering software such as Pro/Engineer®, AutoCAD®, CATIA® and SolidWorks® are widely used in product design and manufacturing industries. However, there are some disadvantages using commercial software packages for those who want to design or customise snowboards.

- Professional CAD/CAM modelling software licence are too costly for individual use and custom design projects.
- They require a significant amount of CAD drawing skill or training to be used.
- System requirements for these packages run on the personal computer are relatively demanding especially for graphical display hardware.
- These software packages do not provide snowboard design features such as performance prediction, stiffness distribution estimation and performance optimisation.
- The flexibility of coupling the commercial software with other custom design programs is very limited.

As a result, the current study has developed a user-centred snowboard design platform especially for snowboard enthusiasts to overcome the problems of using professional CAD/CAM software packages.

In this chapter, we present the architecture of the custom built snowboard design platform, the development of interactive virtual reality visualisation and explain the features of the graphical user interface.
6.2 Design Platform Structure

The parametric snowboard design platform has two main functions which are implemented in two modes shown in Figure 6-1 and Figure 6-2.

- **Design and Customisation** – allow a user to manually design, customise and personalise a snowboard; select material properties; predict customised snowboard performance; estimate the stiffness distribution.
- **Design Optimisation** – allows a user to choose the target performance; select material properties; define design constraints; search for an optimal design snowboard solution; predict the optimised snowboard performance; estimate the stiffness distribution.

Figure 6-1 shows the architecture of the design platform in design and customisation mode. It consists of nine different modules.

![Diagram of Design Platform](image)

**Figure 6-1 – The Architecture of Design and Customisation Mode**

The graphical user interface (GUI) control panel provides interactive controls to the parametric snowboard and allows a user to adjust design parameters and material properties through the handles and editors. The design parameters are transferred to the parametric modelling module to generate a snowboard model template in real time. It is then visualised in a virtual reality environment via the Cortona3D viewer with the
support of VRML Automation and JavaScript. Combined with the material properties, the on-snow performance of the customised board can be predicted through the performance prediction model. At the same time, the bending and torsion stiffness distribution along the board can also be estimated.

Figure 6-2 shows the structure of the design platform in design optimisation mode.

In the optimisation mode, the user enters the desired target performances, board material properties and design constraints such as board dimensions through the control panel. This information will then transfer to the optimisation solvers, Matlab® and/or modeFRONTIER®, to search for an optimal design snowboard that best fits the target performances through SQP and MOSA. The user can further refine the design constraints manually to fine tune the result. The material properties and dimensions of the optimised board are also used to generate the 3D model and to estimate the board stiffness.
6.3 VRML Visualisation

In order to preview the final product of a customised design snowboard in a virtual interactive environment, VRML is introduced to visualise the snowboard parametric model. It is capable of creating vertices and edges for a 3D model along with the visualisation features that is suitable for this research.

The advantages of using VRML for the parametric model visualisation are as follows.

- No licence is required for custom research application development
- It supports VRML Automation and JavaScript for developing interactive control functionality
- It is accessible by most operating systems
- It is suitable for mass distribution project
- The program source is very compact and efficient on computational cost consideration.
- A VRML model is interchangeable with the majority of CAD/CAM software.
- The custom designed board can be exported to specify file type and transfer to CNC machine for manufacturing.

The figures below show the actual VRML snowboard model in a 3D environment in a typical web browser. The user is able to visualise the changes of the model in real time by altering the design parameters. As an example in Figure 6-3, the user is manipulating the dimension of the waist width indicated by the arrows while the other major dimensions are fixed except the side-cut radius which is governed by the contact length, shovel/heel width and waist width. Similarly, Figure 6-4 shows another example of changing the shovel height without altering the shovel length but the vertical shovel radius.
Although VRML is a compact and powerful 3D modelling tool, it required extra support to be developed as a standalone application. In this research, we employ the open license Cortona3D viewer to visualise the VRML model and embed the 3D modelling environment into the design platform with the support VRML Automation.

The Cortona3D viewer was developed by Parallel Graphics Ltd. It was developed as a VRML plug-in for popular Internet browsers and office applications. The improved application programming interface allows a researcher to integrate the Cortona engine into a custom built application with the support of ActiveX technology as well as JavaScript.

By using the methods and functions of VRML Automation, this allows external applications to access and manipulate a virtual model in the Cortona3D environment. It also enables a researcher to create and modify VRML models under the control of other GUI development platforms. As a result, the design platform for this thesis incorporates the VRML Automation into the research program in order to extend the capability of VRML 3D modelling and combines it with GUI development software – Visual Basic (VB).
Figure 6-5 and Figure 6-6 below show the interactive control of geometry and texture of the virtual snowboard model in a custom designed GUI environment.

![Figure 6-5](image1.png)  ![Figure 6-6](image2.png)

Figure 6-5 – Changing the Geometry of the Parametric Snowboard Model in Control Panel

![Figure 6-5](image3.png)  ![Figure 6-6](image4.png)

Figure 6-6 – Changing the texture of the Parametric snowboard model surface in Control Panel
6.4 Graphical User Interface

The current research integrates the developed methods and models, such as the parametric virtual snowboard model, stiffness distribution estimation, performance prediction, and design optimisation, into a single user-centred snowboard design platform. A user-friendly graphical user interface is essential to allow users to fully customise, design, and personalise their own snowboard easily by changing the geometry parameters and appearance of the virtual board without CAD drawing skills or complex calculations. The real-time performance prediction and optimisation function also greatly reduce the time and cost for snowboard enthusiasts and snowboard manufacturers to design a new board avoiding the traditional and unproductive trial and error method.

6.4.1 Main Design Control Panel

Figure 6-7 shows the main control panel of the design platform. The virtual snowboard model is displayed on the left hand side. It allows users to preview the final product of design in real-time while altering the dimensions of the board and type of sidewall in the control panel. The control panel consists of track bars, names and values of the design parameters. The nine pre-defined performance parameters and ratings are displayed on the right.
6.4.2 Composite Layer Properties Editor

Figure 6-8 below shows the user interface of the composite layer properties editor. This editor is an optional feature that targets snowboard enthusiasts and designers who would like to fine tune the material properties of each of the snowboard layers. Typical user without such knowledge can simply select retail materials in the market.

![Composite Layer Properties Interface](image)

Figure 6-8 – Composite Layer Properties Interface

It consists of seven sections.

1. A two-dimensional parametric braid pattern on the top left hand corner illustrates the bi-axial angle spacing and size of the tows. The pattern changes in response to the settings.

2. The input properties section below the braid pattern provide inputs boxes for the tows and matrix including Young’s modulus, shear modulus, Poisson’s ratio, density, and thermal expansion coefficients.

3. The Composite layer properties section next to the braid pattern displays the material properties such as Young’s modulus in x and y direction, shear modulus in x-y plane, Poisson’s ratio, density and thermal expansion coefficients of the layer.
4. The fabric configuration section in the middle allows users to change the bi-
axial angle, fabric thickness, fibre packing factor as well as the spacing and
size of the tows.

5. The undulation angle section displays the angle of tows, fibre volume fraction,
and areal fabric weight. A track bar also allows changing of layup angle.

6. The stiffness matrix is shown on the right hand side of the current layer setting.

7. The current setting can be saved as the upper or lower layer of the board.

6.4.3 Laminate Layer Properties Interface

Figure 6-9 below shows the laminate layer properties interface. The lower and upper
composite layer properties are shown on the top based on the setting in the composite
layer tab. Other than the two composite layers, a snowboard sandwich structure
consists of base, core, topsheet and edge. Each of the sections requires inputs of its
material properties which includes Young’s modulus, shear modulus, Poisson’s ratio,
thickness, density and thermal expansion coefficients. The stiffness matrix of each of
the layers will also be determined and displayed on the right hand corner within the
section. Once the setting is completed, the stiffness distribution of the snowboard can
be estimated by using the stiffness matrices of each layer as well as the completed
board dimensions.

![Image of Laminate Layer Properties Interface]

Figure 6-9 – Laminate Layer Properties Interface
6.4.4 Stiffness Distribution

In Figure 6-10, the estimation of the board stiffness estimation is shown on the top while the top-view and side-view 2D drawing of the custom design board are shown at the bottom. The user can examine the board closely by hovering the mouse cursor on particular position or slide the cursor along the board. The exact values of bending stiffness, torsional stiffness, board width, board thickness and the actual distance between the board centre and the particular position of the board are displayed on the right hand side. Some of the major parameters such as project length, side-cut radius, heel and shovel radius as well as the estimated overall weight are displayed on a status bar at the bottom on the screen. The user can always go back to the design section and make further changes. The stiffness estimation and dimensions of the 2D drawings are then updated in real time.

Figure 6-10 – 2D Drawing and Stiffness Distribution
6.4.5  Design Optimisation Panel

Figure 6-11 shows a sample screenshot of the design optimisation interface. The panel on the left hand side displays a list of the major snowboard dimensions. It allows users to define the upper and lower limits of each of the dimensions. For example, it is recommended that overall length board should be somewhere between the rider’s chin and nose. The user may try different settings on the contact length, shovel and heel length to match with the overall length.

The panel on the right hand side allows users to enter the target performances that would best suit their riding style. In addition, users can further refine the results by setting the upper and lower limits of the particular parameters. Finally, the optimisation tool triggers an external solver to search for an optimal solution and display performances and dimensions on the right hand side of each panel.

![Optimisation Interface](image)

Figure 6-11 – Optimisation Interface
6.5 Conclusions

The chapter presents the integration of all the components developed in this research into a custom built parametric snowboard design platform. It contains a user-centric graphical user interface (GUI) that allows users to fully customise, design, and personalise their own snowboard easily by manipulating the geometry parameters and appearance of the snowboard model in a virtual 3D environment.

The development involves two different programming languages, VB and VRML, with the support of VRML Automation and Cortona 3D Viewer in order to provide interactive control to the dynamic VRML snowboard model. It allows users to preview their own final product of design in real-time without the necessity to use CAD licenced packages. Moreover, material properties of a model design snowboard are key contribution factors in improving snowboard performance. This design platform allows users to “fine tune” the three laminate material properties manually as well as the design parameters of the two separate fabric composite layers of the board.

As a result this parametric snowboard design platform greatly reduces the time and cost for snowboard enthusiasts and snowboard manufacturers to design a new board avoiding the traditional and unproductive trial and error method.
Chapter 7
Conclusions and Recommendations

7.1 Conclusions

In conclusion, this research has resulted in the development of an advanced interactive design platform allowing snowboard riders and enthusiasts to fully customise and personalise a snowboard in a 3D virtual environment without any engineering CAD drawing skills or complex structural analysis. This design platform features and includes the following components, implemented in the completed snowboard design platform:

- geometric and material parametric model of the snowboard;
- structural model of the snowboard enabling estimation of the stiffness distribution along its length;
- Continuous thickness distribution model based on measured data of three different riding style snowboards;
- Performance prediction model encompassing the snowboard instructors’ and experts’ assessment of the snowboard design
- multi-parameter optimisation of the snowboard, satisfying user’s preferences.

7.1.1.1 Geometric and Material Parametric Model of the Snowboard

In this research, a three-dimensional parametric snowboard model has been developed. It is a mathematical model that contains relationships between the geometric parameters, mass and user-defined design constraints as well as material properties and snowboard optimisation design constraints. Development of the parametric model involves vector calculation of a three-dimensional path drawing in a dynamic changing environment. It is found that a total number of 37 design parameters can be used to fully define a snowboard model where 28 design parameters are used to define the geometry, 8 parameters are used for the material properties and one parameter for
its mass. A systematic analysis has been performed for the relationships between all these design parameters categorised into three groups, carefully mapping them to avoid any design conflicts. This parametric snowboard model has been integrated into the interactive design platform to visualise the geometry of the snowboard model in a CAD like environment using Virtual Reality Modelling Language (VRML) with the support of JavaScript and VRML Automation.

7.1.1.2 Continuous Thickness Distribution Model based on Measured Data of Three Different Riding Style Snowboards

As part of the parametric modelling, a thickness distribution model has been developed based on the measured data from three different riding style boards. It is found that the thickness distributions were of the boards have a similar pattern. The thickness distribution was simulated by connecting two hyperbolic tangent functions. A positive \( \tanh \) function replicates the pattern from the tail along to the body centre while a negative \( \tanh \) function replicates the pattern from body centre to the tip. Two custom parameters, \( \delta \) and \( \phi \) were introduced to complete the model. The former represents the distribution slope from the snowboard heel/shovel to the body. The latter represents the position where the thickness transitions from the snowboard heel/shovel to the body.

The comparison between the model and the measurement of the three different boards has shown that the thickness distribution of Freestyle and Freeride style board are both well estimated with a maximum error of 12% and 5.2% at -600mm and 500mm distance from the snowboard centre. However, the distribution of the All-Mountain board is slightly different to the others where the thickness of the tail and tip are not uniform. This leads to an increase in the error to 9.3% at the tail and 10.8% at the tip while the error at the highest point is 7.6% at a distance of -250mm from the board centre. The parameter \( \phi \) ranges from 0.4 to 0.43 while the parameter \( \delta \) ranges from 0.03 to 0.05.
7.1.1.3 Structural Model of the Snowboard Enabling Estimation of the Stiffness Distribution along the Snowboard

A snowboard stiffness distribution prediction model has been developed combining the continuous thickness distribution model with the fundamental theory of fabric composite analysis and 2-D textile composites developed by Hashin [24], Byun [9] as well as the sandwich composite structural model developed by the Brennan [7][8] and Clifton[11][12][13] research. This model is able to specifically predict the bending and torsional distribution of a bi-axial fabric composite sandwich structure snowboard.

The model has been incorporated into the snowboard design platform. The composite layer properties editor allows professional riders or experienced snowboard designers to “fine tune” the composite layer properties manually by adjusting the design parameters such as undulation angle, fill and warp tows properties and fabric configuration. The second interface allows user to configure the material properties such as the Young’s modulus, shear modulus, poison’s ratio and density of each of the laminate layers as well as the edge. While the user can define the thickness of each laminate layer, the core thickness is estimated by using the thickness distribution model developed in this research. The final interface displays the bending and torsional stiffness distribution along the centre of the customised design snowboard using the stiffness matrix calculated for each of the five layers as well as the edge.

7.1.1.4 Multi-parameter Optimisation of the Snowboard, Satisfying Design Constraints and User’s Preference.

Snowboard design optimisation is one of the key features of the design platform. A Least Squares Method has been utilised to formulate the optimisation task, to search for the optimal snowboard design that best fits the user’s expectation of particular performances parameters whilst the solution satisfies all the design constraints. These design constraints include: the user-defined geometry constraints which restrict the snowboard dimensions to reflect user’s preferences, physical constraints which reinforce the relationships between parameters; performance parameter constraints
which represent the lower and upper limits of the performance parameters to prevent under or over design.

SQP and MOSA optimisation techniques were utilised to search for the optimal solutions. Three case studies, representing three riding styles, have been investigated in this research. It is found that both the solutions obtained from SQP and MOSA show the similar minimised objective function values as well as the predicted performance parameters across the three case studies. The two optimisation methods generated two optimal design snowboards that have different geometry but the same optimal performances in all aspects. If one of the design parameters is changed, it affects all the performance ratings in certain amount. As a result, other design parameters are needed to be adjusted to compensate the gain or loss of those particular performance parameters. It is concluded that there are multiple combinations of snowboard geometries that could generate snowboards with similar performance. However, the SQP optimisation obtained better results than MOSA, meaning smaller objective function values, across the three case studies due to the limited number of iteration of the MOSA optimisation. The final optimal design snowboard can be obtained based on the rider’s preferences to further restrict the design constraints.

7.1.1.5 Validation

The research results were validated with the assistance of two snowboard experts. A Freestyle board and an All-Mountain board were chosen and tested on snow. The experts reviewed and rated the performances/feel of the snowboards based on their riding experience. The obtained data were used to compare with the results generated from the model that was developed in this research. The area of validation included thickness distribution estimation, stiffness distribution estimation, snowboard performance prediction and snowboard design optimisation.

The comparison of board thickness shows that the thickness distribution model is able to match with the measured data. The majority of errors on both test boards lie within ±5%. The 12% and 8.7% maximum errors are found at locations close to both ends of the Freestyle board and All-Mountain board respectively.
The thickness distribution model is incorporated into the sandwich composite structural model [11] to estimate the continuous stiffness distribution along a snowboard. The results show that the estimation errors of the Freestyle board managed to stay within ±10% while the majority of errors for the All-Mountain board are less than ±10% with maximum errors of 12% at both ends. It is also found that both bending and torsional stiffness errors are very close to each other and have a similar pattern along both boards except the transition area between the boards’ body and shovel/heel.

The experts’ performance ratings on the test boards have been compared with the performance prediction model as well as the design optimisation model. Most of the performance prediction parameters have errors less than ±0.5 to ±0.8 points with some of the targets parameters by as much as ±1.1 to ±1.5 points for the such as edge grip, feedback and speed for a particular board. It is also found that the prediction model slightly overestimates the overall performance of both test boards.

7.1.1.6 Parametric Snowboard Design Platform

We have integrated all the developed methods and models, such as visualisation and customisation of a CAD-like snowboard model, stiffness distribution estimation, performance prediction, and optimisation, into a single parametric snowboard design platform. The platform contains a user-friendly graphical user interface (GUI) that allows users to fully customise, design, and personalise their own snowboard easily by changing the geometry parameters and appearance of the virtual model. The development involved two different programming languages (VB and VRML) with the support of VRML Automation in order to provide interactive control to the dynamic VRML snowboard model. The platform allows the users to preview their own final product of design in real-time without the necessity to use CAD licenced packages. It greatly reduces the time and cost for snowboard enthusiasts and snowboard manufacturers to design a new board avoiding the traditional and unproductive trial and error method.
Finally, this research has provided a valuable contribution to another software development project at RMIT. It is named RMIT Adaptable Platform for Interactive Distributed Design, Customisation and Optimisation (rapidDCO). It was designed for use in multidisciplinary, collaborative and distributed engineering environments where conflicting design parameters have to be resolved by remote input from a range of disciplines and techniques. The snowboard parametric model and the design optimisation technique has been utilised for the development of the rapidDCO project.
7.2 Recommendations

7.2.1 Asymmetric and Unusual Snowboard Design

This research is focused on the design and customisation of a symmetric snowboard that varies in different shapes such as for the directional, true twins and directional twin board. Although the parametric model is capable of creating an asymmetric snowboard, the performance prediction model is solely developed for symmetric boards. The effect of an asymmetric board with different side-cut radius on the heel and toe side is known by snowboard designers. It is used to balance the forces applied from heel and toe to the board edges during turns. However, there is a lack of research on the effectiveness of the asymmetric design. Further study as a continuous of the research performed in this thesis may involve field testing and development of performance prediction model of asymmetric board.

7.2.2 Research on Other Sport Equipment

The concept and methods of parametric design customisation and optimisation techniques as employed in this thesis can be utilised for other sport equipment. For instance, skis have very similar structure and mechanics to a snowboard. The same technique can be applied to develop a ski design platform with some changes such as the definition of design parameters, a ski parametric model and evaluation of performance with the addition of ski poles being considered.

7.2.3 Snowboard Design for Disabled People

Further research may investigate the snowboard design for disabled people with missing limbs. For example, a person with missing arms will have difficulty turning the board on snow due to the fact that he/she does not have enough power to create the momentum to turn the snowboard. In addition, the weight and balance of an amputee can be very different to an average person. Similar research techniques to those developed in this research can be used for specialised sport equipment which will greatly benefit sport for the disabled.
References


Appendix A – Attached documents for snowboard experts

A.1 PowerPoint Research Summary

Full Customisation, Parametric Modelling and Optimisation of Snowboard Design

School of Aerospace, Mechanical and Manufacturing Engineering

Presented by: Ka Wai Lee (Rex)
Research Supervisors:
Prof. Pavel M. Trivailo
Prof. Aleksandar Subic

Outline

• Motivation
• Research Questions
• Methods
• Results
• Contribution Development
• Conclusions
• List of Publications
Motivation

- The need for snowboard customisation, performance prediction and design optimisation
  - Current snowboard design relies heavily on review and feedback from professional riders or snowboard designers.
  - Snowboard companies are spending huge amounts of money and time on “trial and error” method of design.
  - Snowboard companies offer limited number of off-the-shelf designs
  - Snowboard enthusiasts seek an optimal board design
  - The “Do It Yourself” approach requires certain level of engineering CAD drawing skills and knowledge of snowboard structure and material properties
  - It also requires calculation of board stiffness, assessment of strength and other quality characteristics

Key Research Questions

- How to allow snowboard riders to fully customise and design their own snowboard without having CAD drawing skills and engineering background?
- How to provide quick performance prediction without wasting time and money on “trial and error” process?
- How to quickly estimate the stiffness distribution of a customised snowboard?
- How to optimise the performance of a snowboard for individual use?
Methods

- Parametric Modelling
  - Create a parametric snowboard model

- Visualisation
  - Visualise the snowboard design in 3D using VRML

- Customisation
  - Develop a user-friendly snowboard design platform

- Stiffness Distribution and Performance Prediction
  - Integrate the stiffness distribution and performance prediction model previously developed by RMIT snowboard research team into the design platform

- Optimisation
  - Optimise the snowboard performance using modeFRONTIER® and Matlab®

Parametric Snowboard Design Platform
Parametric Snowboard Design Platform

Parametric Modelling of Snowboard

- We define snowboard geometries using ASTM International Standard with some custom design parameters and modifications
- 24 parameters are used to fully define a snowboard's geometry
- 8 parameters are used to define material properties and 1 parameter for mass
- They are also used to estimate the performance of the snowboard as well as bending and torsional stiffness distribution along the board
Parametric Modelling of Snowboard

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design parameters</th>
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<tbody>
<tr>
<td>$r_f$</td>
<td>Camber Radius</td>
</tr>
<tr>
<td>$r_h$</td>
<td>Vertical Heel Radius</td>
</tr>
<tr>
<td>$r_s$</td>
<td>Vertical Shovel Radius</td>
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<tr>
<td>$L_p$</td>
<td>Projected Length</td>
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<tr>
<td>$L_c$</td>
<td>Contact Length</td>
</tr>
<tr>
<td>$L_h$</td>
<td>Heel Length</td>
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<td>Camber Height</td>
</tr>
<tr>
<td>$H_h$</td>
<td>Tail Height</td>
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<td>$H_s$</td>
<td>Tip Height</td>
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<tr>
<td>$T_h$</td>
<td>Heel Thickness</td>
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<td>$T_b$</td>
<td>Body Thickness</td>
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<tr>
<td>$T_s$</td>
<td>Shovel Thickness</td>
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Parametric Modelling of Snowboard

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design parameters</th>
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<tr>
<td>$b_m$</td>
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</tr>
<tr>
<td>$W_h$</td>
<td>Heel Width</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Shovel Width</td>
</tr>
<tr>
<td>$R_h$</td>
<td>Average Heel Radius</td>
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<tr>
<td>$R_s$</td>
<td>Average Shovel Radius</td>
</tr>
<tr>
<td>$R_{sc}$</td>
<td>Sidecut Radius</td>
</tr>
<tr>
<td>$O_h$</td>
<td>Heel Offset</td>
</tr>
<tr>
<td>$O_s$</td>
<td>Shovel Offset</td>
</tr>
</tbody>
</table>
Parametric Modelling of Snowboard

- Parametric Modelling is the use of parameters to define form via a series of relationships.

![Diagram of network nodes and connections]

- Development of the parametric model with different kind of constraints

![Graphs showing parametric model development]

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Parametric Modelling of Snowboard

- Thickness distribution of three snowboards of different riding styles

![Thickness distributions graph]

- Thickness distribution model
  - To mimic the thickness distribution of a snowboard based on measured data.

- On the heel side
  $$-\mathbf{[T]}_h = \frac{T_h - \bar{T}_h}{2} \tanh \left( \frac{\delta}{\bar{T}_h} \left( \mathbf{[X]}_h + \delta L_c \right) \right) + \frac{T_h + \bar{T}_h}{2}$$

- On the shovel side
  $$-\mathbf{[T]}_s = -\frac{T_s - \bar{T}_s}{2} \tanh \left( \frac{\delta}{\bar{T}_s} \left( \mathbf{[X]}_s + \delta L_c \right) \right) + \frac{T_s + \bar{T}_s}{2}$$

Where $\mathbf{[T]}$ is the vector form of thickness distribution
$\mathbf{[X]}$ is the vector form of X-coordinates of the snowboard parametric model
$\delta$ and $\bar{\delta}$ are custom variables that used to adjust the shape of the thickness distribution model
Parametric Modelling of Snowboard

* A completed parametric model of snowboard in Matlab®
Visualisation

• To visualise the parametric model in a 3D environment

• Virtual Reality Modelling Language (VRML)
  – No license required
  – Supports JavaScript
  – Accessible by most web browsers (IE, Chrome, Firefox, etc)
  – Suitable for mass distribution project

• Cortona3D viewer
  – Open license
  – Supports modern 3D accelerators via DirectX and OpenGL
  – Supports ActiveX technology
  – Supports VRML Automation
  – Couple to custom software

Design and Customisation

• Graphical User Interface (GUI)
Stiffness Distribution

- The modern snowboard design usually has a composite sandwich structure
- It mainly consists of five layers
  - Top sheet (nylon, wood, fibreglass and composites)
  - Upper Fibreglass/Composite Layer (bi-axial or tri-axial configuration)
  - Core Material (Hardwood, aluminium honeycomb and PVC foam)
  - Lower Fibreglass/Composite Layer (bi-axial or tri-axial configuration)
  - Base (P-Tex which is high molecular weight polyethylene plastic)
- We modified and integrated the stiffness distribution model which was developed by RMIT research team, into the Parametric Snowboard Design Platform


Performance Prediction

<table>
<thead>
<tr>
<th>Performance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>How stable the rider feels on the board.</td>
</tr>
<tr>
<td>Feedback</td>
<td>The amount of stress felt on the rider’s body including the effects of board chatter</td>
</tr>
<tr>
<td>Speed</td>
<td>The gliding speed of the board compared to other boards of similar length</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The precision of board movement in response to rider input</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>The tolerance of the board to errors from the rider</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>The level of grip exhibited during turns</td>
</tr>
<tr>
<td>Maneouvrability</td>
<td>How easily the board responds to rider inputs</td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>How easily the board flows from edge to edge</td>
</tr>
<tr>
<td>Board Liveliness</td>
<td>The level of ‘pop’ or spring in the board when performing a jump</td>
</tr>
</tbody>
</table>

Performance Prediction

- Performance Prediction model
  - On-snow tests (8 snowboard instructors)
  - Focus group interviews (9 snowboarding experts)
  - Online surveys (115 respondents)

- Equation \( P_n = \sum_{i=1}^{31} (R \times C) \)
  - \( P_n \) = \( n \)th Parameter performance rating
  - Performance ratings normalised from 1-10
  - \( R \) = Relative Scaling Factor
  - \( C \) = Correlation coefficient
  - Allows performance of any board to be predicted by inputting design data


Design Optimisation

- Parametric snowboard design flow chart

```
User Inputs
Design parameters & Material properties
Design constraints & Target performance & Material properties

Process
Parametric Modelling
Optimisation Solver
Design parameters

Outcome
Performance prediction
Optimal performance & Design parameters
```
Design Optimisation

- In view of multiple conflicting requirements for individual, it is impossible to design a perfect snowboard.
- Optimisation does not mean to maximise the performance parameters of a snowboard
- Try to fit particular performance parameters of the snowboard that most suitable for individual use
- Satisfy users’ requirements and the design constraints.

Design Optimisation – Design Constraints

- User-defined Geometry Constraints
  - Used to restrict the snowboard dimensions to reflect user’s preferences
  - Example: The contact length can be limited to 1200mm or below.

- Physical Constraints
  - Used to reinforce the relationships between parameters
  - Example: The waist width is always smaller than shovel/heel width

- Performance Parameter Constraints
  - Used to define the lower and upper limits of the performance parameters to prevent under or over design
  - Example: The user can limit the speed performance to 8 instead of default 10
Design Optimisation

- **Objective function**

  \[ f(x) = \sum_{i=1}^{n} (P_i - T_i)^2 \]

  where
  - \( T_i \) is the user defined target performance of the \( n \)th predicted performance parameter from 1-10.
  - \( P_i \) is the desired \( n \)th subjective performance parameter rating from 1-10.
  - \( x \) is the design parameters vector

- **Minimise the objective function**

  \[ \min_{x} f(x) \text{ Subject to } \begin{cases} c_i(x) = 0, i = 1, \ldots, m_e \\ c_j(x) \leq 0, j = m_e + 1, \ldots, m \end{cases} \]

  where
  - \( c_i(x) \) is a series of equality design constraints
  - \( c_j(x) \) is a series of inequality design constraints
  - \( m_e \) is the number of equality design constraints
  - \( m \) is the total number of design constraints

**Design Optimisation – Optimisation Software**

- **Matlab\textsuperscript{®}**
  - The performance prediction model is converted into Matlab code
  - The solution is then obtained by using the sequential quadratic programming (SQP) method in the Optimisation Toolbox
  - It requires an iterative sequence to form a direction of search at each major iteration

- **modeFRONTIER\textsuperscript{®}**
  - modeFRONTIER\textsuperscript{®} is an optimisation software that can be coupled with other software packages.
  - We coupled the software to Excel\textsuperscript{®} which contains the snowboard performance prediction model
  - The solution is obtained by using a Multiple Objective Simulated Annealing (MOSA) optimisation solver
Design Optimisation – Example 1

<table>
<thead>
<tr>
<th>Performance</th>
<th>Target</th>
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<tbody>
<tr>
<td>Accuracy</td>
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<td>Edge Grip</td>
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<tr>
<td>Feedback</td>
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<td>Forgiveness</td>
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<td>Liveliness</td>
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<tr>
<td>Manoeuvrability</td>
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<td>Speed</td>
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<td>Stability</td>
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<tr>
<td>Transition Smoothness</td>
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Target Performance

Design Optimisation – Example 1 results

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<th>Performance</th>
<th>Target</th>
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<th>modeFRONTIER®</th>
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## Design Optimisation – Example 1 results

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<th>Upper limit</th>
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<th>modeFRONTIER⁶</th>
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<td>1700 mm</td>
<td>1577 mm</td>
<td>1679 mm</td>
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<tr>
<td>(L_c)</td>
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<td>1300 mm</td>
<td>1185 mm</td>
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<td>(L_h)</td>
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<tr>
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<td>14 mm</td>
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<tr>
<td>(T_s)</td>
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### Design Optimisation – Example 2

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<td>Edge Grip</td>
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<td>Feedback</td>
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<td>Manoeuvrability</td>
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<td>Speed</td>
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<td>Stability</td>
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### Design Optimisation – Example 2 results

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<th>modeFRONTIER®</th>
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![Design Optimisation – Example 2 results](image)
### Design Optimisation – Example 2 results

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<th>Symbol</th>
<th>Design parameters</th>
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<th>Upper limit</th>
<th>Matlab&lt;sup&gt;®&lt;/sup&gt;</th>
<th>modeFRONTIER&lt;sup&gt;®&lt;/sup&gt;</th>
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<tbody>
<tr>
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<td>180 mm</td>
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<td>350 mm</td>
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Design Optimisation – Example 3

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Target Performance

Design Optimisation – Example 3 results

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### Design Optimisation – Example 3 results

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### Design Optimisation – Example 3 results

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<th>Upper limit</th>
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<td>Projected Length</td>
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<td>1700 mm</td>
<td>1577 mm</td>
<td>1515 mm</td>
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<tr>
<td>$L_c$</td>
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<td>1300 mm</td>
<td>1185 mm</td>
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<tr>
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<td>4.69 m</td>
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<td>$T_h$</td>
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<td>6 mm</td>
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<tr>
<td>$T_s$</td>
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<td>14 mm</td>
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<td>$T_s$</td>
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Design Optimisation – Example 3 results

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<td>1577 mm</td>
<td>1515 mm</td>
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<tr>
<td>$L_c$</td>
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<td>$L_h$</td>
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<td>4.69 m</td>
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<tr>
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<td>3 mm</td>
<td>7 mm</td>
<td>7 mm</td>
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</tr>
</tbody>
</table>

Contribution Development

- RMIT Adaptable Platform for Interactive Distributed Design, Customisation and Optimisation (rapidDCO)

- A CAD/CAE research platform which is an extension of distributed component based gaming technology.

- rapidDCO is designed for use in multidisciplinary, collaborative and distributed engineering environments where conflicting design parameters have to be resolved by remote input from a range of disciplines and techniques.
Conclusions

• This research enables snowboard riders and designers to optimise snowboard design and its performance for individual use.

• The design platform is developed to fully customise and design a snowboard without CAD drawing skill and engineering backgrounds

• It provides quick performance prediction to eliminate the traditional time consuming “trial and error” method

• It allows quick estimation of stiffness distribution of customised snowboard

• The research has been used for other software development
List of Publications

Publications related to snowboard design


Publications related to optimisation


Publications related to virtual reality modelling


A.2 Validation Procedure

1. Researcher provides a PowerPoint summary of the research for the snowboard experts or instructors to get familiar with the research.
2. Researcher provides description of the validation procedure.
3. Researcher provides description of the pre-defined performance parameters and custom design parameters in this research.
4. Snowboard experts or instructors select snowboards that they consider optimal boards and suitable for their riding style such as Freestyle, Freeride and All-Mountain.
5. Each selected test board needs to be tested at least twice on-snow or until the rider are familiar with the feel/characteristics of the board.
6. After the field test, snowboard experts or instructors rate the performance of the test boards based on their riding experience and on-snow field tests.
7. Measurements record the dimensions and stiffness of the test boards.
8. Recorded data are compared with the data from the results generated by the research models.
### A.3 Design parameters and Performance Parameters
description

**Snowboard performance parameters definition**

<table>
<thead>
<tr>
<th>Performance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>How stable the rider feels on the board.</td>
</tr>
<tr>
<td>Feedback</td>
<td>The amount of stress felt on the rider's body including the effects of board chatter</td>
</tr>
<tr>
<td>Speed</td>
<td>The gliding speed of the board compared to other boards of similar length</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The precision of board movement in response to rider input</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>The tolerance of the board to errors from the rider</td>
</tr>
<tr>
<td>Edge Grip</td>
<td>The level of grip exhibited during turns</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>How easily the board responds to rider inputs</td>
</tr>
<tr>
<td>Transition</td>
<td>How easily the board flows from edge to edge</td>
</tr>
<tr>
<td>Smoothness</td>
<td></td>
</tr>
<tr>
<td>Board Liveliness</td>
<td>The level of 'pop' or spring in the board when performing a jump</td>
</tr>
</tbody>
</table>
A.4 Snowboard design parameter definitions

The major dimensions and design parameters of the snowboard model are defined below and illustrated in Figure 2-2, Figure 2-3 and Figure 2-4 respectively.

**Board lengths**

- Projected length ($L_p$) - the length of the projection of the snowboard, measured between the snowboard tip and the snowboard tail with the snowboard unweighted on a plane surface. (Figure 2-3)
- Contact length ($L_c$) - the difference between the projected length and the sum of heel and shovel lengths. (Figure 2-3)

**Shovel/Nose design parameters**

- Shovel length ($L_s$) - The projected length of the forward turn-up, measured from the tip to the contact point where an 0.1-mm feeler gage intersects the running surface with the snowboard unweighted on a plane surface. (Figure 2-3)
- Tip height ($H_s$) - The height of the underside of the tip from a plane surface with the snowboard unweighted. (Figure 2-3)
- Shovel width ($W_s$) - The horizontal (XY-plane) perpendicular distance between two vertical parallel planes, placed on either edge of the snowboard shoulder, parallel to the longitudinal centreline of the snowboard. (Figure 2-2)
- Shovel radius ($R_s$) - The horizontal (XY-plane) average radius of the curved portion of the snowboard shovel (Figure 2-2)
- Shovel curvature radius ($r_s$) - The vertical (XZ-plane) radius of the curved portion of the snowboard shovel. (Figure 2-4)
Heel/Tail design parameters

- Tail length \( (L_h) \) - The projected length of the tail turn-up, measured from the snowboard tail to the contact point where an 0.1-mm feeler gage intersects the running surface of the snowboard resting unweighted on a plane surface. (Figure 2-3)
- Tail height \( (H_h) \) - The height of the underside of the tail from a plane surface with the snowboard unweighted. (Figure 2-3)
- Heel width \( (W_h) \) - The horizontal (XY-plane) perpendicular distance between two vertical parallel planes, placed on either edge of the snowboard heel, parallel to the longitudinal centreline of the snowboard. (Figure 2-2)
- Heel radius \( (R_h) \) - The horizontal (XY-plane) average radius of the curved portion of the snowboard heel. (Figure 2-2)
- Heel curvature radius \( (r_h) \) - The vertical (XZ-plane) radius of the curved portion of the snowboard heel. (Figure 2-4)

Body design parameters

- Waist width \( (b_m) \) - The width at the narrowest point of the snowboard body between the heel and the shoulder. (Figure 2-2)
- Sidecut radius \( (R_{sc}) \) - The radius of the line describing the curved portion of the snowboard contour. (Figure 2-4)
- Free bottom camber \( (H_f) \) - The height of the running surface from a vertical plane surface measured at the highest point, with the snowboard held laterally on edge, free from the effect of the snowboard weight. (Figure 2-3)
- Camber curvature radius \( (r_f) \) - The vertical (XZ-plane) radius of the curved portion of the snowboard body. (Figure 2-4)
- Asymmetrical offset \( (O_s, O_h) \) — the distance along the longitudinal axis that each side of an asymmetrical shape is offset from the other side. Offset may be different at the shoulder and heel. (Figure 4)
Thickenes distribution parameters

- Body thickness ($T_b$) - The distance between the upper and lower surface of the snowboard measured from the centre of the board between the two contact points. (Figure 2-4)
- Shovel thickness ($T_s$) - The distance between the upper and lower surface of the snowboard measured in the middle between the shovel contact point and the tip. (Figure 2-4)
- Heel thickness ($T_h$) - The distance between the upper and lower surface of the snowboard measured in the middle between the heel contact point and the tip. (Figure 2-4)
Figure 3 – Side View of a Snowboard Model
A.5 Snowboard Performance Rating and Measurement Form

Name: __________________________

Height: ________________________  Weight: ________________________

Snowboard: _____________________  Board Type/Style: _______________

Performance Rating

<table>
<thead>
<tr>
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<th>Rating (1-10)</th>
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<tbody>
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<td>Feedback</td>
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<tr>
<td>Speed</td>
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<tr>
<td>Accuracy</td>
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<tr>
<td>Forgiveness</td>
<td></td>
</tr>
<tr>
<td>Edge Grip</td>
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<tr>
<td>Manoeuvrability</td>
<td></td>
</tr>
<tr>
<td>Transition Smoothness</td>
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<tr>
<td>Board Liveliness</td>
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Snowboard Dimensions

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<td>Contact Length</td>
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<td>Heel Width</td>
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<tr>
<td>Measurement</td>
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<td>-----------------------------</td>
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</tr>
<tr>
<td>Shovel Width</td>
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<tr>
<td>Camber Height</td>
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<td>Tip Height</td>
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<tr>
<td>Body Thickness</td>
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<tr>
<td>Shove Thickness</td>
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### Material properties

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<td>Laminate (Lower)</td>
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<td>Base material</td>
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| Total Weight (kg) |          |
## Snowboard Thickness and Stiffness Measurements

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