MATERIAL SELECTION, CHARACTERIZATION, OPTIMIZATION, AND USABILITY OF BIO-COMPOSITES USING FUSED DEPOSITION MODELLING

HAZLIZA AIDA BINTI CHE HAMID

DOCTOR OF PHILOSOPHY

2025

Faculty of Mechanical Technology and Engineering

MATERIAL SELECTION, CHARACTERIZATION, OPTIMIZATION, AND USABILITY OF BIO-COMPOSITES USING FUSED DEPOSITION MODELLING

Hazliza Aida Binti Che Hamid

Doctor of Philosophy

2025

MATERIAL SELECTION, CHARACTERIZATION, OPTIMIZATION, AND USABILITY OF BIO-COMPOSITES USING FUSED DEPOSITION MODELLING

HAZLIZA AIDA BINTI CHE HAMID

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

Faculty of Mechanical Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2025

DECLARATION

I declare that this thesis entitled "Material Selection, Characterization, Optimization, And Usability Of Bio-Composites Using Fused Deposition Modelling" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :...

Name : Hazliza Aida Binti Che Hamid

Date : 28/05/2025

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature	:...
Supervisor Name	: Dr. Mastura Binti Mohammad Taha
Date	: 28/05/2025

DEDICATION

This research is dedicated to my family and friends who have consistently provided unwavering attention and affection during my research journey.

This research is also dedicated to my supervisor, Dr. Mastura Binti Mohammad Taha and co. supervisor, Dr. Syahibudil Ikhwan Bin Abdul Kudus, who has provided me with diligent guidance and inspired me to strive for greater objectives in order to create exceptional research.

Lastly, I would want to express my gratitude to all UTeM instructors, personnel, and my research partners for their valuable collaboration in contributing to this work.

ABSTRACT

This research examines the material selection, characterization, optimization, and usability of bio-composites in additive manufacturing (AM). Development of environmentally sustainable egg carton packaging is used as case study and fabricate using Fused Deposition Modelling (FDM). The case study comprises of four primary phases: identifying appropriate bio-composite filament materials, characterizing their mechanical and printing characteristics, optimizing FDM settings, and assessing the usability of the final egg carton prototype. The Fuzzy Analytic Network Process (FANP) identified polylactic acid (PLA) reinforced with 7.5 wt.% sugar palm fibre (SPF) as the ideal material. The SPF-PLA composite containing 7.5 wt.% SPF was selected as the optimum material in this study, owing to its superior mechanical strength, printability, environmental sustainability, and processing stability, as corroborated by both FANP ranking and experimental validation. The printing settings were first optimized by the Taguchi technique, establishing optimal circumstances of 0.1 mm layer thickness, 100% infill density, and a print speed of 25 mm/s to guarantee better print quality and structural integrity. Mechanical and physical evaluations validated the printability and efficacy of the SPF-PLA composite. A functioning egg carton prototype was then produced using FDM based on these proven features. Usability testing was performed with 10 volunteers using the System Usability Scale (SUS), in which participants evaluated 10 assertions on a Likert scale. The findings produced an average SUS score of 80, categorizing the prototype as good within the 4th quartile range. Participants expressed positive opinions about the carton's durability, usability, and environmental benefits. The results confirm the SPF-PLA bio-composite as a feasible material for sustainable egg carton packaging and illustrate the potential of FDM technology for scalable, environmentally responsible production.

PEMILIHAN BAHAN, PENCIRIAN, PENGOPTIMUMAN DAN KEBOLEHGUNAAN BIO KOMPOSIT MENGGUNAKAN PERMODELAN PEMENDAPAN BERSATU

ABSTRAK

Kajian ini meneliti pemilihan bahan, pencirian, pengoptimuman, dan kebolehgunaan bio-komposit dalam pembuatan tambahan (AM). Pembangunan pembungkusan karton telur yang mesra alam sekitar digunakan sebagai kajian kes dan dihasilkan menggunakan Pemodelan Pemendapan Bersatu (FDM). Kajian kes ini merangkumi empat fasa utama: mengenal pasti bahan filamen bio-komposit yang sesuai, mencirikan sifat mekanikal dan keupayaan cetakannya, mengoptimumkan tetapan FDM, serta menilai kebolehgunaan prototaip akhir kotak telur tersebut. Proses Rangkaian Analitik Kabur (FANP) telah mengenal pasti asid polilaktik (PLA) yang diperkukuh dengan 7.5 wt.% serat kelapa sawit (SPF) sebagai bahan yang paling ideal. Komposit SPF-PLA dengan kandungan 7.5 wt.% SPF telah dipilih sebagai bahan optimum dalam kajian ini, berdasarkan kekuatan mekanikalnya yang unggul, keupayaan cetak, kelestarian alam sekitar, dan kestabilan pemprosesan, seperti yang disahkan oleh kedudukan FANP dan pengesahan eksperimen. Tetapan percetakan telah dioptimumkan terlebih dahulu menggunakan teknik Taguchi, yang menetapkan keadaan optimum pada ketebalan lapisan 0.1 mm, ketumpatan pengisian 100%, dan kelajuan cetakan 25 mm/s bagi menjamin kualiti cetakan dan integriti struktur yang lebih baik. Penilaian mekanikal dan fizikal mengesahkan kebolehcetakannya serta keberkesanan komposit SPF-PLA tersebut. Prototaip karton telur berfungsi kemudiannya telah dihasilkan menggunakan FDM berdasarkan ciri-ciri yang telah terbukti ini. Ujian kebolehgunaan telah dijalankan bersama 10 orang sukarelawan mengunakan Skala Kebolehgunaan Sistem (SUS), di mana para peserta menilai 10 pernyataan menggunakan skala Likert. Dapatan menunjukkan purata skor SUS sebanyak 80, yang meletakkan prototaip tersebut dalam julat kuartil ke-4 sebagai "baik." Para peserta memberikan maklum balas positif mengenai ketahanan, kebolehgunaan, dan manfaat alam sekitar bagi karton tersebut. Keputusan ini mengesahkan bahawa bio-komposit SPF-PLA merupakan bahan yang berdaya maju untuk pembungkusan karton telur yang mampan dan menggambarkan potensi teknologi FDM untuk pengeluaran yang berskala dan mesra alam.

ACKNOWLEDGEMENT

In the Name of Allah, the Most Gracious, the Most Merciful. First and foremost, I would like to take this opportunity to express my sincere acknowledgement to Dr. Mastura Binti Mohammad Taha, Chairman of the Supervisory Committee, for her unwavering support and insightful mentorship during the whole of this research project. I would like to express my sincere appreciation to Dr. Syahibudil Ikhwan Bin Abdul Kudus, a member of the Supervisory Committee, for the confidence placed in me, the profound insight provided, and the helpful counsel given over the duration of this research project. I am grateful to all member of the DSAM team, including PM. Ts. Dr. Muhd Ridzuan Bin Mansor, Ts. Dr. Mohd Adrinata Bin Shaharuzaman, Ts. Dr. Nazri Huzaimi Bin Zakaria, Dr. Ridhwan Bin Jumaidin, Dr. Nadlene Binti Razali, Dr. Noryani Binti Muhammad, Dr. Yusliza Binti Yusuf and Dr. Nuzaimah Bte Mustafa, for their unwavering support and encouragement in my academic endeavours. Above all, I am very grateful for the financial assistance provided by Universiti Teknikal Malaysia Melaka for sponsoring my Ph.D. studies.

I am very grateful for the unwavering support of my parents, Che Hamid Bin Che Hassan and Hasnah Binti Zakaria. Their sacrifices and ceaseless prayers have been instrumental in enabling me to persevere and reach this point. Dear siblings and cherished companions, I express my gratitude for the exquisite support and empathy you have shown. Your assistance has enabled me to work diligently towards reaching the end goal. Ibrahim Bin Abdul Anis, the central figure, has consistently comprehended and embraced my fervour for self-improvement and the pursuit of knowledge. Thank you for your assistance and affection. I will forever be appreciative. Furthermore, I want to emphasise my deep affection for my

beloved children, Nur Anis Sophea Binti Ibrahim. I, as a mother, love you more than anything in this world. I really appreciate your patience and understanding during this process. Only Allah is deserving to worship. Allah is the Supreme Being. There is no authority or strength save with the permission of Allah, the Supreme and Powerful. I humbly request your forgiveness, my Lord.

TABLE OF CONTENTS

		PAGES
DECLARATION		
APPROVAL		
DEDICATION		
ABSTRACT		**i**
ABSTRAK		**ii**
ACKNOWLEDGEMENT		**iii**
TABLE OF CONTENTS		**v**
LIST OF TABLES		**vii**
LIST OF FIGURES		**ix**
LIST OF ABBREVIATIONS		**xiii**
LIST OF SYMBOLS		**xvii**
LIST OF APPENDICES		**xx**
LIST OF PUBLICATIONS		**xxi**
CHAPTER		
1.	**INTRODUCTION**	**1**
	1.1 Background	1
	1.2 Problem Statement	2
	1.3 Research Objective	5
	1.4 Scope of Research	5
	1.5 Thesis Outline	6
	1.6 Summary	7
2.	**LITERATURE REVIEW**	**8**
	2.1 Introduction	8
	2.2 Overview of FDM	8
	2.2.1 Design Phase	21
	2.2.2 3D Printing	27
	2.2.3 Post-Processing Methods	37
	2.3 Bio-Composite Filament Material for FDM	38
	2.3.1 Natural Fibre	39
	2.3.2 Bio-Composite Filament Production	52
	2.3.3 Properties of Bio-Composite Filament	64
	2.3.4 Future Trends in FDM Bio-Composite	75
	2.4 Sustainable Packaging	77
	2.4.1 The Importance of Sustainable Packaging	82
	2.4.2 Case Studies on Bio Egg Carton Packaging	85
	2.4.3 Manufacturing Process of Egg Carton	88
	2.5 Summary	91
3.	**METHODOLOGY**	**98**
	3.1 Introduction	98
	3.2 Research Design	98
	3.3 Stage 1: Selection of Bio-Composite Filament	100

3.3.1 Phase 1: Data Collection 100
3.3.2 Phase 2: Prioritizing Criteria 107
3.3.3 Phase 3: Development of the FANP Model for the Selection Process 109
3.4 Stage 2: Optimizing of FDM 3D Printing Parameters using Taguchi Method 114
3.4.1 Design of Experiment (DOE) 115
3.4.2 Sample Preparation 117
3.4.3 Experimental Method on Mechanical Properties Testing 118
3.4.4 Experimental Method on Physical Appearance 120
3.4.5 Morphological Analysis 122
3.5 Usability Evaluation of Egg Carton Packaging 123
3.5.1 Prototype of Egg Carton Packaging 125
3.5.2 Preparing System Usability Scale (SUS) Questionnaire 128
3.5.3 Test Procedure 130
3.5.4 Questionnaire Administration 132
3.5.5 System Usability Scale (SUS) 132
3.6 Summary 134

4. RESULT AND DISCUSSION 135
4.1 Introduction 135
4.2 Selection of Bio-Composite Filament Material for FDM Process 135
4.3 Optimization of FDM Printing Parameters for 3D Printed Bio-Composite Egg Carton Packaging 150
4.4 Evaluation Outcomes for Egg Carton Packaging 169
4.5 Summary 176

5. CONCLUSION AND RECOMMENDATION FOR FUTURE RESEARCH 178
5.1 Conclusion 178
5.2 Recommendations for Future Research 179

REFERENCES 182
APPENDICES 216

LIST OF TABLES

TABLE	TITLE	PAGE
Table 2.1	The methods, typical materials produces, applications, benefits, and drawbacks of the seven systems	14
Table 2.2	FDM design features	26
Table 2.3	Mechanical properties of natural and synthethic fibre	41
Table 2.4	Biochemical composition (Cellulose, Hemicellulose, Lignin, Pectins concentration, and micro-fibrillar angle (MFA)) and mechanical properties of several natural fibres utilized in FDM	44
Table 2.5	Comprehensive overview of MCDM	47
Table 2.6	The linguistic scales with the fuzzy level scale	50
Table 2.7	Advantages and disadvantages of fuzzy set theory in material selection	51
Table 2.8	Various mixing and manufacturing methods composed from diverse natural fibre sources with differing lengths	55
Table 2.9	The effect of chemical treatments on natural fibre's performance	58
Table 2.10	Printing temperature range of polymer filament materials	66
Table 2.11	Mechanical characteristics of typical thermoplastics	67
Table 2.12	Examples of food packaging and disposal food contact products fabricated from bio-based polymers	81
Table 2.13	Design requirements for sustainable egg carton packaging	86
Table 2.14	Summary of research on material selection using MCDM and FANP methods	93
Table 2.15	Review of studies on FDM process optimization using the Taguchi method	95
Table 2.16	Summary of studies utilizing the SUS in usability evaluation	96

Table 3.1 Criteria for bio-composite filaments material selection 101

Table 3.2 Bio-composite filament materials 104

Table 3.3 Fuzzy comparison matrix 110

Table 3.4 Control variables and their corresponding values for the printing parameters in the Taguchi method 115

Table 3.5 Experiment plan based on L9 (3^4) Taguchi orthogonal array design 116

Table 3.6 Five-point closed-ended Likert scale 129

Table 3.7 Evaluation framework for egg carton packaging 131

Table 4.1 Decision matrix for bio-composite filaments material selection problem 136

Table 4.2 Fuzzy decision matrix for bio-composite filament material selection problem 137

Table 4.3 Various criteria pairwise comparison matrix 137

Table 4.4 The unweighted supermatrix 141

Table 4.5 The weighted supermatrix 142

Table 4.6 The limit supermatrix 143

Table 4.7 The final outcomes 144

Table 4.8 Summary of sensitivity analysis results based on four circumstances 149

Table 4.9 Mechanical and physical properties results 151

Table 4.10 Summary table of the normal probability for experimental data 156

Table 4.11 SNR results for mechanical properties and physical appearance 157

Table 4.12 Type and number of participants 171

Table 4.13 SUS questionnaire results 173

Table 4.14 SUS score final results 174

LIST OF FIGURES

FIGURE	TITLE	PAGE
Figure 2.1	The AM process flow	11
Figure 2.2	Classification of AM technologies	13
Figure 2.3	An overview of the steps involved in FDM, where the print head travles in the x-y plane, and the platform descends in the z-axis	18
Figure 2.4	All in one 3D printer test model	22
Figure 2.5	3D printer test sample demonstrates that support is only necessary in specific regions of curved surfaces	23
Figure 2.6	The effect on print quality with a number of FDM-printers bridges of varying spans	24
Figure 2.7	The difference between the slicer diameter and the printed diameter of vertical holes is due to the extruded profile is compressed	25
Figure 2.8	List of parameters affecting the materials' mechanical, thermal, and physical characteristics using the FDM process	30
Figure 2.9	Types of raster angle	31
Figure 2.10	Raster width and air gap in process parameters	32
Figure 2.11	Types of infill pattern	33
Figure 2.12	Build orientation of dog-bone structure. (a) “flat”; (b) “on-edge”; (c) “upright”	35
Figure 2.13	Classification of natural fibres	39
Figure 2.14	An overview of some of the most common sources of natural fibres	40

Figure 2.15 Plant constituents' influence. The rightward-pointing arrows indicate an increase 43

Figure 2.16 The categorizing of currently available filament materials 53

Figure 2.17 Fibre composite filament fabrication process 54

Figure 2.18a A layout of filament fabrication for single-screw extruder 61

Figure 2.18b Schematic diagram of twin-screw extrusion 61

Figure 2.19 Twin-screw extruder cross-section; (a) co-rotating screws and (b) counter-rotating screws 63

Figure 2.20 (a) WF/PLA composite filament; (b) Specimens for tensile properties measurements; (c) a barrel made by FDM 3D printer 68

Figure 2.21 Schematic representation of printed specimen geometry 70

Figure 2.22 Characterization of typical packaging plastics by feedstock origin and biodegradability, bio-based plastic market shares in brackets 81

Figure 2.23 Current design of egg cartons from patents search 88

Figure 2.24 Moulded pulp egg tray making process 90

Figure 3.1 The framework for comprehensive examination 99

Figure 3.2 (a) Procedure for tensile testing, (b) Procedure for flexural testing and (c) Procedure for IZOD impact testing 107

Figure 3.3 Basic structure of the FANP model 108

Figure 3.4 FANP model 108

Figure 3.5 Network structure of the bio-composite filament material selection problem 109

Figure 3.6 Printing parameters for optimization: (a) layer thickness and printing speed; and (b) infill density 118

Figure 3.7 The specimens intended for tensile testing have been produced in accordance with the experimental design 119

Figure 3.8 The specimens intended for flexural testing have been produced in accordance with the experimental design 120

Figure 3.9 The arrangement for measuring surface roughness, Ra, with (a) showing the setup and (b) illustrating the layout of FDM prints and the measurement 121

Figure 3.10 The geographic location of the measurements conducted on the produced items 122

Figure 3.11 The arrangement for measuring morphology of the fracture surface, with (a) SEM machine for morphological and (b) the coating process 123

Figure 3.12 The procedure for usability evaluation of egg carton packaging 125

Figure 3.13 Prototype of 6-egg carton design; (a) top egg box and (b) bottom egg box 128

Figure 3.14 SUS questionnaire 130

Figure 3.15 An examination of the average SUS scores in relation to adjective ratings, overall SUS scores acceptability, and quartile means 134

Figure 4.1 Comparison matrix for "tensile strength" that compares several criteria in terms of their pairwise similarities and differences 138

Figure 4.2 Matrix of pairwise comparisons based on several measures of "flexural strength" 138

Figure 4.3 Impact strength comparison matrix with any criteria 138

Figure 4.4 Various printability measures are compared in a pairwise matrix 139

Figure 4.5 Priorities of the criteria 144

Figure 4.6 Ranking of the bio-composite filaments material with induced disturbance on the FANP derived weightages of (a) tensile strength; (b) flexural strength; (c) impact strength; and (d) printability 147

Figure 4.7 Interaction plot for mechanical properties and physical appearance of: (a) tensile strength; (b) Young's modulus; (c) flexural strength; (d) surface roughness; and (e) dimensional accuracy 153

Figure 4.8	Normal probability plots for mechanical properties and physical appearance of: (a) tensile strength; (b) Young's modulus; (c) flexural strength; (d) surface roughness; and (e) dimensional accuracy	155
Figure 4.9	The main effects graphic illustrates the SNR, where a higher value indicates better performance, for three variables: (a) tensile strength; (b) Young's modulus; and (c) flexural strength	160
Figure 4.10	Main effect plot for SNR (smaller is better) for: (a) surface roughness; and (b) % error of dimensional accuracy	163
Figure 4.11	Composite optimization plot	165
Figure 4.12	SEM images of specimens with fractured surfaces: (a) Run 1; (b) Run 2; (c) Run 3; (d) Run 4; (e) Run 5; (f) Run 6; (g) Run 7; (h) Run 8; and (i) Run 9	167
Figure 4.13	Gender of respondent	172
Figure 4.14	Age of respondent	172
Figure 4.15	Behavioral aspects related to egg carton packaging. (a) The frequency of egg purchases; (b) Purchase of egg carton packaging; and (c) Interest in the concept of environmentally friendly bio-composite egg carton packaging	173

LIST OF ABBREVIATIONS

ABS	-	Acrylonitrile Butadiene Styrene
AD	-	Anderson-Darling
AHP	-	Analytic Hierarchy Process
AM	-	Additive Manufacturing
ANOVA	-	Analysis of Variance
ANP	-	Analytic Network Process
ASTM	-	American Society for Testing and Materials
ASQ	-	After-Scenario Questionnaire
bioPe	-	Biobased Polyethylene
BJ	-	Binder Jetting
C	-	Carbon
C	-	Celcius
CAD	-	Computer-Aided Design
CAM	-	Computer-Aided Manufacturing
CC	-	Contour Crafting
CE	-	Closed-ended
CF	-	Carbon Fibre
CSUQ	-	Computer System Usability Questionnaire
DC	-	Direct Current
DLP	-	Direct Light Processing
DMLS	-	Direct Metal Laser Sintering
DOD	-	Drop on Demand
DOE	-	Design of Experiment

EBM	-	Electron Beam Melting
ELECTRE	-	Elimination and Choice Expressing the Reality
FANP	-	Fuzzy Analytic Network Process
FBG	-	Fibre Bragg Grating
FDM	-	Fused Deposition Modelling
FEA	-	Finite Element Analysis
FFF	-	Fused Filament Fabrication
FG	-	Fibre Glass
FPP	-	Fuzzy Preference Programming
G-codes	-	Geometric Code
H	-	Hydrogen
HDPE	-	High-Density Polyethylene
HIPS	-	High Impact Polystyrene
KRABS	-	Kenaf fibre-reinforced ABS
LBMD	-	Laser-Basedd Metal Deposition
LCA	-	Lifecycle Analysis
LENS	-	Laser Engineering Net Shaping
LOM	-	Laminated Object Manufacturing
MAUT	-	Multi-Attribute Utility Theory
MCC	-	Microcrystalline Cellulose
MCDM	-	Multi-Criteria Decision-Making
N	-	Number of run
NFRC	-	Natural Fibre-Reinforced Composite
O	-	Oxygen
OL	-	Whole Length

OW	-	Overall Width
PALF	-	Pineapple Leaves Fibre
PCL	-	Polycaprolactone
PEEK	-	Poly-ether-ether-ketone
PEI	-	Polyetherimide
PHA	-	Polyhydroxyalkanoates
PLA	-	Polylactic Acid
POE	-	Polyethene-co-octene
PP	-	Polypropylene
PROMETHEE	-	Prefference Ranking Organization Method for Enrichment Evaluations
PS	-	Polystyrene
PSSUQ	-	Post-Study System Usability Questionnaire
POE	-	Polyethene-co-octene
rPP	-	Recycled Polypropylene
RSM	-	Response Surface Methodology
r-WOPPC	-	Recycled wood PP composite
SEM	-	Scanning Electron Microscope
SLA	-	Stereolithography
SLM	-	Selective Laser Melting
SLS	-	Selective Laser Sintering
SNR	-	Signal-to-Noise Ratio
SPF	-	Sugar Palm Fibre
St. Dev	-	Standard Deviation
SUMI	-	Software Usability Measurement Inventory
SUS	-	System Usability Scale

T	-	Thickness
TBC	-	Tributyl Citrate
TOPSIS	-	Technique of Ranking Preferences by the Similarity of the Ideal Solutions
TPU	-	Thermoplastic Polyurethane
TSL	-	Surface Tessellation Language
UAM	-	Ultrasonic Additive Manufacturing
USE	-	Usefulness, Satisfaction and Ease of use
UV	-	Ultraviolet
V	-	Voltage
VIKOR	-	Vlse Kriterijumska Optimizacija Kompromisno Resenje
W	-	Width
WF	-	Wood Flour
WAMMI	-	Website Analysis Measurement Inventory
3D	-	Three-Dimensional
3PB	-	Three-point Bend

LIST OF SYMBOLS

mm	-	Millimeter
XY	-	The x-coordinate is measured along the easr-west axis, the y-coordinate is measured along the north-south axis
Z	-	The z-coordinate measures height or elevation
mm/min	-	Millimeter per minutes
$^{\circ}$	-	Degree
%	-	Percent
μm	-	Micrometer
$S1$	-	Outside layer
$S2$	-	Middle layer
$S3$	-	Interior layer
L/d	-	Length/diameter
$Pa.s$	-	Pascal-second
GPa	-	Giga Pascal
MPa	-	Mega Pascal
ρ	-	Density
Tg	-	Glass transition temperature
Tm	-	Melting point
S	-	Tensile strength
E	-	Tensile modulus
E/ρ	-	Specific modulus
$wt.$	-	Weight

kg/h	-	Kilogram per hour
m^3	-	Cubic meter
G	-	Target
n	-	Number of groups
C_{i}	-	Element groups
SC_{jl}	-	Main cirteria
k	-	Number of experts
l_{iuv}	-	Lower limit
SC_{iu} and SC_{iv}	-	Weights of components
$w_{\mathrm{u}}/w_{\mathrm{v}}$	-	Degree of membership
s_{iuv}	-	Represents the agreement between the solution weight and expert opinion
$()^{\mathrm{T}}$	-	Weight vector
W_{ij}	-	Submatrix
W	-	Unweighted supermatrix
A	-	Weighted matrix
$\overline{W}$	-	Super-weighted matrix
T	-	Network layer
w_{pq}	-	One-step priority
p	-	The degree to which indicator
q	-	Influence indicator
ω_k	-	Criterion weight
$\dot{\omega}_k$	-	Altered criterion weights
β_k	-	Unitary ratio
mm/s	-	Millimeter per second