Advanced Digital Twins for Conditions Monitoring, Examinations, Diagnosis and Predictive Remaining Lifecycles Based Artificial Intelligence

The Thesis Submitted for the Degree of

Doctor of Philosophy

By

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Abstract

Digital Twins (DTs) continue to evolve; however, there is a lack of standardisations, DTs not compliant with the description in the literature, lack of physical design background, lifecycles still based on estimates or ideal scenarios, no attention to the simulation during systems operation, and lack of integration between AI and DTs.

This research provides a comprehensive systematic review methodology for DTs while incorporating the science mapping methods. This research deeply examines DTs' concepts, maturity, creation, values, applications, techniques, and technology to identify and create the most suitable way to implement DTs in the Predictive Maintenance (PdM) of suspension systems. This research proposes a novel concept to conceptualise DTs: "***Four dimensions digital replica that continuously simulates the entire behaviour of anything***". The hypothesis of the four dimensions presented is computationally fast, easy to implement and cost-effective. This research uses physics-based simulation models and the DT concept to assess the PdM and forecast the Remaining Useful Life (RUL) of primary springs used in suspension systems. The Euler technique is employed with DTs to solidify the concept of DTs based on physics models and predict springs' conditions in Current Real Time (CRT) as a novel method and unique technique to these primary springs. This method simulates physics-based models to monitor and predict spring conditions without intrusive methods.

This research decreases the dimensions of the DTs modelling from five to four (Physical, Digital, Connection, and CRT), reducing the systems' complexity and cost. This research reduces the predetermined design average load compared to the regular simulation and experimental results by 35.7 %. This research increases the average lifecycles of coil springs by 12 and 9 times more than the simulated and experimented results. This research increases the average lifecycles of the coil springs by 19.7% compared to the wireless DT model results. Artificial Intelligence (AI) is then integrated with the DTs to maximise efficiency, improve the performance of DTs models, and classify the types of faults that occur with the coil springs. A validation model is proposed and shows a prediction error of less than 0.0001 % and classifying the system's defects with regression accuracy throughout training, validation, and testing were 0.99997, 0.99954, and 0.99931, respectively, for a total accuracy of 0.99986

Keywords: Digital Twin, Internet of Things, Machine Learning, Artificial intelligence, predictive maintenance, fault classifications, and Remote Condition Monitoring.

STATEMENT OF ORIGINALITY

I certify that the work done in the thesis is my work under regular supervision. The thesis contains no materials accepted or examined for awarding any other degree or diploma in any university.

The thesis does not include materials previously published or written by another person except those referenced in the text.

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NOMENCLATURE

Abbreviations within the Body of The Thesis			
AI	Artificial Intelligence	IBM	International Business Machine
ADT	Advanced Digital Twins	IoT	Internet of Things
AE	Autoencoder	kNN	k-Nearest Neighbours
AMS	Any Body Modelling System	LCM	Live Condition Monitoring
ANN	Artificial Neural Networks	LF	Low Frequency
AR	Augmented Reality	LR	Linear Regression
BD	Big Data	LSTM	Long Short-Term Memory
BL	Biophysics Lab	MCtF	Mean Cycle to Failure
CB	Computational Biochemistry	ML	Machine Learning
CAD	Computer Aided Engineering	MLR	Multiple Linear Regression
CB	Condition Based	MLS	Moving Least Square
CB	Computational Biochemistry	Mo	Morrow
CBM	Condition Based Maintenance	MPH	Mater Private Hospitals
CC	Cloud Computing	MSE	Mean Square Error
CE	Connection Entity	NF	Natural Frequency
CF	Crest Factor	ODE	Ordinary Differential Equation
CAE	Computer Aided Engineering	PA	Picture Archiving
CM	Condition Monitoring	PAv	Product Avatar
CoM	Coffin-Manson	PC	Processing Capacity
CNN	Convolutional Neural Network	PDE	Partial Differential Equation
CoM	Coffin Manson	PE	Physical Entity
CP	Computational Power	PF	Particle Filter
CPE	Cyber-Physical Equivalent	PS	Physical System
CPS	Cyber-Physical Systems	PSD	Power Spectra Density
CPU	Central Processing Unit	PT	Physical Twin
CRT	Current Real Time	PDE	Partial Differential Equaiton
CS	Communication System	PdM	Predictive Maintenance
CT	Cognitive Twin	PLM	Product Lifecycle Management
DC	Digital Counterpart	PO	Physical Object
DD	Data Driven	PTC	Parametric Technology Corporation
DE	Digital Entity	PvM	Preventive Maintenance
DeT	Decision Tree	QoV	Quarter of Vehicle
DL	Deep Learning	RD	Real Data
DM	Digital Model	RES	Renewable Energy Systems
DO	Digital Object	RF	Random Forests
DS	Digital Shadow	RFID	Radio Frequency Identification
DT	Digital Twin	RL	Real Data
DTW	Digital Twin Web	RMS	Root Mean Square
DTh	Digital Thread	RT	Real-Time
EBa	Ensemble Bagging	RUL	Remaining Useful Life
EM	Euler Method	RtF	Run to Failure
ESD	Effective Strain Damage	StD	Synthetic Data
FBD	Free Body Diagram	SEM	Scanning Electron Microscopy
FD	Fatigue Damage	SFV	Steady Forced Vibration

FEA	Finite Element Analysis	SL	Strain Life
FF	Fatigue Failure	SLDT	Self-Learning Digital Twin
FFN	Feed Forward Network	SM	Slight Machine
FFV	Free Vibration	SS	Software Solution
FIR	Fourth Industrial Revolution	SVM	Support Vector Machine
FL	Fatigue Life	SWT	Smith Watson Topper
FRF	Frequent Response Function	TFV	Transient Forced Vibration
GE	General Electric	TPU	Tensor Processing Unit
GPR	Gaussian Process Regression	VHF	Very High Frequency
GPU	General Processing Unit	VH	Virtual Human
HCF	High Cycle Fatigue	VPG	Virtual Population Group
HDT	Hybrid Digital Twin	VPH	Virtual Physiological Human
HF	High Frequency	VS	Virtual System
HLA	High Level Architecture	VT	Virtual Twin
Abbreviations for Equations			
A	Maximum Amplitude in Eq (2)	ε	Normal Strain
B_1	Constant Used in Eq (20)	σ	Normal Stress
B_1	Constant Used in Eq (20)	σa	Alternating Stress
Ca	Actual Damping	ξ	Damping Ratio
C_c	Critical Damping	Ø	Phase Angle
C*	Spring Compliance (1/K)	ε	Normal Strain
d	Wire Diameter	σ	Normal Stress
D	Hole Diameter	ω_a	Actual Frequency
D1	Inner Diameter	ω_n	Natural Frequency
D2	Mean Diameter	ω_d	Driving Frequency
D3	Outer Diameter	ω_a	Actual Frequency
E	Young's Modulus	ε	Normal Strain
F	Applied External Force	σ	Normal Stress
G	Shear Modulus	σa	Alternating Stress
k	Spring Rate	ξ	Damping Ratio
K_e	Equivalent Spring Rate	X0	Constant in Eq (22)
K_s	Wahl Stress Factor	X1	Constant in Eq (32)
L_s	Solid Length	X2	Constant in Eq (33)
m	Mass	X3	Constant in Eq (34)
n	Divided Segments	y	Deflection
Na	Number of Active Coils	$\dot{y}$	Velocity
NT	Number of Total Coils	$\ddot{y}$	Acceleration
P	Pitch Height	α	Coefficient of Initial Relative Velocity
t	Time	δt	Time Interval
T	Period	Δx	Normal Strain
TF	Tension Force	y	Normal Stress
Ts	Tensile Strength	$\dot{y}$	Alternating Stress
v	Poisson Ratio	$\ddot{y}$	Damping Ratio

CHAPTER 1
Introduction and Fundamentals

1 INTRODUCTION

Digital twins (DTs) technology is a new and developing technology of the Fourth Industrial Revolution 4.0 (FIR). It is a significant component in creating a smart factory by intelligently linking the manufacturing machinery. Investigating manufacturing system simulations to integrate the digital and physical worlds enables data analysis and system monitoring to stop issues, prevent downtime, create new opportunities, and even prepare for the future through simulations. A virtual software version of a real-world system or item is called a "digital twin" [1]. These DTs are accomplished by gathering sensor data to rebuild the system. Using DTs makes it possible to smarten and connect old and out-of-date technology. The DT has numerous applications. Examples of using DTs include monitoring and enhancing the current system and forecasting when a system fails. Human-robot collaboration is another area in which it can be applied. The DT promotes cooperation between people and machine systems. No matter what purpose DTs serve, their fundamental tenet is that "information replaces squandered physical resources" [2].

Twins utilise their position as links between the physical and digital worlds to reduce resource consumption by getting the appropriate information to the correct location. DTs are the final component needed for the Internet of Things (IoT) to function correctly. When an IoT device sleeps to conserve its physical resources, its DT is still up and ready to respond to outside inquiries and wake the device up if necessary. DTs can also offer intelligence to inanimate items that can be recognised but lack computational capability. In the future, as embedded software is needed to produce mechatronic devices, digital twins may even be necessary to create cyber-physical products. There will be an explosion in the number of devices connected to the IoT, beginning with the fifth generation (5G) of communications and continuing further IoT. As a result of the ever-increasing demands placed on those networks concerning their performance, dependability, and safety, the management of IoT networks is getting more challenging. These complications result from contemporary network management techniques relying almost exclusively on mathematical network models. These models take the current state of the network as input and incorporate actions and performance feedback at the level of individual devices and protocols [3].

However, in the current IoT networks, the enormous number of IoT devices and the massive amounts of data they produce present a significant challenge to implementing model-driven approaches. This challenge creates the impression that such a management mechanism is ineffective because it gives the impression that there are too many devices and data. Several distinct methods of machine learning, including Decision Trees (DeT), Support Vector Machines (SVM), and Artificial Neural Networks (ANN), are all possibilities for classifying the circumstances of suspension systems by the degree of precision that the goal variable possesses. The ideal conditions that have been determined are utilised to construct the guidance for Real-Time (RT) intervention. A digital copy of the part is made as it is being monitored in Current Real-Time (CRT), and this copy immediately incorporates every activity and unplanned event. The strategy with the most potential for success with the actual thing will be applied to utilise its digital counterpart as a point of reference. Two components that are necessary for the implementation of intelligent manufacturing systems are known as Cyber-Physical Systems (CPS) and DTs [4].

CPS improves communication between intelligent manufacturing entities (sensors, actuators, and control, amongst many others) and cyber computing resources to simplify monitoring, data collection, perception, analysis, and RT control of production resources. CPS also enables more intelligent manufacturing. Advanced Digital Twins (ADTs) are complex mechatronic systems integrated with artificial intelligence (AI). These systems comprise many items, each of which has various characteristics. To fulfil the requirements of ADTs, a multi-domain unified model needs to have a close connection with all of the ADT's life stages. This model will consider overall performance and the coupling between each component, which is a crucial basis for the realisation of self-adjustment, self-prediction, and self-assessment, all of which may be summed up as Self Learning Digital Twins (SLDTs). SLDTMs are developed at this time with the assistance of various programs and software; one of the most appropriate packages is the unified modelling language (MATLAB), High-Level Architecture (HLA), and multi-domain system modelling and simulating techniques.

1.1 *Coil Springs in Automotive and Railways*

A suspension system is a collection of mechanical and electronic components that connect a vehicle to its wheels and allow it to "suspend" the wheels above the road surface. The main features of a suspension system are the springs and shocks or dampers. The suspension system in a vehicle is responsible for supporting the weight of the car and its occupants and providing a smooth and comfortable ride. It consists of several components, including the springs, shock absorbers, and linkages, which work together to absorb the energy from bumps and irregularities in the road surface and reduce the motion transmitted to the vehicle body. The suspension system also helps maintain the vehicle’s stability and handling characteristics, allowing it to navigate safely through turns and changes in road conditions. Automotive suspension components are exposed to several forms of stress, which may be broadly categorised as deterministic and unpredictable loadings [5]

Fatigue Failure (FF) is the term used to describe the occurrence of failure when loads are repeatedly applied until the initiation of a fracture is seen. Such failures often occur in vehicle suspension components, typically fabricated from steel [6]. The conventional approach to fatigue analysis of automobile suspension components usually involves using stress or strain time history in conjunction with fatigue laws and damage accumulation rules [7]. Executing this procedure requires a substantial amount of time and computer resources, mainly owing to the vast quantity of data that must be processed. A new approach for evaluating tiredness in the frequency domain was introduced for random loadings to address the concern about time. The frequency domain methodology enables the consideration of nominal acceleration loadings, namely in the form of Power Spectra Density (PSD), to forecast the Fatigue Life (FL) of automotive components. This technique has the advantage of requiring fewer computational resources [5]. The suspension system serves several purposes, including:

A. Providing a smooth and comfortable ride by absorbing bumps and vibrations.

B. Keeping the wheels in contact with the road by maintaining a consistent distance between the wheels and the surface, even when the vehicle encounters uneven terrain.

C. Improving handling and stability by controlling the movement of the wheels.

D. Supporting the weight of the vehicle and distributing it evenly across the wheels.

A car's suspension system can be of many types in the traditional set-up; it includes Coil springs and shock absorbers commonly known as McPherson Strut, leaf springs, semi-elliptical leaf springs, and five-link suspension. Also, there are active suspension systems which use electronic control to adjust the stiffness of the suspension and air suspension, which uses compressed air to adjust the suspension. There are several standard components found in both automotive and railway suspension systems:

1. Springs: Springs support the vehicle’s weight and absorb shocks and vibrations from the road surface or tracks. In automotive suspension systems, standard springs include coil and leaf springs; in railway suspension systems, coil and air springs are more commonly used.
2. Dampers or Shock Absorbers: Dampers control the movement of the springs and dissipate the energy of the vibrations and shocks that the springs absorb. They are also used to

maintain the stability of the vehicle. Dampers are often located within automotive suspension systems' struts or suspension arms. In contrast, in railway suspension systems, they can be found between the wheels and the car body or between the wheels and the bogie.

1.2 *Machines Condition Prediction*

Intelligent manufacturing is a production paradigm that optimises resource allocation by including RT analysis, intelligence, refinement, and agile perception of the market and customer's RT status [8]. The evolution of manufacturing mode is progressing from digital manufacturing to digital-networked manufacturing and finally to the new-generation intelligent manufacturing [9]. Throughout this process, the manufacturing industry undergoes a transformation characterised by increased intelligence, networking, and digitization. The proposed modification introduces issues related to defect diagnosis and prognosis. The new approach is expected to consider the operating environment's impact on prediction, improve the accuracy of prediction outcomes, and tailor the production process accordingly. The concept of DTs involves the creation of a dynamic representation of a physical system using various supporting technologies such as multi-physics simulation, machine learning, augmented reality, virtual reality, and cloud services. It facilitates the ongoing adaptation to environmental or operational changes and yields optimal business results.

This technology has significant opportunities for enhancing operational efficiency and maintenance practices while expediting new product development. The DTs paradigm encompasses many technological features, including CPS, the Internet of Things (IoT), AI, and Unique Identifiers (UI). It also involves resource allocation considerations, such as energy efficiency, and encompasses processes like cloud manufacturing, diverse data management, communication, and physical-virtual interaction. CPS, characterised by their computational and physical capacities, have the potential to establish a strong connection between individuals and the digital realm of information [10]. The IoT can handle substantial volumes of diverse data using various sensors, including radio frequency identification, infrared induction, and global positioning.

These sensors enable the IoT to perform risk detection, fault localization, and safety management [11]. The proposed ADT in this research offers many services from a security perspective, including process control and monitoring, fault diagnosis and prognosis, alarm management, and a reduced mean time between failures. The DT concept enables effective communication between humans and machines, facilitating RT interactions with the environment and physical things. The tool system is exclusively linked to a distinct identification. The ADT paradigm incorporates several forms of AI, such as ontologies, Machine Learning (ML), and Deep Learning (DL). The DT model's feedback mechanism can efficiently rectify faults throughout the tool system design stage. This technology accurately identifies the specific location of failures, whether inside the feed system or the tool itself.

1.3 *Simulation-Based Digital Twins*

In addition to the inherent difficulties associated with the development of intricate items, organisations are progressively endeavouring to oversee and regulate the operational performance of those products to enhance safety, efficiency, and consumer contentment [12]. Model-based methodologies and physics simulation techniques are highly effective in developing a digital replica of a physical asset in operation. This simulated counterpart of the asset identifies irregularities in its performance and forecasts its overall condition and remaining operational lifespan. According to [13], the insight mentioned above can be used with machine learning algorithms to enhance operational downtime, initiate proactive maintenance measures, and minimise expensive breakdowns. The study presents a simulation modelling approach for multi-domain systems, which may be used with several machine learning analytics engines, such as PTC ThingWorx [14]. However, the specific details of these engines are not extensively covered in this paper.

The automotive sector produces many cars that operate under various circumstances. These vehicles require regular maintenance to replace worn components and rectify any defective situations. The present methods of managing the health of cars depend on the field of data science, which has gained significant strength [15]. Nevertheless, the involvement of engineering and physics is restricted and primarily encompasses simplified relationships, material data, and similar elements. As a result, the scope of health management systems has been limited to diagnostics and controlled maintenance for a select number of automotive components and systems. The need for advanced functionalities such as prognostics for essential elements and procedures, such as the engine, exhaust after-treatment, and safety features, is propelling the development of vehicle health management.

DTs provide the automotive industry with an advanced capability to identify abnormal situations and forecast the remaining usable life of degradable components, thereby enhancing the safety and happiness of vehicle owners. A methodology that integrates physics-based modelling approaches (0-D, 1-D, 3-D) at the system level is employed to develop a DT capable of forecasting brake pad wear in a traditional passenger car. In contrast to relying only on physical data, using a simulation-based methodology yields a high-fidelity model capable of forecasting brake pad wear under specific operating circumstances. Moreover, the physics-based models undergo failure scenarios that may result in abnormal brake pad wear and dangerous circumstances. These models are then simulated to analyse the sensor signatures, which in turn assist in enhancing the identification and reduction of hazardous or undesired situations in the vehicle.

1.4 *Predictive Maintenance in the Automotive Industry*

Technological advancements offer numerous benefits, such as expediting digital data collection processes, streamlining production timelines, enhancing the quality of goods while reducing costs, and providing comprehensive information for informed strategic decision-making within the business [16]. Integrating Physical Systems (PS), namely machines, with information technology systems forms the fundamental basis of FIR in production. [17] provides a comprehensive analysis of the key technological trends that form the foundation of the FIR. The authors search into the possible technical and economic advantages these trends provide to manufacturers and suppliers of production equipment. In the framework of FIR, the gathering and thorough assessment of data from diverse sources, including equipment and production systems, as well as business and customer management systems, will be widely used to facilitate RT decision-making.

The impact of FIR, namely in the automotive industry, has resulted in a shift in the maintenance paradigm [18], [19], including vehicle manufacturing [6], [20] as well as following maintenance activities [21]–[23]. It may be said that the automotive industry is at the forefront of embracing the IoT [21]. This cutting-edge technology enables the development of diverse features and services that would have been unattainable to create only a few years ago. For illustrative purposes, we may examine several applications of the administration and upkeep of automobiles. Using sensors and IoT management systems mitigate maintenance activities' inconveniences and time constraint[22]. The use of edge computing systems enables the analysis of vehicle characteristics and the timely notification of operators on any essential problems.

This feature enables timely notification to the driver or vehicle management in advance, indicating the need for potential intervention in the vehicle. By doing so, it helps prevent the occurrence of significant damage and ensures the safety of all on board. Acknowledging conventional management strategies is essential to comprehend the advantages of Predictive Maintenance (PdM). In the realm of industrial and process facilities, it is customary to implement three distinct categories of maintenance management [23]. Run-to-failure (RtF), also known as reactive maintenance, is a maintenance approach in which maintenance activities are carried out only in response to the incidence of problems. This particular strategy is often used in situations when equipment malfunction does not have a substantial impact on the overall functioning or output.

Planned preventative Maintenance (PvM) is a maintenance approach based on time or a predetermined schedule. It entails implementing appropriate measures and procedures to minimise the probability of equipment failure and to avert accidents or malfunctions proactively. Regular performance of maintenance tasks is essential to prevent unexpected equipment failure while it is still operational. Hence, about intricacy, this maintenance approach is within the spectrum that sits between the RtF method and Predictive maintenance (PdM). PdM is a methodology that utilises Condition Monitoring (CM) technology to assess equipment performance. This PdM is achieved via integrating IoT systems, which facilitate connecting electronic devices and mechanical and digital machinery. Consequently, a substantial volume of data can be collected for analysis. Data is gathered over time to monitor the condition of equipment and develop models that may aid in preventing failures.

1.5 *Coil Springs Fatigue Reliability*

Engineers have long been concerned about structural and component failures, characterised by ruptures or significant deformations, for many decades. Fatigue is an essential contributor to mechanical failures in engineering, accounting for 50% to 90% of such failures, with a particular emphasis on metallic components [24]. Static or monotonic loading and cyclic or fatigue loading are two loading phenomena that may result in structural failure. This occurrence is essential when the load is below the threshold of static resistance [25]. Component failure occurs due to cyclic loading, which involves the repeated application and removal of loads. The evaluation of fatigue reliability has significant importance within the failure analysis of cyclic loading since it encompasses the investigation of the durability and reliability of structures. It is vital that car components, particularly vehicle coil springs, be constructed to minimise the likelihood of failure and maximise the inclusion of safety measures, ensuring their durability throughout their operational lifespan [26].

The analysis of vibration fatigue is a growing practice within the automobile sector [27]. For example, [28] conducted an experimental study to accelerate the wheel hub, aiming to reduce the time and expenses associated with measuring the vibration fatigue of a vehicle body using the Dirlik approach. The study by [29] examined an automobile brake to evaluate the impact of load input orientations of FL prediction via vibration fatigue analysis. The existing body of literature highlights the significance of load instances in studying FL in engineering components. Researchers have tried to characterise the specific loadings involved in this process accurately. As a result, the subsequent stages of post-processing and analysis in structural dynamics often include a two-fold examination of vibration fatigue. In this context, the assessment of structural dynamics has the potential to identify areas of fatigue concentration by accurately forecasting stress and strain reactions.

After acquiring stress responses, vibration fatigue analysis has been effectively completed. Various technologies can acquire stress and strain data from structures. These technologies include finite element modelling, operational modal analysis, and accelerated vibration testing. Hence, it is crucial to direct attention towards the post-processing result as a significant component of the vibration fatigue study [30]. Using post-processing techniques, it is common practice to quantify the fatigue-induced damage resulting from strain or stress reactions. The fatigue life analysis may be conducted utilising a widely used time domain methodology, whereby stress and strain responses are evaluated over time. However, PSD function can determine a significant portion of the stress/strain responses shown by actual structures. Hence, the PSD function employs the frequency domain approach as an input for forecasting fatigue life. This function allocates the power of the time signal across different frequencies [31]. Vibration fatigue studies often use the frequency domain technique [32], [33]. Natural Frequencies (NF) occurrence in car components is anticipated to align with the frequency range of road excitation in engineering.

1.6 *Fatigue Life Estimation*

Extensive research has been conducted on fatigue testing under conditions of constant amplitude loading, particularly about High Cycle Fatigue (HCF). Examining fatigue analysis under varied amplitude loading has garnered significant attention recently. There are a variety of cycle-counting algorithms. The authors of [34] analyse fatigue life calculation for helical springs subjected to multiaxial constant amplitude stress using the critical plane technique. The authors of [35]assessed the multiaxial strength of suspension springs using the Von Mises-Juvinall and essential plane criteria. The investigation conducted in [36] focused on assessing the FL of compressor springs subjected to start-stop conditions and examining failure on the cracked surface. The study conducted in [37] focuses on estimating the fatigue life of compressor springs subjected to start-stop conditions and examining failure on the cracked surface. The factors affecting stress distribution in a helical coil spring have been examined in a previous study [38].

The conventional practice involves estimating the FL of mechanical springs by considering the fatigue strength for torsion [39]; however, while conducting fatigue tests on compression springs with a high index, it has been shown that the primary fatigue fractures are generated and spread due to the oscillation of the significant tensile stress, rather than the maximum shear stress. Moreover, the beginning of the fatigue fracture is probably situated on the external surface of the helix, precisely where the major tensile stress reaches its highest amplitude. Several variables, including surface roughness, material decarbonization, and material flaws, such as inclusions, influence helical coil springs' FL. The FL of springs, particularly those produced by cold coiling [35], [39], is controlled by residual stress distribution inside the spring coils. An experimental study was undertaken in [35] to evaluate residual stress's impact on helical springs' fatigue characteristics. Empirical evidence has shown a correlation between the spring fatigue limit and the residual stress field [35].

1.7 *Fatigue Life Prediction*

In the automotive sector, the utilisation of aluminium alloys is constrained by their comparatively elevated cost and less advanced production procedures than steel. Nevertheless, aluminium alloy has the notable benefit of reduced weight, rendering it more prevalent in the automotive sector over the last three decades. Its utilisation mainly encompasses engine blocks, engine components, braking elements, steering components, and suspension arms, providing substantial weight reduction potential [40]. The growing use of aluminium alloys may be attributed to its advantageous characteristics in terms of safety, environmental impact, and performance. Additionally, using aluminium contributes to enhanced fuel efficiency owing to its lightweight nature. The un-sprung weights of suspension components, tyre rims, and brake components need significant weight reduction to enhance ride quality, responsiveness, and overall vehicle weight reduction. The primary objectives of automobile suspensions are the optimisation of passenger comfort and the enhancement of vehicle control.

Comfort is achieved by isolating vehicle occupants from road disturbances, such as bumps or potholes. Control is attained by using measures that prevent excessive rolling and pitching of the automobile body while ensuring optimal contact between the tyre and the road surface. The fatigue qualities of an aluminium alloy represent a significant structural constraint. The primary focus of this research is on the automotive sector, with particular emphasis on a wrought aluminium suspension system. The paramount consideration in this investigation is the aspect of safety. Most of the time, leading up to failure is attributed to the commencement of cracks. Conservatively, it is common practice to consider a component as failed once a fracture has begun [28]. This simplification enables designers to use linear elastic stress outcomes derived from multibody dynamic finite element simulations for FL analysis. The suspension arm experiences cyclic stress, rendering it susceptible to fatigue-induced damage.

Uncertainty in the suspension arm pertains to the anticipated stresses exerted on the automotive component due to diverse driving styles and varying road conditions. Hence, FL estimation exhibits reduced precision even when conducted inside controlled laboratory settings. Therefore, numerical simulation is justified due to its cost-effectiveness, ease of execution, and ability to provide valuable insights into the underlying mechanisms. The study by [41] focused on using Finite Element Analysis (FEA) to assess a component's durability in a two-stroke piston linear engine. The study specifically examined the effects of changing amplitude loading on the part. The authors discussed using FEA to forecast a component’s FL and ascertain its crucial areas. The study also examined the impact of mean stress on the outcome. It demonstrated the ability to generate contour plots depicting the FL histogram and damage histogram at the place of highest criticality.

The fatigue evaluation of the aluminium suspension arm was explored by [42]. While the techniques discussed in this study apply to other structural alloys, the author emphasises their use in aluminium alloys utilised in automobile constructions. The author concluded that the computing demands of the dynamic FEA were substantial. Hence, the model must be characterised by simplicity and may be limited to distinct compartments inside the vehicle. The authors of [43] also used the Coffin Manson (CoM), Smith-Watson-Topper (SWT) parameters, and Morrow (Mo) mean stress correction in their analysis. They discovered that the stress-life approach is strongly associated with HFL. However, it is essential to employ the strain-life strategy when plastic overloads are seen.

[43] used a combination of vehicle simulation, FEA, and computational approaches to develop FL contours for the chassis component. This FL was achieved by integrating automotive proving ground load history results with computational methods. The researchers determined that integrating dynamics modelling and FEA is an available approach for the fatigue design of automotive components. The study of [44] examined a methodology for modelling dynamic loads in automobiles, focusing on durability considerations. The fatigue phenomena of nodular cast iron vehicle suspension arms have been investigated by [45]. The researchers discovered

that casting faults are the primary factor influencing FF in casting components. The dominant factor influencing the HCF characteristics is mostly surface imperfections, such as dross flaws and oxides. Conversely, numerous fractures originating independently from defects occurring during casting primarily control Low Cycle fatigue (LCF).

The study undertaken by [46] focused on predicting FL using varied amplitude testing, specifically for specified applications. The study analyzed three engineering components, subjecting them to constant amplitude loading and various load spectra. The approach is based on the Palmgren-Miner hypothesis but provides the potential to validate the theory by restricting its application to a particular context. The first experiment involved subjecting automobile spot weld components to two distinct synthetic spectra and then extrapolating the results to predict the behaviour under new service spectra. In the second scenario, an examination is conducted on the fatigue characteristics of a rock drill component. This analysis involves subjecting the component to both constant amplitude testing and spectrum tests. Subsequently, a comparison is made between the two sets of reference tests. The third scenario involves the analysis of butt-welded mild steel, focusing on its load level crossing capabilities and other irregularity causes.

The study by [43] examined the impact of varying amplitude loading on the FL and failure mechanism of adhesively bonded double strap joints composed of clad and bare 2024-T3 aluminium. The authors concluded that the FL of a loading spectrum with varying amplitudes may be reasonably estimated using an effective stress range versus the FL curve. The study [43] evaluated the fatigue crack development spectrum using variable amplitude data. This study summarises a contemporary semi-empirical model that demonstrates the potential to provide more precise forecasts of fatigue life. The model uses flight load spectra derived from genuine in-service use.

The present study presents a novel model with an alternate approach to interpreting fatigue test results at full-scale and coupon levels. Additionally, this model demonstrates its capability to produce accurate forecasts of FL across various scenarios. The capability above has significant importance, especially when there is limited capacity for conducting a comprehensive fatigue test, potentially resulting in more cost-effective utilisation of airframes. The primary aim of this research is to do a fatigue study on an aluminium suspension arm using the FE, considering changing amplitude loading. The primary goals of this study are to use the Strain Life (SL) approach to forecast the FL of the suspension arm and determine the essential point inside the arm. Additionally, optimising the material for the suspension arm is intended to be achieved.

1.8 *Finite Element Analysis (FEA) for Fatigue*

Historically, fatigue analysis has been conducted towards the latter phases of the design process because loading information can only be obtained by direct measurement, necessitating a prototype [47]. Multibody dynamics can forecast the loads experienced by components, allowing designers to conduct a fatigue evaluation before the physical realisation of a prototype [47]. The primary objective of analysing a structure at the first stages of the design cycle is to mitigate the duration and expenses associated with its development. The purpose of this endeavour is to ascertain the essential area of the structure and enhance the design before the construction and testing of prototypes. When used for fatigue analysis, the FEA method may be regarded as a comprehensive engineering analysis technique for the component. Estimating FL may be conducted for each element inside the finite element model, allowing for the acquisition of contour plots depicting the distribution of life degradation. The geometric data is obtained from the FEA results of each load situation. The FL analysis of a component may be effectively conducted by an integrated method encompassing multibody dynamic analysis, FEA, and fatigue analysis. This technique ensures a cohesive and comprehensive prediction of the component's FL [44].

Fatigue assessments may be conducted using one of three fundamental approaches: stress-life, strain-life, and fracture growth. The stress-life approach was first used more than a century ago, focusing on examining nominal elastic stresses and their correlation with the lifespan of a material. This methodology for assessing component fatigue is effective when only elastic loads and strains are present. Nevertheless, although most components may exhibit cyclic elastic stresses within their nominal range, the presence of stress concentrations in the component might lead to localised cyclic plastic deformation. In the given circumstances, the local strain-life technique employs the local strains as the predominant fatigue parameter. The strain-life technique has the potential to be used proactively for a component in the first phases of design. The local SL technique is recommended in cases where the loading history exhibits irregular patterns, and the influence of mean stress and load sequence effects is deemed significant.

The SL approach encompasses many methodologies for transforming the input of loading history, shape, and material characteristics (both monotonic and cyclic) into a forecast of fatigue life. The sequential execution of operations is necessary in the prediction process.

Initially, an estimate is made for the stress and strain occurring at the crucial location. Subsequently, the load-time history is reduced using the RainFlow cycle counting approach [48]. The subsequent procedure involves using the FE approach to transform the load-time history that has been reduced into a strain-time history.

Additionally, this method is used to compute the stress and strain inside the region experiencing significant stress. Subsequently, the fracture initiation procedures are used to forecast the FL. The accumulation of fatigue damage is facilitated by the use of the simple linear theory, as put forward by Palmgren [49] and Miner [50]. Ultimately, the cumulative damage values of each cycle are aggregated until a threshold is met, known as the critical damage total or failure criterion.

1.9 *Condition-Based Maintenance of Coil Spring*

Condition Based Maintenance (CBM) is a maintenance strategy that focuses on monitoring the condition of a component or system and performing maintenance only when needed. This approach to maintenance is based on the idea that by monitoring the condition of a component and acting only, when necessary, manufacturers, maintenance companies, and owners of vehicles can reduce costs and improve the overall performance and reliability of the component or system. For coil springs, CBM typically involves monitoring the springs for signs of wear or damage, such as rust, corrosion, deformation, or sagging. Other parameters like spring rate and alignment are also monitored.

1.10 *Condition-Based Maintenance Procedure*

1. **Sensor installation:** Install sensors or monitoring devices on the spring, such as strain gauges or accelerometers, to measure the load and movement of the spring and to detect any changes in its condition.
2. **Data Analysis**: Use data analysis to monitor the spring's condition over time and to detect any unusual patterns or trends that may indicate a problem.
3. **Maintenance Schedule:** Schedule maintenance or replacement of the spring based on the data collected rather than on a fixed schedule or a set number of miles driven.
4. **History:** Keep records of the data collected and the maintenance performed to establish a history of the spring's condition and performance.

Implementing a CBM strategy for coil springs can help improve the suspension system's performance and reliability, increase safety, and reduce maintenance costs by avoiding unnecessary repairs and replacements. However, it is essential to remember that it can also be more complex and require more resources to implement and maintain than traditional PvM strategies.

1.11 *Coil Springs Maintenance Based Digital Twins*

A DT is a virtual representation of a physical object or system that can be used to simulate and analyse its performance in a virtual environment. DTs can be used in many different industries, including manufacturing and transportation, and can be integrated with maintenance strategies to improve the performance and reliability of components and systems. For coil springs, DT technology can be used to simulate the performance and condition of the springs over time, allowing maintenance engineers to:

1. Create a DT of the coil spring: Using data from the physical spring, such as its design, material properties, and load history, a DT of the spring can be created and used to simulate its performance and behaviour in a virtual environment.
2. Monitor the DT: Sensors can be placed on the physical spring to collect data on its load, movement, and other characteristics. This data can be used to update the DT in RT, allowing engineers to monitor the performance and condition of the spring over time.
3. Analyse the DT: By analysing the data from the DT, engineers can identify potential problems with the spring, such as deformation sagging, and predict when maintenance or replacement will be needed. The equipment and sensors used to collect the data, the types of the collected data, and how the data was processed and analysed from the Physical Twin (PT) to the DT model are discussed in detail in ***Chapter 4*** (in particular ***Section 3*** and ***Section 6***) and ***Chapter 5*** (in particular ***Section 3***)
4. Use DTs for simulation: Engineers can also use the DT to simulate different scenarios, such as changes in loading conditions, temperature, and humidity, to understand how these factors might affect the spring's performance and to predict how long it will take for the spring to reach its end of life.
5. Schedule maintenance: Based on the analysis and simulation, maintenance can be scheduled and performed only when needed, thus improving the overall performance and reliability of the spring.

Integrating DT technology with the maintenance of coil springs makes it possible to improve maintenance activities' precision, efficiency and cost-effectiveness, thus avoiding unnecessary repairs and replacements.

1.12 *Advanced Digital Twins for Coiled Springs*

This research integrates ML with DTs for CRT CM and predictive fatigue lifecycles, making the DTs models become an ADT model that can benefit industrial operations. ADT is a virtual replica of a PS, such as a machine or equipment that can monitor and predict the asset's performance. By integrating ML into the DTs, it can be possible to use data from the asset (the type of data mentioned in **1.13**) to train machine learning models to detect patterns or anomalies that may indicate a potential failure or other problems with the asset. Overall, using DT technology to maintain coil springs can improve the performance and reliability of the suspension system, reduce maintenance costs, and optimise the use of resources. It also offers a deeper understanding of how the spring behaves in different conditions and how long it will take to reach the end of life.

1.13 *Digital Twins for Predictive FL and Maintenance*

The concept of DTs has novel prospects for implementing PdM in industrial machinery. This approach enables the consideration of the impact of operational conditions on cutting tools, hence enhancing comprehension and utilisation of the projected outcomes. The present trajectory of technical growth has led to the gradual emergence of intelligent manufacturing, resulting in a shift from mass production to customised manufacturing. RT data is obtained and recorded into an Excel sheet. The data sets contain information about the coiled springs static and dynamic conditions data, some shown below and discussed in detail in ***Chapter 5***. The following data is divided into columns representing sensor input as follows:

1. Static Load (N)
2. Dynamic Load (N)
3. Static Force (N)
4. Strain
5. Velocity (m/s)
6. Dynamic Force (N)
7. Horizontal Deformation (mm)
8. Vertical Deformation (mm)

The signals comprise the predictor variables; the final column for the response variable will be for the output response. This integration between DTs and ML can allow for more proactive maintenance, reducing downtime and prolonging the lifetime of the assets. Additionally, the integration of ML can predict possible failures, allowing for PvM rather than reactively fixing it after the failure.

1.14 *Benefits of Integrating ML With DTs for Maintenance*

ML is an AI method used to analyse data and make predictions. Integrating ML with DTs can bring several benefits, as shown in ***Chapter 5***, such as:

1. **Predictive Remaining Lifecycles**: ADT can monitor the health of equipment in RT. Applying ML to this data can detect anomalies, indicating potential failures and allowing for timely intervention.
2. **Process Optimization: Predictive Fatigue Damage (FD) and Remaining Useful Life (RUL;** ML can analyse the data from DTs to identify inefficiencies or sub-optimal configurations in processes. Optimizations can be iteratively applied to improve performance as the system learns from real-world operations and feedback on the performance and reliability of the suspension system.
3. **Enhanced Decision-making**: Decision-makers can use insights from ADT to make informed choices about system modifications, resource allocation, and other operational factors.

1.15 *Contribution to the Research Field*

1. **Advanced Modelling Techniques**: The intersection of ML and DTs challenges researchers to develop more sophisticated models capable of handling complex datasets.
2. **Interdisciplinary Collaboration**: This convergence brings together experts from computer science, engineering, data science, and domain-specific experts to collaborate and contribute to novel solutions.
3. **Enhanced Simulation Capabilities**: ML-driven DTs offer a much more nuanced and accurate representation of real-world scenarios for research that depends on simulation.
4. **New Avenues for Innovation**: As researchers access more granular data and advanced analytical tools through ADTs, new opportunities for innovation in various sectors, from manufacturing to healthcare, become apparent.

In summary, integrating ML and DTs enhances current practices and allows ground-breaking research in multiple domains.

1.16 *Why Those Objectives and Not Others?*

The objectives or benefits mentioned earlier regarding the integration of ML with DTs emerge from the current needs and challenges faced by industries and researchers such as:

1. **Technological Evolution**: As digital technology and computational capabilities advance, they allow for complex simulations, data processing, and RT monitoring.
2. **Immediate Needs of Industries**: Industries are continually seeking ways to improve efficiency, reduce costs, and enhance product quality. PdM, process optimization, and RT monitoring address these direct needs.

3. **Economic Considerations**: Cost savings, reduced downtimes, and resource optimization directly impact the bottom line for companies. Therefore, objectives that contribute to these economic benefits become priorities.
4. **Safety and Reliability**: In critical industries (like aviation, nuclear energy, or healthcare), ensuring system safety and reliability is paramount. Objectives that enhance safety, such as advanced modelling techniques, are essential.
5. **Research and Innovation**: The academic and research community often pursues objectives that might not have immediate commercial applications but push the boundaries of what is possible, leading to long-term innovation.

It is worth noting that the objectives and benefits of ML with DTs are not exhaustive. As technologies evolve, industry needs shift, and societal priorities change, the objectives can also evolve. Other objectives might not be mentioned, and they could be equally valid based on the context or specific applications.

2 PROBLEM STATEMENT

This work's primary objective is to create a DT model that might be applied to improve coil springs design and maintenance techniques. In order to improve spring design techniques, this effort set out to define DTs and create proof-of-concept to be used as a reference across theory and practice. Additional objectives of the investigation included identifying value-adding applications for DTs and determining whether every product might have a DT, which is doable. Additionally, information from various sources is expected to be combined by the DTs. Additionally, there is no common consensus among the DTs across theory and practice. As a result, the intended objective of enhancing machine design methodologies could not be realised, and the later stages were devoted to creating DTs as a general tool that could be applied to machine design in future works. Therefore, this research focuses on creating a DT that shares a common understanding and platform to be presented to the research and development process.

2.1 *Types of Faults with Coiled Springs*

Coil springs are an essential component of many suspension systems, and when they become damaged or worn, it can lead to various problems with the vehicle's handling and ride comfort. Here are some common faults that can occur with coil springs:

1. **Sagging / Weakness:** Coil springs can lose their tension and sag over time, which can cause the vehicle to sit lower on one side and affect ride comfort and handling. The spring rate may be reduced, affecting the suspension performance.
2. **Over-compression** occurs when the springs are compressed too much, which can cause them to lose their shape and affect the vehicle's handling and ride comfort.
3. **Fatigue:** This occurs when the springs are repeatedly stressed and become weak. This fatigue can result in cracking or breaking and cause the vehicle to ride unevenly.
4. **Breakage:** Coil springs can break due to corrosion, rust, or fatigue, leading to sudden loss of suspension and possibly a wheel falling off, making the vehicle undrivable.
5. **Deformation:** If a coil spring is subjected to excessive force or loading, it can become deformed, affecting the suspension's performance and handling.
6. **Misalignment:** Misalignment of the spring with the rest of the suspension system can cause abnormal wear and affect the handling and stability of the vehicle.

If any of these problems are noticed, a professional must inspect the suspension system to determine the cause and ensure that necessary repairs or replacements are made to restore the vehicle's performance and safety.

3 MOTIVATIONS

PROS (as deduced from the literature)

1. ADTs are a promising technology widely used in various industries to monitor performance, optimise processes, simulate outcomes, and predict potential faults.
2. ADTs play various roles throughout the product lifecycle, including design, manufacturing, delivery, use, and the end-of-life cycle.
3. ADTs may simplify the future of product design, development, and innovation by simultaneously operating two identical products: DT and the physical product.
4. ADT technology can transform and provide solutions to industrial and research issues.
5. ADTs allow predictive maintenance through remote monitoring, fault detection and diagnosis, reducing downtime, preventing sudden breakdown, and offering lower maintenance costs.
6. Due to improved optimisation, ADTs increase equipment reliability and offer faster production lines in the cycle times of critical processes.
7. ADTs improve productivity, product quality, and performance of multiple RT applications and environments, improving customer service.

CONS (As deduced from the literature)

1. There is a need to consolidate a comprehensive research analysis of the DT technology to maintain a common and shared understanding of the technology across the targeted theory and practice and ensure that future research efforts are based on a solid foundation.
2. There is a need to identify what is still missing to make DT technology compliant with its description in the literature.
3. Simulation-based on the theoretical and static model has been a conventional and powerful tool for verifying, validating, and optimising a system in its early planning stage. However, no attention is paid to the simulation application during system run-time.
4. Lack of a comprehensive examination and analysis of techniques must be utilised within each domain of knowledge and application to maximise the benefits of DTs.

4 AIM AND OBJECTIVES

The rationale for choosing suspension systems as a case study evolved from the gaps, challenges, and limitations of the method in the literature, as shown in ***Chapter 2***, ***Section 6.6***. and ***Section 7.*** The references in ***Table 2.14*** show the importance of the coiled springs used in suspension systems in both the railway and automotive industries and show how critical it is to monitor and diagnose faults as early as possible before a catastrophic failure occurs. Additionally, ***Table 2.14*** shows the most recent methods used to diagnose faults of suspension systems, some of which were in 2023. ***Table 2.14*** shows the limitations of each method; also, it is worth mentioning that none of these methods can monitor the suspension systems in operation due to the complexity and variety of the dynamic load applied continuously during operation and the vast variety of different environmental conditions. More importantly, none of these methods used Digital Twins before for the suspension systems. DTs have shown the reliability of condition monitoring using CRT data. DTs can solve the complexity of the dynamic load applied continuously during operation, allowing engineers to consider the degradation of the suspension systems over time.

4.1 *Aim*

This research aims to implement ADTs to evaluate the live conditions of the primary coiled springs used in suspension systems and predict their Remaining Useful Life (RUL).

The aim is reached through the following four phases:

1. Comprehensive and systematic deep investigation of DT technology from origin to future

- History
- Concept
- Levels
- Development
- Applications
- Challenges
- Gaps and Future Work

2. Implementing Physical and analytical models based on Euler's method into DTs for any scenario that may have an impact on the primary spring at any moment in time

Linear Vibration

A- DAMPED
- Free forced
- Steady forced
- Transient forced

B- UNDAMPED
- Free forced
- Steady forced
- Transient forced

Transient Vibration

A- DAMPED
- Free forced
- Steady forced
- Transient forced

B- UNDAMPED
- Free forced
- Steady forced
- Transient forced

3. Experimental design and AI merging with DTs of the proposed method

- Implementation
- Evaluation
- Validation
- Verification

4.2 *Objectives*

1. Utilise a systematic review methodology and incorporate the science mapping method to conduct an in-depth review of the current research state regarding DTs' concepts, key components, development, and industrial applications.
2. Consolidate a comprehensive research analysis of the DTs technology to maintain a shared understanding of the technology across theory and practice and ensure that future research efforts are built on a solid foundation.
3. Determine what is required to bring DT technology into compliance with its description in the literature.
4. Integrate ML with DTs technology to make an ADT technology from a live virtual representation to a self-learning technology.
5. Propose a practical implementation model of DTs using a primary springs application. The application provides a foundation for addressing the practical implementation gaps identified in the literature.
6. Simulate the primary spring using both wired and wireless DT models.
7. Compare the results of the practical experiments, simulation, and wireless DT with the wired DT model.
8. Comprehensively examine and analyse all techniques and methods used to maximise the benefits of DT.
9. Pave the way for future research to close the gap between theory and practice application of DTs in industries through the developed ADT model.

5 RESEARCH QUESTIONS

This research is organised to answer the following research questions to utilise ADT technology to monitor and forecast maintenance and the RUL of the primary springs used in suspension systems. Therefore, these research questions are strictly related to the mechanical structure of the primary coiled springs.

Q1 What are the actual characteristics of the DT concept for standardisation across theory and practice?

Q2 How to implement ADTs into PdM of mechanical springs used in suspension systems? So that it can predict FD and RUL

6 THESIS CONTRIBUTION

The contribution of this thesis can be summarised as follows:

1. Provides a comprehensive systematic analysis of the DTs' technologies; the literature shows little to no integration between the review and science mapping of DTs. This thesis uses a systematic review methodology while incorporating the science mapping method resulting in the consolidation of different types and definitions of DTs throughout the literature to quickly identify DTs from the rest of the favourable terms such as 'Product Avatar (PAv)', 'Digital Thread (DTh)', 'Digital Model (DM)', and 'Digital Shadow (DS), (CPS), Cyber Physical Equivalent (CPE)' as shown in ***Section 6.3*** **Chapter 2**.

2. This research deeply examines DTs' concept, maturity, creation, values, applications, techniques, and technology, narrowing the dimensions of the DTs modelling from five to three (Physical, Digital and Connection). The literature shows a minimum of five dimensions to implement DTs [51]; the more dimensions there are, the more cost, complexity, and difficulty implementing the DTs.

3. The research improves the predetermined design average load of the primary springs of simulation and experimental results by 35.7 %. This research improves the average lifecycles of primary springs by 12 and 9 times more than the simulated and experimental results. Additionally, it improves the average lifecycles of the primary springs by 19.7% compared to the wireless DTM results, as shown in ***Chapter 4***. The proposed DTM continuously visualises and evaluates the springs' mechanical conditions in RT.

4. This research integrates AI with DTs to advance the DTs models and proposes an ADTM with a prediction error of less than 0.0001 % and classifying the system's faults with regression accuracy throughout training, validation, and testing were 0.99997, 0.99954, and 0.99931, respectively, for a total accuracy of 0.9998 as shown in ***Chapter 5*****.**

7 THESIS OUTLINE

CHAPTER ONE ***(Introduction):*** This chapter presents the Background of DTs and fatigue analysis methods used for coiled springs, Problem analysis, Project aim, Research questions, Project limitations, and Motivations.

CHAPTER TWO ***(First Contribution):*** Presents a comprehensive systematic review analysis and includes the publication contribution of a paper titled "***Comprehensive Systematic Analysis of Digital Twins: History, Concepts, Development, Applications, Challenges, Gaps and Future Work***".

CHAPTER THREE ***(Second Contribution):*** Presents a physics-based DT model and outlines the approach to problem-solving using Euler's mathematical theories for the prediction used in the DTs technology. Additionally, it includes the second publication contribution of a paper titled "***Physics-Based Digital Twins for Vibration Fatigue Analysis and Modelling from Theory to Concept Implementation***."

CHAPTER FOUR ***(Third Contribution):*** Presents *Implementation, Evaluation, Validation, and Verification of the proposed method* through a case study used to compare and validate the proposed mathematical analysis. Additionally, it includes the third publication contribution of a paper titled "***Digital Twins for Fatigue Damage and Lifecycles of Coil Springs Used in Suspension Systems***."

CHAPTER FIVE ***(Fourth Contribution):*** Presents the integration between DT models and ML to advance the DT technology and bring the self-learning models as a revolution in industry 5.0. Additionally, it includes the fourth publication contribution of a paper titled "***Advanced Digital Twin Modelling for Predictive Fatigue Lifecycles of Coil Springs Based Machine Learning***".

CHAPTER SIX ***(Conclusion):*** Presents the final chapter of the thesis; this chapter gives the conclusion statements regarding the findings in this thesis to demonstrate how to implement and deploy DTs in physics-based modelling from theory to practice with the mechanical structure of the primary springs used in suspension systems. This chapter summarises the outcome of the research and the results achieved in the thesis titled "Conclusion."

CHAPTER 2

Comprehensive Systematic Review Analysis of Digital Twins and Fatigue Analysis

1 CHAPTER OVERVIEW

Digital Twins (DTs) continue to evolve as they expand into new applications in theory and practice, continuously increasing the variety of definitions and concepts of DTs in the literature, resulting in misconception and confusion about the technology and the term DTs being wrongly used in different disciplines. Many reviews on DTs [52]–[61], but none provide a comprehensive systematic analysis of the DTs' technologies. Therefore, there is a need to consolidate a comprehensive research analysis of the DT technology to maintain a common and shared understanding of the technology across theory and practice and ensure that future research efforts are based on a solid foundation. The literature states that DTs apply to all industries for any application; however, most industries lack integration of actual DTs. Therefore, there is a need to identify what is still missing to make DT technology compliant with its description in the literature.

This review deeply examined DTs' concept, maturity, creation, values, applications, techniques, and technology and created the most suitable way to implement DTs in theory and practice through 500 publications. This review guides the status of DT's development and application in today's theory and practice environment. This review also outlined the current challenges and possible future work directions. This review consolidated the different types of DTs and definitions throughout the literature to quickly identify DTs from the rest of the favourable terms, such as Product Avatar (PAv), Digital Thread (DTh), Digital Model (DM), Digital Shadow (DS), Cyber-Physical System (CPS), and Cyber-Physical Equivalent (CPE).

This chapter provides a study that includes the DTs technology using a systematic review methodology while incorporating the science mapping method. This chapter intends to guide the status of DT development and application in today's theory and practice environment. This chapter also outlines the current challenges and possible future work directions. A generalised concept/definition emerges, encompassing the breadth of options available and providing a detailed characterisation that includes criteria to distinguish DT from other digital technologies. The proposed concept/definition is "***Four dimensions virtual replica that continuously simulates the entire behaviour of anything.***"

2 INTRODUCTION

Digital Twins (DTs) have transformed the Fourth Industrial Revolution (FIR) from the Internet of Things (IoT) to highly detailed virtual replicas of machinery or systems. Many businesses already use DTs to detect defects and improve efficiency. As information technologies advance, the digitalisation process accelerates, particularly with the emergence of a new generation of information technologies such as IoT, Cloud Computing (CC), Big Data (BD) analytics, and Artificial Intelligence (AI) [62], [63]; they were divided into four stages: digital enablement, digital support, digital control and linkage, and cyber-physical integration. Many consider John McCarthy's 1956 "Dartmouth Summer Scientific Project" workshop on AI the official introduction of AI as a research topic [64]. Since 1956, AI research has yielded intelligent systems capable of performing physical tasks, reasoning, forecasting future events, and making decisions. Machine Learning (ML), Deep Learning DL, Central Processing Unit (CPU), Graphics Processing Unit (GPU), Tensor Processing Unit (TPU), and Processing Capacity (PC) have all aided in the widespread adoption of AI applications in our daily lives.

NASA pioneered the Physical Twin (PT) concept through system engineering and Condition Monitoring (CM) 1970. For Apollo 13, two identical spacecraft were built; one was flown into space to complete the mission, and the other remained on Earth. NASA used the one that stayed on earth to investigate what was happening in space [65]. They recognised the DT phenomenon and immediately began investigating the technology's impact on business. Michael Grieves made the first proposal to use the word "(Digital Twin)" in 2002; naturally, the notion was presented in the context of Product Lifecycle Management (PLM). According to [66] definitions, DT is a three-dimensional representation of the actual Physical System (PS): (A) Physical Entity (PE), (B) Digital Entity (DE), and (C) Connectivity. On the other hand, Grieves' definition was not a formally defined term. Grieves classified his 2002 concept of DT into three categories in 2005, further subdividing it into three subcategories. (A) DT prototype (B) DT aggregate (C) DT instance. With the advent of Industry 4.0 and IoT, data collection methods rapidly evolved from manual data collection on paper to digital data collection via sensing technologies, vision systems, image processing, laser, coordinate measuring machines, and actuators [67].

Physical measures are now digitally gathered, stored, analysed, and shown. The introduction of AI, ML, DL, CPU, TPU, GPU, and IoT laid the groundwork for the DTs, enabling visual monitoring, control, and optimisation of products [68]. In 2010 NASA characterised DT in modelling, simulation, information technology, and a processing roadmap. Between 2005 and

2010, a spate of technology improvements occurred, and NASA and the US Air Force used DT for the structural management of aircraft. NASA and the US Air Force selected the DT as a critical and promising technology for future vehicles in a joint paper 2012 [69]. Following this publication, many academic studies in aerospace and aeronautics were conducted to propose the Airframe DT for design and maintenance. Grieves introduced the three-dimensional structural DT [66], allowing other sectors apart from aerospace to begin using the DT. Researchers forecasted various concepts of DT technology and integrated them into multiple technologies for a brighter future.

Theory and practice pioneered the DT concept and developed product and service business strategies. Service sectors include health care and medicine [70], automotive DT Bring Value to Radio Frequency Identification (RFID), IoT Data, and oil and gas [71] are examples of service industries. Lockheed Martin Company of Space Systems named DT one of the top six promising aerospace and future defence technologies 2017 [72]. In 2018, the official global research and advisory firm (Gartner) declared DT one of the top ten promising future technologies [73]. DT technologies have received widespread attention; however, despite significant work and discovery that promises a prosperous future in integrating DT into industries, the state of the research is opaque [74]. The concept is not well understood, impacting the technology's future development. The primary outcome of this chapter is to develop and base scientific knowledge as it tries to:

1- Deeply examine DTs' concept, maturity, creation, values, applications, techniques, and technology to identify and create the most suitable way to implement DTs in theory and practice through a comprehensive systematic analysis of 500 publications.

2- Classify different types of DTs and definitions throughout the literature to select the appropriate DT development methodology from the wide range of definitions, such as

3- Propose a generalised concept/definition encompassing the breadth of options available and providing a detailed characterisation that includes criteria to distinguish DTs from other digital technologies. The proposed concept is "***Four dimensions virtual replica that continuously simulates the entire behaviour of anything.***"

The rest of this chapter is organised as follows: ***Section 3*** Describes the scope of this review; ***Section 4*** is the literature methodology; ***Section 5*** presents the literature review; ***Section 6*** is the literature analysis; ***Section 7*** is the literature gaps; ***Section 8*** shows the chapter summary.

3 SCOPE OF THE REVIEW

The scope of this review is to remove the misconception of the DTs and propose a concept that can be used as a reference across theory and practice. Additionally, to answer the following research questions, use ADT technology to monitor and forecast maintenance and the Remaining Useful Life (RUL) of the primary springs used in suspension systems. Therefore, these research questions are strictly related to the mechanical structure of the primary coiled springs. **Q1** What are the actual characteristics of the DT concept for standardisation across theory and practice? **Q2** How to implement ADTs into Predictive Maintenance (PdM) of mechanical springs used in suspension systems? So that it can predict Fatigue Damage (FD) and RUL. The first stage in any review is to define the scope of the study to establish the study's restrictions, boundaries, and objectives. ***Table 2.1*** shows the summary of the scope for this review, keeping in mind that the scope is within the frame of the research questions. [75] specified six dimensions to be followed while deciding the scope of the review. The author determined the scope in line with [75] as follows:

Focus: Using citations; the author directed the study's attention to the DTs' concepts, applications, methods, and findings. ***Aim:*** Regarding the second dimension, the author conducted this study to discover limitations, gaps, and concerns that ultimately result in the inability to use technology accurately and correctly. ***Perspective***: This research's authors present the review objectively and without bias. ***Coverage****:* This review will be representative, and the authors are committed to ensuring that it covers all relevant areas to accomplish the purpose. ***Organisation****:* The organisation is conceptual and is determined by the scope and perspective. ***Audience****:* The author addresses this work to engineers, engineering academics, and technology scientists.

Table 2.1 Summary of the scope of the literature

Dimension	Summary
Focus	Concept, value, methodology, applications and results
Aim	Identifying limitations and gaps
Perspective	Neutral representations
Coverage	All areas which represent the focus in a representative manner
Organisation	Conceptual
Audience	Academics, engineers, scholars and practitioners

4 LITERATURE METHODOLOGY

a comprehensive review must be carried out at the first stage of the research to add new scientific knowledge to the existing literature and identify the gaps in the literature; many articles and authors highlight the importance of carrying out the relevant review study [74]. *Figure 2.1* shows the overall methodology for the comprehensive systematic analysis adopted in this thesis. The related work review identified what was done relative to the area of research. It is critical to avoid duplication of research and properly recognise the authors of prior work. This investigation begins with the fundamental issues surrounding DT technology. Additional sources like Google Scholar eliminated bias toward specific scientific publishers. The author of this thesis considers this review method appropriate and enough for this research in line with [76]. Although the time was not strictly specified, the literature started in November 2019 and continued to be updated until 2023 at the time of submission. The study focused on "DT", "IoT" " fatigue analysis and "CM" to reach the aim of the research.

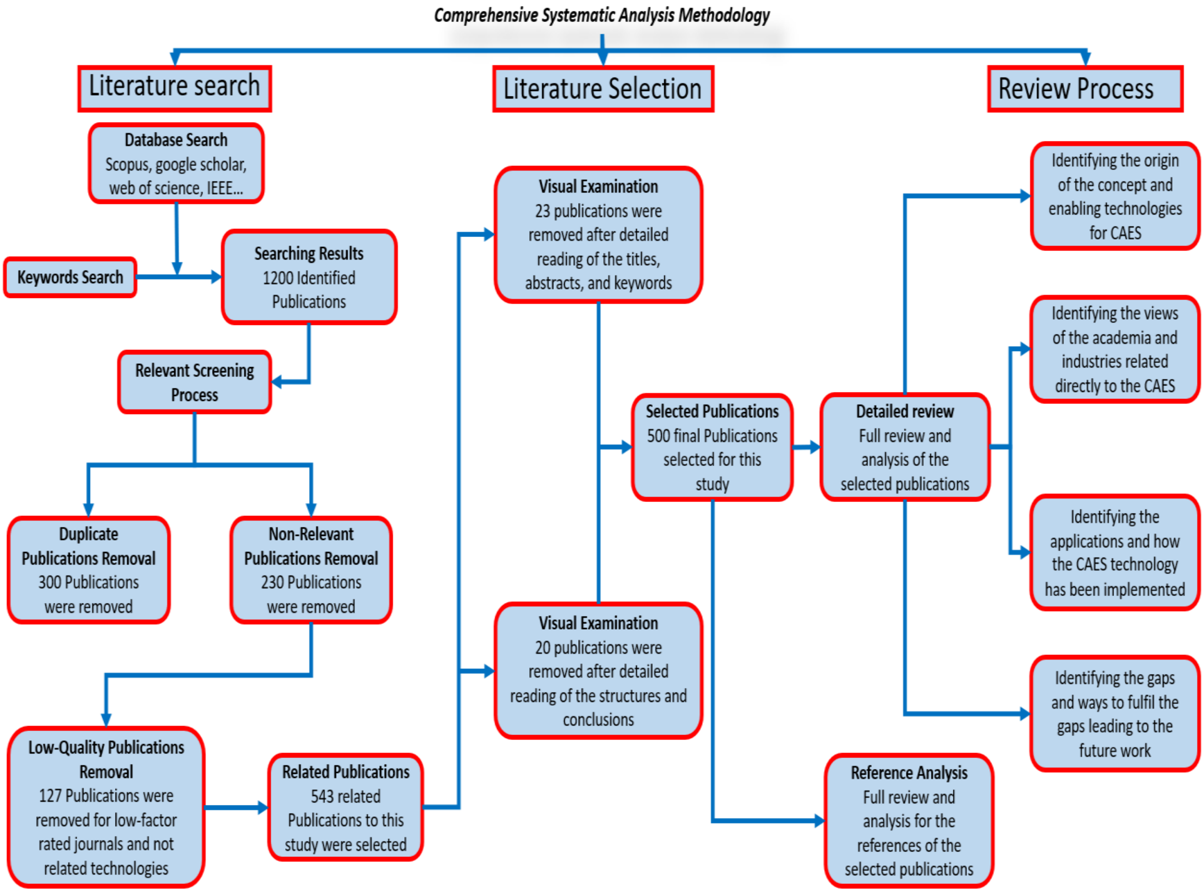


Figure 2.1 Overview of the comprehensive systematic analysis process

This study employed a systematic review, which is vital for the research method to provide an overview of prior research in a given field of study and identify any knowledge gaps in the previously published publications [77], [78]. This approach abides by the standards, including a systematic review or presentation of a transparent process, replication and updates, and summarising and analysing the research's primary topic. This study modified the Refs' [79]–[81] methodologies to evaluate and review the substantial literature within the defined domain. An initial literature search using various databases, a filtration process, and content analysis are required. As a result, a thorough content analysis was done after selecting academic journal articles in three stages, choosing closely related publications.

4.1 *Literature Search*

The time frame for the literature search is established from 2000 and continues to be updated to 2023. Additionally, "article", "review", "state of the art", and "literature review" were chosen as the document type since they represent the most trustworthy and influential sources of information [82]. [83] produced and advised using the idea matrix areas in which additional research and analysis are necessary for the current research stage.

4.1.1 *Database Search*

Since Scopus contains a broader selection of scientific papers [84], [85], it was chosen for the initial literature search. In addition, search engines like Web of Science, PubMed, and Google Scholar perform worse than Scopus [85], as shown in ***Table 22.*** [84] noted that compared to other databases, the Scopus database includes conference papers, has a quicker indexing procedure, and is available for more current publications. A thorough search was done using two parts. The first part of the search was a search string in the Scopus "article title/abstract/keyword" field. Keywords relating to "digital twins", "real-time condition monitoring", "internet of things", "virtual counterpart", "digital replica", or "virtual twin" made up the first section. ***Table 2.4*** shows the journals which they have related papers to DTs.

Table 2.2 Summary of the database used in the research

Database	Specifications
IEEE	"Title, Subject, Abstract"
Scopus	"Title, Keywords, Content Item Title, Subject, Abstract"
Web of Science	"Title, Keywords, Subject, Abstract"
Google Scholar	"Title, Keywords, Content Item Title, Subject, Abstract"
SpringerLink	"Title, Keywords, Subject, Abstract"
Science Direct	"Title, Subject, Abstract"
AIS Electronic Library	"Title, Keywords, Content Item Title, Subject, Abstract"
EBSCOhost	"Title, Subject, Abstract"
Emerald	"Title, Keywords, Content Item Title, Subject, Abstract"

4.1.2 *Selected Journals*

Table 2.3 Selected journals for the study and the number of articles selected

JOURNAL NAME	No
Automation in Construction Journal of Cleaner Production	6
Applied Sciences	4
AIP Conference Proceedings	4
applied system innovation	7
Advanced Engineering Informatics	6
Buildings	8
CIRP Journal of Manufacturing Science and Technology	6
Computers in Industry	8
Computers and Structures	9
Computers Integrated Manufacturing Systems, CIMS	5
Decision Support Systems	7
Energy and Buildings	4
Frontiers in Built Environment	9
IEEE Access	7
IEEE Transactions on Industrial Informatics	9
IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)	8
IEEE International Journal of Production Research	8
International Journal of Advanced Manufacturing Technology Robotics	11
International Journal of Computer Integrated Manufacturing	7
International Federation of Automation Control (IFAC)-Papers Online	6
International Journal of Safety and Security Engineering	7
Journal of Management in Engineering	6
Journal of Ambient Intelligence and Humanized Computing	11
Journal of Manufacturing Systems	10
Journal of Intelligent Manufacturing	5
Proceedings of the 18th International Conference on Industrial Engineering (IJIE)	9
Procedia Manufacturing	6
Procedia CIRP	3
Proceedings of the 25th American Conference on Information Systems	8
Robotics and Computer Integrated Manufacturing	7
Sustainability	7
Structure and Infrastructure Engineering	4
ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb	4
WasserWirtschaft	4
TOTAL	230

4.1.3 *Selected References*

In line with [83] characteristics, the meta-data will include the meta-information about the used articles in the study, as shown in ***Table 2.4*****.**

Table 2.4 Summary of the analysis of the references

Characteristics	Domains	# Articles	
Timeline	2000-2006 2007-2013 2014-2017 2017-2022	17 26 38 51	∑ = 132
Keywords	DT Internet of things Simulations PAv CPS CPE	39 26 32 27 14 9	∑ = 147
Aim	Employed prototype Visualisation's methods Monitoring methods Fundamental understanding	19 21 14 6	∑ = 60
Objectives	Added knowledge Enhancing the standards	16 24	∑ = 40
Literature	Information technology Lifecycle management Visualisations Other	32 21 15 30	∑ = 98
Industry	Manufacturing Aerospace Automotive Energy	17 22 15 26	∑ = 80
Research method	Mathematical Empirical Conceptual Other	31 25 16 28	∑ = 100

In line with [75], The literature extensively uses a solid framework to demonstrate the more inductive and deductive procedures. Within the confines of this study, it is impossible to analyse the concept matrix in theory and practice; instead, the author of this paper concentrates on the features that are relevant only throughout the process. The reference analysis is the final stage before the literature selection; the initial reference for the closely related articles was 760; the further study revealed 30 additional publications, as shown in ***Figure 2.1***. DT and CM were then formed as categories for article analysis to fit and match the study's topic; ten additional references were added during the research to make the study more comprehensive and concrete.

1. *Timeline*

In line with the total number of 132 published articles, it is clear and observed that the DT technology is in its early stage of maturity. The growth is exponential, and the interest in technology is becoming more dominant in all industries. From 2010 to 2021, it shows a strong growth curve in theory and practice. Keywords- in line with 147 published articles, the term

DT with the highest number of 39 articles, observed that the digital win is more prevalent and dominant in theory and practice. Compared with the notion of simulations, the author observed that simulation is the closest notion to the idea of the DT, with a total number of 32 published articles, as shown in ***Table 2.4.***

2. *Aim*

With 60 published articles, it is clear that most articles are fundamental and conceptual. The lack of publications is because of various research fields where the concept is misunderstood and implemented wrongly across theory and practice. The employed prototypes and visualisations are close to 19 and 21, respectively; others are neglected, as shown in ***Table 2.4.***

3. *Objectives*

The literature shows two more apparent goals than any others, with 40 published articles; the number is significant compared to other destinations. Most academic research focuses on adding knowledge where new values are added; with 16 academic articles, the efficiency is still high, as shown in ***Table 2.4***.

4. *Literature*

In line with 98 published articles, the observation of information technology takes the most significant portion of 32 published papers, yet an increasing number of 21 in lifecycle management is challenging to ignore. The growing number is due to lifecycle management in all industries, where lifecycle management plays a significant and vital part in modelling and simulations, as shown in ***Table 2.4.***

5. *Industries*

With 80 published articles, the DT concept was investigated in-depth, and it observed that the energy industry takes the most significant portion of 26 articles, followed by the aerospace industry with 22 articles; the rest are coming close in numbers. The investigation shows the importance and dominance of DT technologies in all industries, as shown in ***Table 2.4*****.**

6. *Research Methods*

Concerning the research methods, the findings show a total of 100 published articles; the mathematical approach is more accessible with 31 articles than 21 empirical articles; this is verified due to the low cost and ease of use of the mathematical despite the importance of the practical. Again, this domain shows the significance of the DT technologies over other methods, as shown in ***Table 2.4.***

7. ***Audience***

The research vigorously employs scholars in academia, where the dimensions of this domain are not exclusive. Still, with 44 articles, the journal articles take 24 as the highest number, as shown in ***Table 2.4*****.**

8. ***Searching Results***

This search query resulted in 736 papers for analysis. After retrieving a small number of papers from Scopus, we expanded our search to include more databases, including ScienceDirect and Web of Science and others, as shown in ***Table 2.4***, which led to the discovery of 353 new publications. This expansion of database search was done to guarantee adequate research results on applying DTs with a total search results of 1200 publications.

9. ***Articles Refinement***

The first step is to collect good quality publications, and with practical screening through the last ten years, [86] identified further steps to refine the articles, as shown in ***Figure 2.1*****.**

A. ***Removing duplicates:*** 300 Publications were removed for duplications; the author of this thesis retrieved a total of 1200 publications, including journal articles and papers presented at conferences

B. ***Non-Relevant Publications Removal****:* 230 Publications were removed. The last decade's publications worth in the study area were compiled, including articles, theses, and conference papers. However, industrial papers and commentaries will be eliminated due to the high quality of the publications collected.

C. ***Low-Quality Publications Removal:*** 127 Publications were removed from low-factor rated journals after the author identified essential terms associated with the DTs, such as IoT and CPS, VR, AR, and CM; however, they were not related to the DTs technology and the *criteria* of removing low-quality publications are as follows:

- *Lack of Peer Review:* Reputable journals and conferences have a rigorous peer-review process. If a publication has not been peer-reviewed, its quality might be questionable.
- *Unclear Methodology:* The absence of a transparent, replicable methodology can signify a low-quality paper. Good research should detail its methodology so others can replicate and verify the results.
- *Data Issues:* Missing data, too-small sample sizes without justification, or unexplained data sources can indicate poor quality.
- *Over generalization:* Drawing broad conclusions from limited data or specific cases without proper justification indicates weak research.

- *No Citations or Poor Citations:* A lack of references or relying on non-academic or non-reputable sources can suggest a lack of thorough research.
- *Publication in Predatory Journals:* Predatory journals charge authors to publish without providing proper editorial services or peer review, leading to several sub-par papers being published. Checking against known lists of such journals can be helpful.
- *No Clear Contribution:* If the paper does not clearly state its contribution to the existing body of knowledge, it might not be of high quality.

A. ***Related Publications:*** 543 papers were obtained from various periodicals and conference proceedings. The total number of citations received by each of the 500 publications is displayed in ***Table 2.3*****.** This method provides a measurement of the impact and influences the papers chosen for this exercise have had

4.2 *Literature Selection*

4.2.1 *Visual examinations*

Forty-two publications were removed after a detailed reading of the titles, abstracts, and keywords. The primary goal of extensively examining the keywords is to ensure they meet the study's goals. Thus, when the databases returned 1200 results when the keywords were used, the articles were selected for further refinement and analysis. Ten publications were removed after a detailed reading of the structures and conclusions.

4.2.2 *Selected Publications*

Five hundred final Publications were selected for this study.

4.3 *Review Process*

This step is independent of the publishing date and is focused on the selection benchmark. The author will disregard whether the work was published in the present or the past. Instead, the author will focus on the application and concept of DT. This method emphasises the CM perspective. The benchmark is summarised into two steps; the first is Application and scenario optimisation, and the second is Providing a comprehensive analysis of trends to assess the DT and framework.

4.3.1 *Detailed Review*

A. Complete and detailed review and analysis of the selected publications

B. Identifying the origin of the concept and enabling technologies for DTs

C. Identifying the views of the theory and practice related directly to the DTs

D. Identifying the applications and how the DTs technology has been implemented

E. Identifying the gaps and ways to fulfil the gaps leading to the future wo

5 LITERATURE REVIEW

This literature review involves meticulously exploring and synthesising existing knowledge on DTs and fatigue analysis. This scholarly endeavour does not merely summarise available literature but critically engages with it, identifying patterns, gaps, and nuances within the existing body of work. This literature review traverses various academic sources, including books, journal articles, and conference proceedings, weaving a tapestry that presents a comprehensive overview of the prevailing discourse on the subject matter. The author of the thesis embarks on this investigative voyage to establish a foundational understanding, ensuring that the research endeavours are not insular but are, instead, anchored in and dialogic with the existing academic landscape. Thus, a literature review is a pivotal bridge, connecting past and present knowledge while illuminating pathways for future scholarly exploration. The astute amalgamation of various perspectives and findings fosters a robust and multifaceted understanding of the topics, ensuring that research is rooted in a rich, contextually informed soil from which novel insights can sprout and flourish.

The literature review section is organised to answer the following research questions to utilise DT technology to monitor and forecast maintenance and the RUL of the coiled springs. The questions are: **Q1** is: What are the actual characteristics of the DT concept for standardisation across theory and practice? Moreover, **Q2** is: How to implement DTs for PdM and Fatigue Failure (FF) of mechanical springs used in suspension systems? So that it can predict the FD and remaining life cycles. Therefore, the literature review section is organised within two main areas: the first is to review DTs, and the second is to review coiled springs failure detection methods.

5.1 *Origin to Present of Digital Twins*

The history of the concept and its progression throughout its existence is broken down into the following subsections. While focusing on the term "digital twin," it also includes other synonyms and phenomena that coincide with the digital twin concept, at least partially. This inclusion is critical when documenting the early origins of the concept.

PRE-2000: According to the most widely accepted theory and practice consensus, Dr Michael Grieves was the first to introduce the DT concept in his presentation in 2002 [87]; however, this statement is not valid. Because the concept, which was taken in 2002, contained only real and virtual space and connection. The concept was introduced only in the context of PLM, then called the conceptual ideal for PLM. Some scholarly articles have established a link between DTs and Plato's "Allegory of the Cave" [62], [88], [89].

Figure 2.2 Twinning shadow of the physical reality from [90]**.**

They show that the basic concept of mirroring the real world, as shown in ***Figure 2.2***, which is essential to the DTs concept, has existed since Ancient Greece. Making DTs is a natural human instinct, it would seem. Many people now consider the workshop on AI held as part of the Dartmouth Summer Research Project in 1956 and was organised by John McCarthy to be the field's official declaration as a research field in AI [91].

Since 1956, AI research has produced intelligent systems that can make decisions, reason, predict the future, and perform physical tasks. The applications of AI are now an integral part of daily life due to the development of ML, DL, CPU, GPU, TPU, and Computational Power (CP) Through the use of system engineering and CM in the years (1961-1972), NASA was the first organisation to conceptualise the idea of a PT, as part of the Apollo 13 mission as shown in ***Figure 2.3***. two spaceships that were completely identical to one another were constructed; however, only one of the spaceships was sent into space to complete the mission [92]. The other spaceship remained on Earth, as shown in ***Figure 2.3*****.**

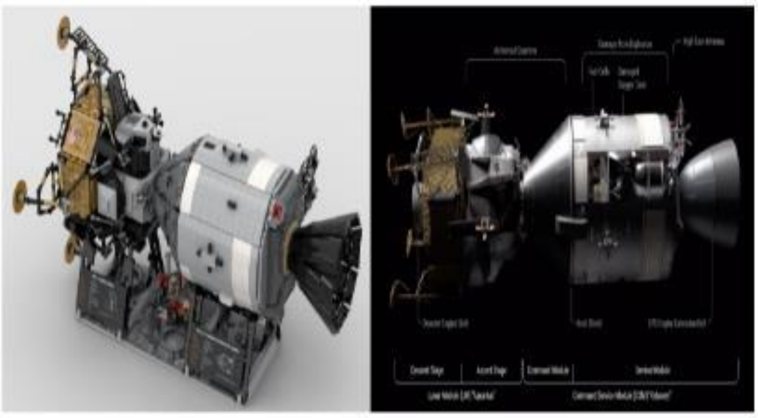


Figure 2.3 Physical twin as part of the Apollo 13 mission [92]

NASA used the satellite allowed to return to Earth to research events in space. They were aware of the phenomenon surrounding the DTs technology and immediately began investigating the effects that the technology would have on business [55], [93]. Sir Tim Berners-Lee proposed the World Wide Web (WWW) in 1989. He stated that each information node of the proposed system should "represent or describe one particular person or object [94] The book "Mirror Worlds" by David Gelernter in 1991 is where the first detailed conceptualisations of mirroring the real world with software appear to have been published [95].

Additionally, the same book was considered the initial concept by recent research on the DT [96], [97]. Solutions for the closely related paradigm IoT which aims to close the gap between the physical and digital worlds, began to emerge in the latter part of the second millennium [98]–[100]. In 1998, Bruns referred to the virtual counterparts of his "integrated real and virtual prototyping" solution as "twin objects", another term that he coined [101]. Despite this, the idea of a DT had not been sufficiently formalised by the turn of the millennium. The evolution of the IoT closing the gap between the physical and digital world [102].

2000-2010: The beginning of the new millennium marked the beginning of the commercialisation of research on the IoT, which meant that an increasing number of individual physical objects from the real world started to have a digital presence ***Figure 2.4***. Several researchers primarily focused on computer science have recently begun using the term "virtual counterpart". Many different terms could be used to describe the phenomenon [97], such as product agent [103], and Product Avatar (PAv) in [104].

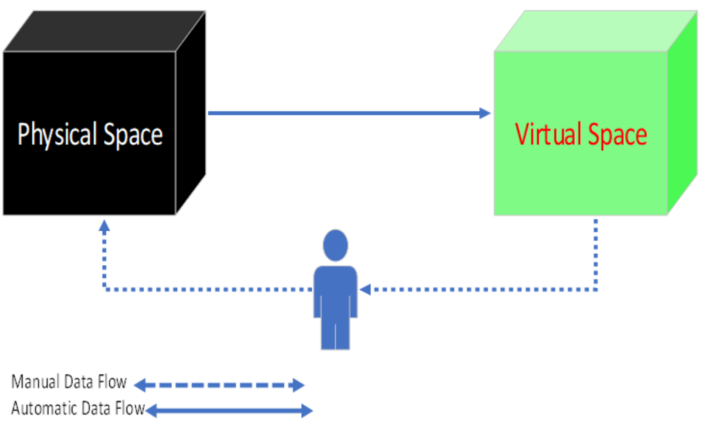


Figure 2.4 Early concept of the DT

PLM a methodology for managing the engineering data associated with a product, was being developed simultaneously [66]; in 2003, Grieves introduced DT in the framework of PLM, but the definition used to introduce them was ambiguous, and the notion was confusing even within the context of PLM. The term DT was first used in a conference paper in 2005 but has yet to be widely adopted [105]. Overall, the decade demonstrated academic development of the DT concept on various fronts in computer science, control engineering, and mechanical engineering.

2010-2015: Rather than using a technical mirroring method, Puig and Duran's DT conference paper emphasised the creation of recognisable human avatars.; these human avatars illustrate that DT can have meanings outside engineering circles [106]. NASA published a draught of its strategic roadmap in November 2010, defining the DT as a simulation-based system engineering approach. The DT is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and many more to mirror its flying twin [107].

The new DT paradigm created a buzz among aerospace researchers, including a general description of DT aspirations for NASA and the US Air Force and more targeted investigations on modelling and predicting structural life[53], [108], [109]. NASA and a few aerospace industry members [68] started simulating different rockets and aeroplanes. Since then, DT has become a trendy topic; all industries began using other techniques and naming them DT. Because the actual concept and definition were not specified, academia brought further confusion and imprecision to the idea, modern procedures, obsolete technology, and even the present-day DT [110].

2015 – Present: In 2015, DT was used significantly more frequently in academic publications. While concentrating on aircraft's implications, [111] reviewed the concept and compared the twin and avatar terms. [109] outlined the application of DTs in manufacturing. 2016, several publications focused on general manufacturing and simulation helped break the academic use of the term DT free from its association with the aerospace industry. [112] described the DT concept as the next wave in simulation technology, which features assistance along the entire life cycle through linkage to operational data as an upgrade from simulation-based system design. In other words, the DT concept is an evolution of simulation-based system design [93].

[113] explored the visualisation of DT using web services and augmented reality, extending the concept beyond the scope of simulation. [114] described DT as a solution to manage industrial IoT devices throughout their lifecycle by employing a graph-focused approach in which a subgraph of nodes represents real-world objects. This approach was developed in response to the [114] identified problem. [114] described that IoT devices' lifecycle can be

managed using a graph-focused approach, where nodes in a subgraph of the graph represent real-world objects.

[115] carried out an in-depth literature review for the DT concepts in manufacturing, covering several related terms. Research using other terms frequently resulted in the development of certain aspects of DTs. For instance, data proxies were used to estimate the state of objects with minimal input data [116], [117]. A review of the DT concept from the point of view of manufacturing was written by [118]. [103] evaluated the cost-effectiveness of the DT concepts by contrasting them to the Manhattan project and concluded that it would be impractical to implement them fully. [119] developed a DT reference model primarily focused on managing geometrical variations. [120] published a book section outlining the history and significance of a digital twin. According to Scopus, a paper [121] on general design, manufacturing, and service is the most highly cited on DT, and a paper [60] reviews state art in the sector. [122] published several papers on DTs that significantly impacted, including one that presented the "DT Shop-Floor" paradigm.

The decade's final years also saw publications from fields other than manufacturing [123], [124]. However, the Nature Commentary makes more DTs, which emphasises manufacturing but also mentions other application fields like forest management, providing a good summary of the overall situation at the turn of the decade [125]. As a result of the previous history discussion, DTs can be considered a mathematical and symbolic representation of a physical system or process throughout its lifecycle that enables monitoring, evaluation, optimisation, and prediction for future decisions. However, [126] introduced two more dimensions, DT date and DT services, to make it a total of five sizes compared to the previous one. These two dimensions can add more accurate and comprehensive data to the full visualisations of the system.

5.2 *Academic View on Digital Twins Concepts and Definitions*

Since 2016, there has been an overwhelming number of publications on DTs, as shown in ***Figure 2.5***; however, none comprehensively review DTs. Some of the most important ones are summarised below. Following this, institutions and scholars submitted their definitions of DTs, including extensive and varied precise descriptions. It depends on the research as long as the report covers the three critical aspects of Grieves' framework [66].

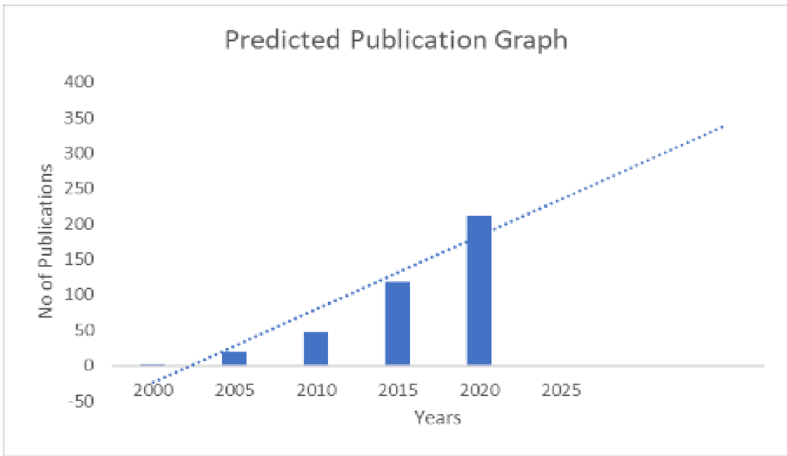


Figure 2.5 Predicted DTs growth of publications

1. ***The US Air Force Research Laboratory, University of California- Los Angeles, the University of Illinois at Urbana – Champaign University of South Carolina*** defined DTs as a highly accurate representation of the state of an aircraft as it was created and maintained, with particular reference to the materials and production requirements, controls, and method used to construct and maintain a specific airframe [127], [128].
2. ***The University of Cincinnati*** defined DTs as a digital representation of a real machine that functions in the cloud platform and replicates the health status using integrated knowledge from data-driven analytical algorithms and other available physical knowledge [129].
3. ***The Belarusian State University of Informatics and Radio-electronics*** defined DTs as a digital replica of a real-world physical installation that can be used to verify the consistency of monitoring data, perform data mining to forecast current and upcoming problems and use artificial intelligence knowledge engines to make sound business decisions [130].
4. ***Vanderbilt University GE Global Research Centre*** defined DTs as: "If the DM follows the same load history as the actual aircraft wing, it can integrate various uncertainty sources over the entire life of the aircraft wing as well as heterogeneous information. It can also reduce the uncertainty in model parameters, track the time-dependent system states using measurement data, and predict the evolution of damage states if no measurement data is available [131].
5. ***The University of British Columbia, Lowa State University, and the Department of National Defence Canada*** defined DTs as RT sensory data, a living model that can continuously adapt to environmental or operational changes. This living model can also predict the future of corresponding physical assets for predictive maintenance [132].

6. ***The Polytechnic University of Madrid and AIRBUS Group*** defined DTs as the creation of a digital counterpart to a product that exists throughout the product lifecycle, from conception to design to usage and servicing, and that is aware of the product's past, present and future states, as well as the facilitation of the development of product-related intelligent services [133].
7. ***Friedrich Alexander-Universitat Erlangen-Nurnberg, University Paris-sud*** defined DTs as a bidirectional relationship between a physical artefact and a collection of virtual models that efficiently execute product design manufacturing, servicing, and a variety of other activities throughout the product life cycle [134].
8. ***The Ruhr University of Bochum*** defined DTs as Having high semantic content and considering virtual product models and feedback data from the physical product throughout its lifecycle [135].
9. ***The Federal University of Rio Grande de Sul*** defined DTs as the product lifecycle represented by models from various product lifecycle stages. These models include system models, functional models, 3D geometric models, functional models, manufacturing models, and usage models, which constantly interact with one another [136].
10. ***Technische Universität Berlin, Fraunhofer Institute Production Systems and Design*** defined DTs as virtual product and manufacturing process models that link enormous amounts of data to fast simulation, allowing for the early and efficient assessment of the consequences and performance and quality of design decisions on products and manufacturing lines [137].
11. ***Technology Guangdong University of Technology*** defined DTs as the cyber layer of CPS, which evolves independently and integrates closely with the physical layer [138].
12. ***The University of Stuttgart*** defined DTs as a digital representation of a physical asset containing all its states and functions and collaborating with other DTs to achieve a holistic intelligence that allows for a decentralised self-control line [139].
13. ***Politecnico di Milano*** defined DTs as a virtual and computerised counterpart of a physical system that can benefit from RT synchronisation of sensor data collected in the field linked to Industry 4.0 [140].
14. ***The Chalmers University of Technology*** defined DTs as digital replicas of a product or production system used throughout the design, preproduction, production phases, and RT optimisation [141].

15. ***Fraunhofer-Chalmers Centre for Industrial Mathematics, Reutlingen University*** defined DTs as a digital replica of a product or production system used throughout the design, preproduction, and production phases or RT optimisation [142].
16. ***University of Applied Sciences of Southern Switzerland*** defined DTs as a digital avatar encompassing CPS data and intelligence, representing the associated CPS's structure, semantics, and behaviour and providing services to mesh the virtual and physical worlds [143]. ***The Pennsylvania State University, Indian Institute of Technology*** defined DTs as an addition to providing a rigorous validation for the additive manufacturing process, predicting the most crucial variable that influences the metallurgical structure and properties of the components, and replacing extensive numerical experiments with rapid, low-cost numerical experiments are also being investigated [143].

5.3 *Industrial View on Digital Twins Concepts*

Grieves defined the idea of DTs for the first time in PLM in 2003. On the other hand, his concept encompassed three structural dimensions: the physical, virtual, and connection between physical and virtual products. Nonetheless, his description of DTs lacks any clear or convincing explanations of what DTs are. By 2010, NASA had developed a more precise and complete definition of DTs. Space vehicles are "an integrated multi-physics, multi-scale simulation of a vehicle or system that takes advantage of the most precise data from the Physical Twin and sensor updates to mirror its corresponding flying twin" [68]. The DTs concept defined by the Department of Defence is an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system. It uses sensor updates, fleet history, and other data to mirror the life of its corresponding flying twin." Interestingly, this concept appears consistent with the approach presented by [65], who defined the concept as the system modelling and simulation by the actual product usage data and information.

5.4 *Digital Twins Software / Platforms*

Numerous organisations provide different tools and software for DTs to visualise actual products and increase business through various industry sectors.

1. ***Altair*** provides Computer Aided Engineering (CAE) tools, "A capability with which product performance is predicted, optimised, tracked, and measured throughout the product life cycle" [144]
2. ***Amazon EC2*** is a "Cloud-based environment for cloud deployable web application" [145]
3. ***ANSYS*** provides CAE tools, "Combining all organisation's digital information on a specific product and merging physics-based understanding with analytics" [146]

4. ***Autodesk*** provides reality capture technology and design software, “Spanning both the factory and product and using the augmented reality technologies borrowed from an IoT cloud services platform provider.” [147]
5. ***Bsquare*** Provides Bsquare IoT, a “Digital representation of RT configuration and state information of physical devices” [148]
6. ***Dassault*** offers a 3D experience platform, “A virtual equivalent to a physical product, which can improve manufacturing excellence by allowing people across the enterprise to collaborate and achieve continuous process improvement” [149]
7. ***Deloitte*** provides an IoT solution, “An evolving digital profile of the historical and current behaviour of physical object and process that helps optimise business performance” [150]
8. ***Docker*** is a product that uses operating system-level virtualisation to develop and deliver software in containers [151]
9. ***General Electric (GE)*** provides Predix platform “providing software representation of a physical asset based on Predix platform and enable companies to understand better, predict, and optimise the performance of each unique asset” [152]
10. ***Infosys*** provides Infosys Nia TM platform, “Virtual replication of physical products, systems, and process that are indistinguishable from their real counterparts” [153]
11. ***Intellectsoft*** provides an Augmented Reality (AR) solution in construction, “RT digital representation of a physical object that continuously monitors changes in the environment and reports back the updated state in the form of measurements and pictures” [154]
12. **SAP** Leonardo platform, provided by *International Business Machines (IBM)*, is a “Virtual representation of a physical object or system across its lifecycle, using RT data to enable understanding, learning, and reasoning” [155]
13. ***Microsoft*** provides Azure IoT Hub Microsoft Hololens, “Visualising the physical world, being intelligent, collaborative, interactive, and immersive, and providing a method to simulate electronic, mechanical, and combined system outcomes” [156]
14. ***Oracle*** provides Oracle IoT cloud, “An important concept that will be strategic to business operation as IoT deployments proliferate through the organisation” [157].
15. ***PACCAR*** provides a data virtual system, “A virtual version of an engine based on sensor data from the real-world versions to manage the maintenance and repair of engines” [158]
16. **PTC Creo** provided by *Parametric Technology Corporation (PTC),* simulation and another analytics tool, “A digital depiction of a field-based object, encompassing its current and previous configuration states, taking into account serialised parts, software versions, options, and variants” [159].

17. ***Siemens*** provides Siemens PLM software, "production of DT for manufacturing and production planning, and DT for performance, and acting on operational data" [160]
18. ***Sight Machine*** provides a platform "Offering sets of analytical models that mirror the production process, encompassing machines, plants, or supply chains."
19. ***SIM-CI*** provided by Simulating Critical Infrastructures which provides DTs cities platform, "A digital copy of a city allowing us to mimic its vital infrastructures accurately" [161]
20. ***TIBCO*** Software provides Project Flogo and TIBCO graph database, "A software representation of a device that can create efficiencies across product lifecycle" [162].
21. ***Twin Thread*** provides a Software solution as a "digital representation of any physical asset, including the asset's current and historical running conditions" [163].

5.5 *Digital Twins Levels*

According to the literature [127]- [163], DTs do not have a standard concept/definition; it is instead a collection between Computer Aided Engineering (CAD), IoT, Finite Element Analysis (FEA), and Cyber-Physical Systems (CPS). That means the authors in the literature are reusing an existing technology or reusing a combination of the existing technologies and naming it a DT, while in reality, it is not an actual DT; in fact, this could be related to different levels or the entities which adding up together to make a DT.

A- Digital Twins (DTs)

Other physical or digital items may cause the digital object to undergo state changes. A change in the PE's state directly affects the DE's state and vice versa, as shown in ***Figure 2.6***. According to the literature, the term DT was coined for the first time in 2002 by Michael Grieves in the context of PLM, and it was published in the journal science. It had an informal definition/ concept; when the DTs were first introduced, Greaves defined DT informally as a replica of the actual physical system under consideration.

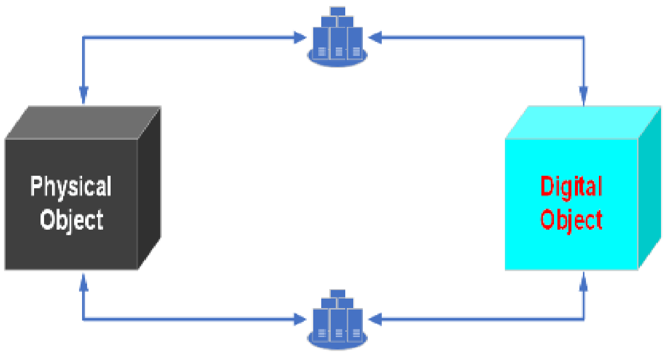


Figure 2.6 Data flows between Physical Objects (PO) and Digital Objects (DO)

According to him, this replication has three dimensions: PE, DE, and a connection between them. Although this was not a formal definition/concept, it was a good start. However, the informal description resulted in a significant breakthrough in the industries, but it also caused confusion and misunderstanding about the concept, which led to Grieves' resignation. In 2005, he revisited his 2002 definition and divided it into three categories, which he first presented in 2001 and revised in 2005 [66], (A) DT prototype, (B) DT aggregate, and (C) DT instance. A more transparent and explicit conceptualisation was presented [68].

B- Hybrid Twins (HTs)

The HT is an extension of the DT in which the isolated DT models are interlaced to recognise, foresee, and communicate less optimum but predictable behaviour of the physical counterpart well before such behaviour occurs. The connection is made to maximise the overall system's efficiency. ***Figure 2.7*** Shows the HTs integrate data from various sources (such as sensors, databases, and simulation) with the DTs models and apply AI analytics techniques to achieve higher predictive capabilities.

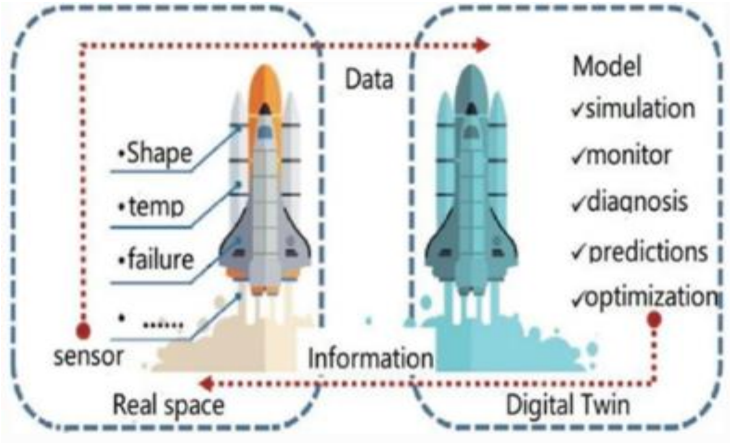


Figure 2.7 Hybrid Twin [164]

While simultaneously optimising, monitoring, and controlling the behaviour of the PS. In other words, the HTs can do all these things to achieve synergy among the DTs models; the HTs are often manifested as a collection of all related models.

C- COGNITIVE TWINS (CTs)

Cognitive Twins (CT) is an extension of "HT" that incorporates cognitive features that enable sensing complex and unpredicted behaviour and reasoning about dynamic strategies for process optimisation. This cognition results in a system continuously evolving its digital structure and behaviour. In this sense, a CT is a hybrid, self-learning, and proactive system that maximises its cognitive capacities over time based on the data it will gather and the experience it will gain throughout its existence, as shown in ***Figure 2.8***. By integrating the knowledge of subject matter experts with the capabilities of HT, a CT can produce novel solutions to newly arising problems. Therefore, a CT will accomplish this. The synergy between the HT and the expert and problem-solving expertise it possesses.

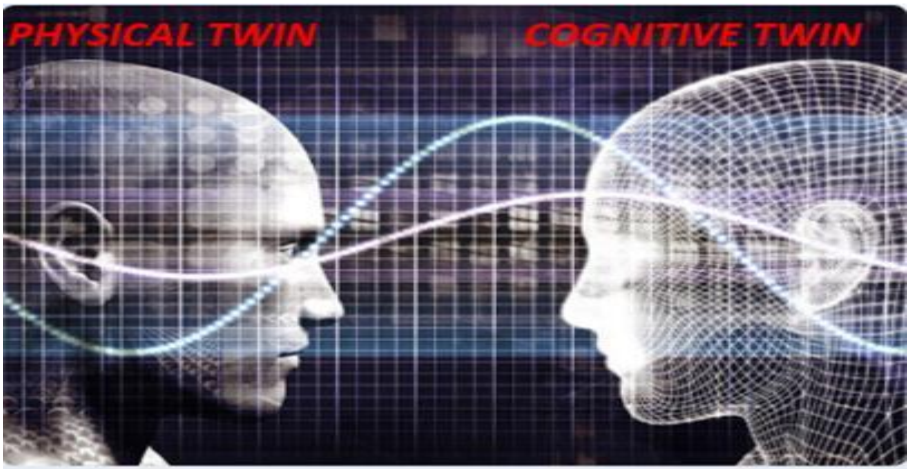


Figure 2.8 CogniTwin behaves exactly like the physical Twin [165]**.**

5.6 ***Digital Twins Applications***

In the following part of our examination, we will focus on the various applications of DTs. Future applications of DTs will be investigated as the first step in this process. We will address the industry, the domain, and the particular obstacles DT technology must surmount. The concept of a DT and the term DT is gaining acceptance among academics worldwide. AI and IoT breakthroughs make it possible for this growth to accelerate. [166]–[171]. Currently, the primary areas of concentration are smart cities and manufacturing, with some uses of DT's technology identified as related to the healthcare industry.

1- Manufacturing

DT technology is being tested and evaluated for its next potential application in manufacturing. The fact that manufacturers are always looking for new ways in which their products can be tracked and monitored to minimise costs and save time is the primary cause of this phenomenon. This live monitoring is the key motivator and driving force behind any manufacturing process. DTs appear to have the most significant impact inside this context due to this fact. Analogous to this, constructing a smart city is one of the vital motivating drivers for utilising DTs in the manufacturing industry. Connectivity is an essential part of this, which takes advantage of the connection of various devices to make the idea of a DT a reality for the processes involved in production [172]–[176]. DTs can provide RT feedback on the operation of production lines and information regarding the performance of machines. Additionally, DTs can provide these statistics in an easily digestible format. It allows the creator to foresee potential issues at an early stage.

The utilisation of DTs encourages connectivity and feedback between devices, ultimately resulting in gains in both performance and reliability. AI algorithms associated with DTs can attain higher accuracy since the machine can store enormous volumes of data, which is essential for performance and prediction analysis. Establishing an environment to test products and a system that acts on RT data by DTs can be a precious asset within a manufacturing environment [177]–[180]. Numerous manufacturing-related works use the DTs to optimise every product- and process-manufacturing step. Among these, [181] emphasises how using DTs may enable the establishment of a computerised system that oversees each manufacturing stage using a modular approach. More specifically, [182] presents a modular approach to smart manufacturing, where autonomous modules conduct high-level activities without human control, choose from a variety of alternative actions, and react to failures or unexpected events without interfering with the operation of other modules thus avoiding changes and reconfigurations at the supervisory level.

However, the modules must have access to realistic data outlining the state of the process and the goods. These tasks and achievements can be accomplished by employing a DT, a faithful virtual representation of the actual PE. The work of [181] shows its potential in the manufacturing industry. The DTs appear to be a realistic model or simulation capable of constant communication with its actual twin, which is an overly simplified way of explaining it [181]. DTs should not be confused with simulations or avatars generated by virtual/augmented reality applications [183]. As stated, AI and continuous or at least periodic RT data interchange between the physical and virtual counterparts distinguishes simulated models or PAv from a DT. Furthermore, the DTs must be built by combining information offered by human specialists with genuine historical data acquired by current and previous systems [184].

Such data are required to explain the behaviour of the PT and generate solutions applicable to the actual system [112], [185]. DTs are customised simulations, specifically developed for their intended function, that evolve with the physical system during its entire life cycle. [186] showed the benefits of a Data-Driven (DD) smart manufacturing strategy utilising DTs, similar to [181], [187], [188], placed more emphasis on the intelligent applications called services embedded in the virtual parts and the fused data from various sources when describing their concept of the DTs shop floor. The DT model is broken into five enabling components according to [189]; PS, Virtual Systems (VS), Sensors, Integration Technologies, and Analytics. Through the communication interface and security, sensors enable bidirectional RT communication between PS and VS Analytics methods that derive prescriptions based on the results of simulations used to process exchanged data. The importance of the DTs' continual interaction, convergence, and self-adaptation is highlighted by several cutting-edge activities in the manufacturing sector for ensuring complete synchronisation between the DTs and their PTs, which is required for constant monitoring, optimisations, and PdM operations, among other things.

Indeed, multi-modal data acquisition allows for the linkage of the production system with its digital equivalent to minimise the time between data acquisition and the construction of the DTs. [190] expressed their vision of a CPS governing a specific manufacturing company by managing and optimising all machinery and equipment operations through the interconnection of DTs in manufacturing optimisation. In this sense, they defined a DT of a machine or piece of equipment as a coupled model operating in the cloud platform and simulating the health status with integrated knowledge from data-driven analytical algorithms and other available physical knowledge. Because modularity enables RT reconfiguration and self-adaptation, [191] provides a conceptual approach to intelligent product reconfiguration. The technique monitors, regulates, and reconfigures it by directly working with the object's DTs. The approach's efficacy is prototypically proven by contemplating a model environment for smart cars that are momentarily altered during their use phase, recalling the clever Tesla cars.

2- Aviation

While DT technology is valued in manufacturing for enabling predictive maintenance and optimising and speeding up production, it is primarily used in aviation for PdM [192] - for example, to detect dangerous changes in structural aircraft and trigger self-healing mechanisms - decision support, optimisation, and diagnostics. The DTs model that best reflects the multi-physics, fluid-thermal-structural you-piling suitable to hypersonic flow circumstances of aircraft may be chosen by specifying a quality measure as a decision-making metric for autonomous model fidelity selection [193]. [194]described an aircraft DTs for studying crack tip deformation and propagation in aluminium alloy and steel utilising automatic picture tracking. Throughout the aircraft lifecycle, the DTs models can predict sub-cycle fatigue fracture growth mechanisms of aviation materials, lowering development and maintenance costs [195].

DTs were developed by [196] to model how the performance of composites is impacted by microstructural changes brought about by multi-physical environments such as electrical fields. [197] suggested DTs for detecting fatigue cracks using an aviation wing's shape memory alloy particle-filled finite element model. The authors studied the response of localised particles to an aircraft wing subjected to flying stresses to detect structural changes. In order to identify and forecast damaged aircraft structures, the study proposed in [198] employed the FEA Method to compute the stress intensity factor. [199] improved Moving Least Squares (MLS) law to compute fatigue crack growth rates [200]. [201] describes a DT that regulates aeroplane wings using a modified dynamic Bayesian network. Based on a related concept, [202] developed a computational steering framework for fatigue-damage prediction in full-scale laminated composite structures and tested it on wind turbine blades. It combined FD modelling iso-geometric analysis of thin-shell structures monitoring.

Modern aircraft DTs evaluate guided-wave responses to foresee damage [203] instantly. As the directed wave collides with harm, it weakens and reflects. Signal strength and phase changes differ between damaged and unharmed structures. During damage identification and evaluation, a genetic algorithm is used to properly quantify damage size, position, and orientation [204]. An aeroplane tyre at touchdown was built as DT models by [205].

3- Healthcare

DTs are initially used in healthcare for PdM and medical device performance enhancement in examination speed and energy consumption. DTs also improve the lifetime of hospitals. The DTs from GE Healthcare improve hospital management. This international corporation's predictive analytics technologies and AI solutions convert medical data into actionable intelligence. The goal is for hospitals and government organisations to manage and coordinate patient care operations. To improve decision-making at Johns Hopkins Hospital in Baltimore, GE Healthcare created a "Capacity Command Centre" [206]. The hospital improves service, safety, experience, and volume by establishing a DT of patient pathways that forecasts patient activity and plans capacity based on demand. Siemens Healthineers created DTs to optimise the Mater Private Hospitals (MPH) in Dublin [207], which was experiencing increased patient demand, increasing clinical complexity, ageing infrastructure, a lack of space, increased waiting times, interruptions, delays, and rapid advances in medical technology, which necessitated the purchase of additional equipment.

MPH and Siemens Healthineers redesigned the radiology department using an AI computer model. Medical DTs enable digital process optimisation by simulating workflows and assessing unique operational situations and architectures. The DTs' realistic 3D simulations and descriptive and quantitative reporting allow for the prediction of operational scenarios and the analysis of various options for transforming care delivery. The expansion and advancements that enable technology in the healthcare business are unprecedented because they make things previously unachievable feasible. These challenges are because the enabling technology makes things previously unattainable possible. The surge in connection can be attributed to the fact that IoT devices are becoming less expensive and more straightforward to implement [208], [209]. As a result of the increased connectivity, the future applications of DTs utilisation within the healthcare business are only growing to become more extensive.

The production of a DT of a person, which would allow for an RT study of the body, is one application that has the potential to be used in the future. DT, a more practical application currently being implemented, replicates the effects of various medicines. Building human DTs is a goal for the medical and clinical fields. By evaluating the real twin's personal history and present circumstances, a human DTs can reveal what is happening inside a linked PT's body, making it more straightforward to predict sickness [210]. This DT model would enable a paradigm shift in the delivery of therapies in medicine, moving away from one-size-fits-all to customised treatments based on the person's PT, which includes structural, physical, biological, and historical components. Precision medicine focuses on a patient's genetic, biomarker, phenotypic, physical, or psychological features [211]. Patients are not treated per a "norm" or "Standard of Care" but rather as unique individuals [212], [213]. Virtual Physiological Human (VPH) is a computer model created to look at the entire human body. With a VPN, clinicians and researchers can test any medication, and in-silico clinical studies can be conducted using a VPN [214].

AnyBody Modeling System (AMS) shows how the human body interacts with the environment and was created due to a study into VPH. Muscle forces, joint contact forces and moments, metabolism, tendon elasticity, and antagonistic muscle activity can all be calculated using AMS. A DT-virtualized physiological model could predict organ behaviour. Automated CAD analysis may assess the efficacy of individualised therapies, advancing precision medicine. Picture Archiving (PA) and Communication Systems (CS) [214], which provide affordable storage, quick access, and the interchange of medical examinations, mainly images from different modalities, are crucial in this field. Some organs DTs have been used in clinical practice as a reliable tool for experts, while others are being validated. The Living Heart [215]was built by Dassault Systèmes and introduced in May 2015. The preliminary results of the experimental testing were promising. The human respiratory system is another organ DTs produced by Oklahoma State University's Computational Biochemistry and Biophysics lab

(CBBL) [216]–[219]. CBBL researchers used ANSYS computational fluid dynamics simulations to explore the precision delivery of a cancer-destroying inhaler.

The CBBL built the Virtual Human (VH) V2.0 on the foundation of their virtual person V1.0 using an MRI image and the patient's lungs' geometry. CBBL researchers used the V2.0 DT to create a large population of human DTs Virtual Population Group, or VPG, consisting of high-resolution anatomical models. The VPG allowed researchers to analyse population or subgroup differences, boosting statistical validity. Writers could recreate various particle travel scenarios by adjusting particle sizes, inhalation flow rates, and drug placement. These simulations showed that confining the size and location of active drug particles within the aerosol instead of distributing them would boost the local deposition efficacy of pharmaceuticals to 90% [220]. Surgeons can simulate procedures and research the connection between implants and aneurysms using the customised DT. Many implants can be checked in less than five minutes to optimise the procedure. Initial tests have yielded positive results [221], [222], delivering high-quality 3D-Angiography basis data. Understanding the effect of device-dimension adjustments on results requires further analysis.

4- *Smart Cities*

DTs are gaining popularity due to the tremendous developments in connectivity made possible by the IoT. They have the potential to be immensely useful in smart cities and are currently being employed in growing numbers. The use of DTs is expected to increase due to the growth of smart cities, resulting in more excellent connectivity among communities. Additionally, collecting more data from the IoT sensors integrated into our primary principal services opens the door for research focused on developing powerful artificial intelligence algorithms [223]–[225]. Levels of capability possessed by the infrastructure and services of a smart city. Having sensors installed throughout a city and monitoring it with internet-connected gadgets are two approaches to preparing a city for the future. It can be put to use in a variety of ways to support the ongoing creation of additional smart cities as well as the planning and development of the smart cities that already exist. There are benefits associated with planning but also benefits related to energy conservation.

These facts explain excellent comprehension of the procedures used to manage the circulation and consumption of our utility services. The idea of utilising technology that creates DTs is a step in the right direction for developing smart cities. It can make a living testbed within a Virtual Twin (VT), which can accomplish two things: first, it can test different scenarios, and second, it can enable DTs to learn from their surroundings by analysing changes in the data they collect. This learning is accomplished through its ability to create a living testbed within a VT. This capability can promote growth by making the process easier to complete. Both data analysis and monitoring are potential applications for the information acquired. More opportunities for connectivity and more data can be used as more smart cities are developed [92], [226]–[228]. The idea of DT will become increasingly realisable due to this.

5.7 *Mechanical Springs Failure Detection Methods*

The suspension systems of vehicles rely heavily on coiled springs. Coil, cantilever, torsion, and multi-leaf springs are just a few of the suspension systems that utilise them. By absorbing and softening the vibrations and shocks from the road, these springs are intended to give a pleasant and smooth ride. In research by [229], they looked at the basic stress distribution, the properties of the materials, the production techniques, and the typical failures of vehicle suspension coil springs. The research also looked at the numerous factors that affect coil spring quality. Comprehending these variables is crucial to developing and producing high-performance suspension systems. The investigation on the premature failure of a suspension coil spring was carried out using various experimental techniques, which include a) Microstructural analysis and fractography by Scanning Electron Microscopy (SEM), b) Inclusion rating by optical microscopy, c) Hardness testing, d) Residual stress measurement by X-Ray Diffraction (XRD), and e) Instrumental chemical analysis [229].

These techniques were used to understand the material's composition, structural properties, and potential defects that could have led to the spring's failure. In [229], they used a look-ahead Rao Blackwellized Particle Filter (la-RBPF) as a method for failure analysis. The authors employ this method to address the problem of sample impoverishment in all Particle Filter (PF) algorithms. In la-RBPF, the fittest particles at a given time are chosen using the information at the next time step, leading to an efficient algorithm. Assumptions were made, like considering the transition prior to the proposal distribution or the conditions under which the optimal proposal distribution satisfies the Bayes rule. The paper also discusses using a quarter-of-vehicle (QoV) model that represents an automotive suspension, which assumes an equivalent load distribution among the four corners and has a linear dependency for the translational and rotational chassis. If these assumptions are not met, it could limit the validity of the findings in specific scenarios and applications.

In [36], a Monte Carlo model was developed based on a linear damage theory to predict the Fatigue Life (FL) of the helical suspension springs during start/stop conditions, and the model was then used to predict FL requirements on the bench test such that the reliability goals for the start and stop testing would be met, thus reducing the risk in qualifying the compressor. Furthermore, their conclusion stated that the Helical springs failed due to fatigue during start/stop testing. They analysed the reason for early failure due to Poor surface texture on springs. However, the springs had unacceptable surface texture, reducing FL. Additionally, the design was marginal, even for springs with acceptable surface texture. Many more authors [230] to [254] and [298] to [303] carried out the failure analysis of the coiled springs; however, none of which was under Current Real Time (CRT) operation and or non-compliant tests.

On the other hand, [230] uses a probabilistic approach called the Effective Strain Damage (ESD) model for FL assessment in his paper. This model considers load cycle sequences' effect on a coil spring's FL. It is applied to account for the random strain signals and the reliability properties of the FL data. The paper further assesses the model's results by comparing it to conventional Strain Life (SL) models based on the Mean Cycle to Failure (MCtF). Additionally, [231] their study aimed to accelerate fatigue tests using simulated strain signals and simulated strain signals to maintain FD decrease testing time, and in their results, they claimed that they proposed simulation for generating realistic strain signals and reduced testing time by up to 33.9%, however, their external forces not considered due to equipment limitations and also the influence of engine operations and tires not considered.

5.7.1 *Stress Relief Impact on Fatigue*

Significant stresses and plastic strains are generated during the production process of helical compression springs, namely via the cold coiling method. After the cessation of the procedure, the resulting permanent strains give rise to residual stresses that impose constraints on the FL and operational effectiveness of the spring. Tensile residual stresses are well acknowledged to be undesirable due to their propensity to facilitate fracture formation and subsequent propagation [232], [233]. The spring formation process results in the development of tensile residual stresses on the inner surface of the coil, while compressive residual stresses are formed on the outer surface of the coil.

Limited information is accessible in the public domain on the fatigue characteristics of helical springs, and no relevant findings have been identified concerning the influence of heat treatment on the fatigue properties of springs. The analysis conducted in reference [234] examined the influence of stress amplitude on the onset of fatigue cracks in spring steel specimens. However, it should be noted that hour-glass-shaped specimens were used in this study. A previous study by [234] established a relationship between the microstructure and fatigue parameters of two high-strength spring steels. These particular steels are often used in the production of automobile diaphragm springs. Stress relaxation refers to the phenomenon whereby the spring's "constant" or load-free length experiences a reduction when the spring is exposed to repetitive loading. It is important to remember that the spring constant is defined as the force required to cause a unit-length deformation in the spring.

Hence, the relaxation phenomenon may be attributed to the reduction in spring force experienced by a material under a certain deformation. The relaxation of springs has greater significance when subjected to temperatures beyond ambient conditions, with its magnitude being influenced by factors such as stress, temperature, and material properties. This study examines the impact of stress reduction on the parameters of spring fatigue. Experimental relaxation findings resulting from cyclic loading are also given. The first section of this report outlines the experimental methodologies used for measuring spring relaxation, residual stresses using X-ray diffraction, and the determination of FL curves. The subsequent findings are given and afterwards discussed.

5.7.2 *Fatigue Behaviour-Based Finite Element*

FEA is a computational engineering methodology developed in the 1960s by the aerospace and nuclear power sectors. Its primary purpose is to get practical and approximate solutions for problems characterised by several intricate variables. Moreover, it should be noted that this field of study serves as an expansion of both derivative and integral calculus. It extensively uses considerably larger matrix arrays and mesh diagrams to compute stress points, load movement, forces, and other fundamental physical phenomena [235]. In the realm of engineering, it is uncommon to find precise analytical solutions for a majority of issues. As a result, approximate numerical analysis methods become necessary; FEA is often regarded as the predominant numerical method used by engineers in contemporary practise. The approach above exhibits versatility and may effectively address various engineering challenges. In the last several years, there have been advancements in techniques that integrate elements from two analytical approaches, namely FEA and FF phenomena, as discussed in references [236]–[238].

These methodologies have been applied to various components. The vehicle may be seen as a composite construction, including several mechanical components that experience intricate cyclic loading due to regular use. In recent decades, many researchers have shown great interest in active car suspensions. For example, the fatigue evaluation of a suspension arm was carried out by [239] using deterministic and probabilistic methodologies. The study by [240] focused on the lower suspension arm and proposed a novel structural optimisation approach incorporating fatigue life considerations. The study of [241] analyzed the hydroforming process of a car's lower limb. They used the finite element programme HydroFORM-3D to ensure appropriate design and process control. The research conducted by [238] included the implementation of several experiments to examine the impact of gauge and material strength on the fatigue characteristics of a fusion welded automobile suspension arm.

The reliability of FE modelling and fatigue prediction approaches has been assessed in the context of their application to thin strip steel. The study conducted by [242] primarily focused on investigating the load-strain relationship. Specifically, the researchers concentrated on the examination of stress and strain, which is a crucial step in predicting the lifespan of a material or structure. Extensive research has been undertaken to investigate using the FE approach for durability calculations in automotive applications. Additional detailed surveys are available in the published works of [243]–[245]. This research aims to attain satisfactory levels of precision in the fatigue linear analysis of lower suspension arms in automotive applications. This will be accomplished by using a local strain technique to evaluate the durability of the components integrated into DTs. FE estimated strains may be verified by comparing them with strain gauge road data. This comparison is considered a crucial need for ensuring the correctness of FEA.

The field of vehicle design is characterised by competing criteria, such as the need for vehicles to possess both lightweight characteristics and high levels of dependability. There is a growing need within the automotive sector to decrease the duration required for the development of new designs until they reach the manufacturing stage [48], [246], [247]. Simultaneously, it is essential for the vehicles under development to possess the appropriate characteristics, including durability and low weight, in order to sustain competitiveness [46], [246], [248]–[250]. Developing novel and enhanced designs within the automobile industry may provide a substantial competitive advantage and determine the overall outcome of a range of products [40]. The suspension system is tasked with absorbing shock loads generated by disturbances on the road [251]–[253]. The system comprises three distinct components: the spring, the force-bearing element; the damper, which functions as the oscillation-damping component; and the structural member. FF is a significant design consideration for suspension systems.

In order to meet the necessary criteria, a design must demonstrate the ability to withstand prescribed design loading conditions without experiencing fatigue-induced failure [41]. The spring is composed of SAE 9254, a steel alloy often used to produce coil springs. The engineering drawings include the design details for the spring [254]. The present work examined fatigue using the strain-life approach, explicitly focusing on variable amplitude loading situations. Initially, a loading history was derived based on the fatigue test data provided in the spring design. This loading history was represented by a triangle wave with a frequency of 4 Hz.

Additionally, a second loading history was used, which followed the standard SAESUS protocol. Both historical records were adjusted and modified based on the highest and lowest deflection observed throughout the design process. The highest deflection corresponds to the complete bump, while the minimum deflection corresponds to the full rebound. The objective of this study is to use the finite element analysis methodology to forecast the fatigue characteristics of springs employed in automotive suspension systems.

5.7.3 *Maintenance Strategies*

Because maintenance is the key to extending the lifespan of anything, it is also the fundamental component of safety. When determining when and how maintenance actions must be carried out, one option is to use maintenance strategies as a guide [255]. ***Figure 2.9*** shows the types of maintenance as follows:

1. Reactive maintenance
2. Preventive Maintenance (PvM)
3. Condition-based maintenance
4. Predictive Maintenance (PdM)
5. Prescriptive maintenance

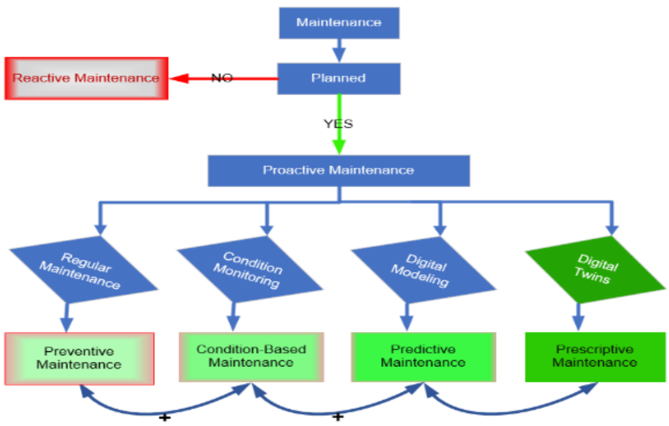


Figure 2.9 Maintenance process to get to the DTs used in maintenance.

A- Reactive Maintenance: The first technique is corrective or failure-based maintenance, called reactive maintenance. It pertains to any serious emergency; a malfunction or breakdown has brought that on. These events were not included in any prior planning considerations [256].

B- Preventive Maintenance*:* This strategy is based on the knowledge of the plant infrastructure asset manager, who schedules various maintenance tasks at various intervals over time to prevent service interruptions or, if necessary, reduce their impact by scheduling them in advance. Even though this level is significantly better than the reactive, it is still far from ideal: In this kind of plan, the trend is to over-maint the asset, resulting in a high economic cost [257].

C- Condition-Based Maintenance: CBM anticipates asset maintenance based on indications of deterioration and deviation from the asset's usual behaviour. CBM is also referred to as diagnosis-based maintenance. The maturation of technologies such as IoT and cloud computing, which are used to monitor the asset's condition, enables the detection of these anomalies. CB techniques can be augmented by diagnostic and status data acquisition algorithms based on AI [258].

D- Predictive Maintenance*: PdM* Various methods can be utilised to combine all relevant data for making maintenance predictions with maximum precision. An algorithm for analysing data is constructed based on the data at hand. It yields information on the trends before the asset's behaviour [259], [260]. On the other hand, model-driven methods necessitate creating a mathematical asset representation. Analytical, physical, and numerical models are valid forms of modelling. These models can reliably describe component degradation. Since this model has a relatively high cost, developing more efficient computational methods has increased its likelihood of success. [261] claimed that Pre PdM was one of the most computationally intensively researched issues in the current wave of Industry 4.0 research.

E- Prescriptive Maintenance: The final strategy is knowledge-based maintenance, often called prescriptive maintenance. It alludes to planning maintenance better using forecasts. It is committed to prescribing an action plan and employing historical and RT data analysis to forecast the status of a necessary asset [262], [263]

5.7.4 ***Importance of Predictive Maintenance in the Automotive Industry***

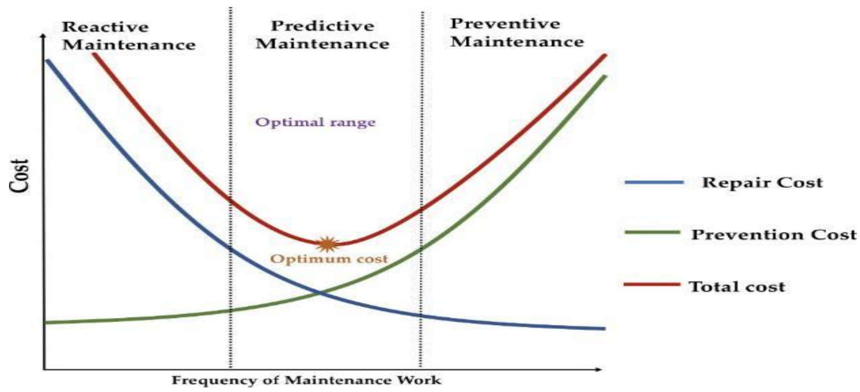


Figure 2.10 Comparison of maintenance strategies with cost and frequency [264]

According to the research published by the US Department of Energy [265], using a predictive strategy rather than depending only on scheduled PvM may result in potential energy savings of around 8-12%. The use of predictive maintenance strategies has been shown to positively impact the longevity of assets and reduce equipment downtime and associated expenses related to replacement parts and labour, as shown in ***Figure 2.10***. Furthermore, this methodology enhances worker safety and plant dependability and optimises the functioning of the equipment, resulting in immediate energy savings. However, this particular strategy necessitates an initial investment in cash to procure and install diagnostic equipment.

Furthermore, successfully implementing the company's selected PdM system requires substantial staff training investment. In a general sense, the benefits of this strategy are greater in magnitude than the drawbacks. According to surveys conducted on the industry average savings, it was seen that enterprises had a significant improvement in their operational efficiency after adopting the PdM programme. Specifically, these companies reported a reduction of around 70-75% in asset breakdown, a decrease in maintenance expenses by 25-30%, and an increase in output by 20-25%. The average return on investment (ROI) was ten times, indicating a favourable investment, as shown in ***Figure 2.10***.

6 **LITERATURE ANALYSIS**

This section encompasses a multifaceted exploration and evaluation of the review of written works, unravelling the intricate layers of meaning embedded by the authors. Delving deep into character development, plot construction, thematic elements, and stylistic devices, it seeks to elucidate the nuanced messages and artistic expressions encrypted within the reviewed papers. The literature analysis offers a window into the creator's world and facilitates a richer understanding of the societal, psychological, and philosophical implications embedded within the artistic creation, establishing a bridge between the text and the multifarious interpretations it can engender. This rigorous inquiry invites readers to traverse beyond mere plot summaries, provoking more profound thought, fostering empathy, and enabling an enriched engagement with the text.

6.1 *Distribution of Digital Twins Worldwide*

The implementation and deployment of DT technology have unfolded diversely across the globe, embedding itself into various industries and becoming a pivotal tool in numerous applications. Let us explore a brief analysis, contemplating DTs' global distribution and applications. Throughout the past few years, there has been a rise in the number of DT papers focusing on product design. This rise has been slow but steady. As seen in ***Table 2.5***, institutions in countries such as China, the United States of America, and Germany, regarded as the world's industrial powerhouses, have a keen interest in applying DT research to the design and development of products.

Figure 2.11 shows the distribution of DTs technology worldwide, and ***Figure 2.12*** shows the top applications of DTs worldwide. This application is particularly the case in China. Academic institutions in China and Germany have made the most significant contributions to this area of research. Other prominent nations in Asia and Europe, such as Singapore, the Netherlands, Italy, the United Kingdom, New Zealand, France, and Russia, are the world's technological and manufacturing. Successful manufacturers worldwide work in the automotive and aerospace industries, which benefit from using DTs.

Figure 2.11 Distribution of DTs worldwide

6.1.1 ***Industry Specific Distribution***

A. Manufacturing: Automobiles, Aerospace, and Electronics: Countries like Germany, the USA, and China have adopted DTs for optimizing manufacturing processes, product designing, and predictive maintenance.

B. Healthcare: Patient Management and Device Modelling: The USA, Sweden, and the UK leverage DTs for enhancing patient care, optimizing hospital management, and innovating medical devices.

C. Smart Cities: Urban Planning and Management: DTs are instrumental in developing smart cities in regions like Singapore, the UAE (especially Dubai), and European cities, focusing on sustainable living, efficient resource management, and improved public services.

D. Agriculture: Countries like India, Brazil, and the Netherlands use DTs for precision farming, crop monitoring, and optimizing agricultural practices.

E. Energy: Grid Management and Renewable Energy Systems (RES); Denmark, the USA, and South Korea have focused applications in managing energy grids and enhancing renewable energy production through DTs.

6.1.2 ***Geographical Distribution***

A. North America: The USA and Canada exhibit a wide application in healthcare, manufacturing, and urban planning, given the technological advancements and industry-driven economy.

B. Europe: With a balanced focus on sustainable living and efficient manufacturing, countries like Germany, the UK, and Sweden utilize DTs in various sectors, including healthcare, urban planning, and manufacturing.

C. Asia-Pacific: Varying applications are noticed in the region: manufacturing in China, smart city developments in Singapore, and agricultural applications in India. The region represents a mix of diverse economic and developmental agendas.

D. **Middle East and Africa:** Primarily observed implementations in smart city projects and resource management, with countries like the UAE and Qatar leading in urban applications and some African countries exploring applications in resource management and agriculture.

E. **Latin America:** Brazil, Mexico, and Argentina are gradually navigating towards incorporating DTs in agriculture and urban planning, reflecting an adaptation to technological advancements.

6.1.3 *Challenges and Future Implications*

A. **Technological Disparity:** A stark contrast in technological capabilities across countries impacts the extent and efficiency of DT applications.

B. **Data Privacy and Security:** Managing data security and privacy across different countries, each with its regulatory framework, is a prominent challenge.

C. **Integration and Standardization:** Creating unified standards for data management and system integration in DT deployment needs attention.

Table 2.5 Distribution of DTs applications vs top countries using DTs

Ref	Description	Application
Aurus (Russia) [266]	DTs were used to carry out virtual prototyping and verification to mimic the model of a physical product that may be represented, analysed, and tested as a real machine. The luxury car's production cycle was shortened from 5 to 7 years and four months.	Automotive, manufacturing, and maintenance. (Reduced the production time from five or seven years to only two years after using DTs
Maserati (Italy) [267]	created the DT models for the car's development using the Siemens PLM software. Vehicle development time can be slashed by 30% thanks to virtual modelling and simulation that eliminates the need for costly, real-world prototypes, wind tunnel tests, and test drives.	Design, Automotive, and manufacturing. They reduced the cost of production by 30 per cent after using DTs
Tesla, Boeing, SpaceX (USA) [268]–[270]	Every vehicle constructed would have DT models that link it to the factory and allow simultaneous data transmissions. The information gathered from the drivers enables better software and resource allocation for their vehicles.	Design, Production, Automotive, Aerospace, Manufacturing, and Healthcare. They had a big cut in the cost and the time taken for production.
Airbus (France) [271]	built a data lake to serve as a repository for all currently operating aircraft. The A350 XWB aircraft installs 50,000 onboard sensors for each trip, generating 250 gigabytes of data. The data repository can be used to examine the components' lifespan performance and to gather information to enhance upcoming designs	Design, Automotive, Maintenance, and manufacturing. They reduced the cost of production by 30 per cent after using DTs

Rolls Royce (UK) [272]	The engineering team simulates the functionality and condition of the actual machines using a digital twin. Scaled-down computer reproductions of actual engines emulate the rigorous testing necessary for engine certification.	Automotive, manufacturing, and maintenance.
Schunk, (Germany) [273], [274]	The whole engineering process, from the initial design to the mechanical, electrical, and software systems, has been digitalized. To help with product development, they employ DTs.	Design, Production, Automotive, Aerospace, Manufacturing, and Healthcare. They had a big cut in the cost and the time taken for production.
Philips (Netherlands) [275]	They assisted their design progress by developing a DT of their medical equipment, which could be used in hospitals or for personal health gadgets	Automotive, manufacturing, and maintenance.

6.2 *Distribution of Digital Twins Applications Worldwide*

As Shown in ***Table 2.5,*** The proliferation of DT technology has permeated various industries and regions across the globe, offering innovative solutions, enhanced efficiency, and insightful simulations across disparate sectors. Here's a brief analysis of the distribution of DT applications worldwide, reflecting its diversity and extent in various domains and regions. The distribution of the DT applications worldwide is shown in ***Figure 2.12***.

6.2.1 *Industry Specific Distribution*

A. **Manufacturing and Production:** Extensive use of DTs in manufacturing sectors, including automotive, aerospace, and electronics, especially in countries with robust manufacturing bases like Germany, China, and the USA. Applications include product lifecycle management, predictive maintenance, and production planning.

B. **Smart Cities and Urban Planning:** Utilization in developed and developing countries for managing urban infrastructures, traffic systems, and utilities. Notable applications can be observed in Singapore, Amsterdam, and Dubai. Implementations often focus on improving sustainability, efficiency, and citizen services.

C. **Healthcare:** Adoption in healthcare systems for patient monitoring, management of healthcare facilities, and medical device modelling, with prominent applications in countries with advanced healthcare technologies like the USA, UK, and Sweden.

D. **Agriculture:** Deployed in precision farming and optimization in countries with prominent agricultural sectors like India, Brazil, and the Netherlands.

E. **Energy and Utilities:** Utilization in energy grid management, renewable energy systems, and utility management, with noteworthy applications in countries investing in smart grid technologies like Denmark, the USA, and South Korea.

6.2.2 ***Geographic Distribution***

A. **North America:** Predominantly used in manufacturing, healthcare, and urban development, given the technological advancements and investments in IoT and AI technologies.

B. **Europe:** Extensive application in manufacturing sectors, smart city initiatives, and healthcare, focusing on enhancing sustainability, efficiency, and citizen services.

C. **Asia-Pacific:** Notable applications in smart city developments, manufacturing, and agriculture, reflecting the diverse economic bases and development agendas across the region.

D. **Middle East and Africa:** Emerging applications in smart city developments, resource management, and infrastructural development, focusing on enhancing resource efficiency and sustainability.

E. **Latin America:** Applications primarily in agriculture, resource management, and urban planning, reflecting the regional economic and developmental priorities.

6.2.3 ***Challenges and Disparities***

The global distribution of DT applications reveals disparities in adoption, primarily dictated by technological capabilities, economic priorities, and infrastructural developments. Developed economies often demonstrate diverse applications across multiple sectors, while developing economies might exhibit focused applications in specific industries pertinent to their developmental agendas.

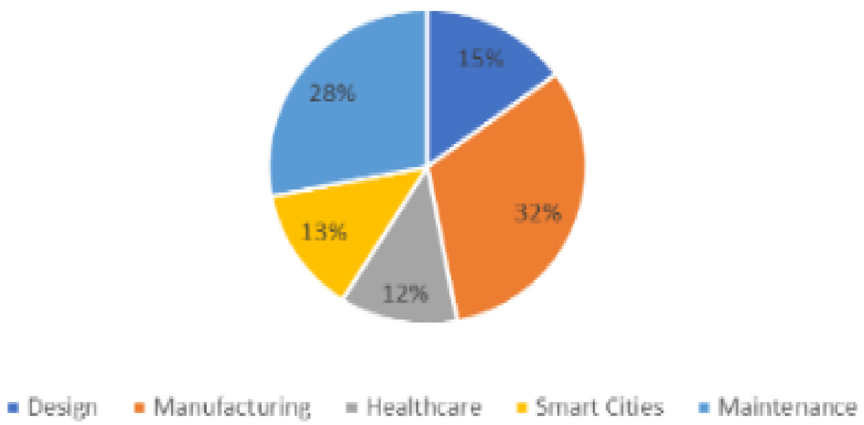


Figure 2.12 Applications percentage of DTs worldwide

6.3 *Misconceptions and Clarifications*

DTs have emerged as a pivotal innovation in the bustling arena of technological advancements, particularly in IoT engineering and manufacturing. However, navigating DTs often confronts many misconceptions that can potentially obscure this technology's true breadth and application. While widely recognized as a digital replica of physical entities, the scope and utility of DTs often transcend this simplified perception. These DTs not only mirror the physical characteristics but also embody their physical counterparts' dynamic processes, interactions, and behaviours.

Misconceptions might revolve around the belief that DTs are merely sophisticated 3D models, underestimating their predictive, analytical, and integrative capabilities. This section seeks to unravel the intricate tapestry of DTs, elucidating their multifaceted nature and demystifying the prevalent misconceptions that shroud this transformative technology, thereby paving the way towards an enriched understanding and optimized utilization in diverse domains.

6.3.1 *Product Avatar (PAv):*

PAv and DTs often discuss digital replication and simulation, especially in industries leveraging IoT, AI, and data analytics. However, they are subject to misconceptions, primarily due to their overlapping domains. ***Table 2.6*** shows a summary of the analysis that aims to elucidate and differentiate the concepts of a PAv and a DTs: The concept of the PAv is rooted in efficient specific information management [276]; however, [277] highlights and emphasises that the notions of PAv and product agent are utilised interchangeably. [278] revisited his definition in 2006 to introduce a new description of the PAv as a distributed approach to interacting with and managing item-level product lifecycle; information has been developed for use in the manufacturing industry. Despite the different concepts of the product avatar, the work still focuses only on the product-service systems [279], [280].

Table 2.6 Summary of the misconception and clarification between DTs & PAv

Misconceptions and Clarifications	
Depth and Breadth of Application	**Misconception:** They are interchangeable because they both deal with digital representations. **Clarification:** PAv primarily focuses on visual and interactive aspects, often in specific scenarios like virtual showrooms, whereas DTs dive deep into replicating and simulating physical and operational aspects, with broader applications in various industries.
Functional Complexity	**Misconception:** The functionality and utility of Product Avatars and DTs are similar. **Clarification:** DTs usually involve higher functional complexity, simulating and analysing various parameters and conditions, while PAv might primarily be constrained to visual interaction.

Data Utilization	**Misconception:** Both leverage data in similar ways. **Clarification:** DTs leverage real-time data for dynamic simulations and predictive analytics, whereas PAv might not always utilize real-time data or focus on predictive functionalities.
User Interaction vs. Operational Insight	**Misconception:** They serve the same user bases and purposes. **Clarification:** PAv often caters to end-users, enhancing their interactive experiences, while DTs might be geared towards operators, engineers, and decision-makers, providing operational insights and predictive analyses.

6.3.2 ***Cyber-Physical System / Equivalent (CPE)***

The concept of CPE is not new; however, it should be considered in the context of CPS [281], which was defined in 2008 as the connection of computation with processes of the PT, where the embedded sensors and computers, along with the network, can monitor and control the physical processes which was a newly emerging technology in 2015.

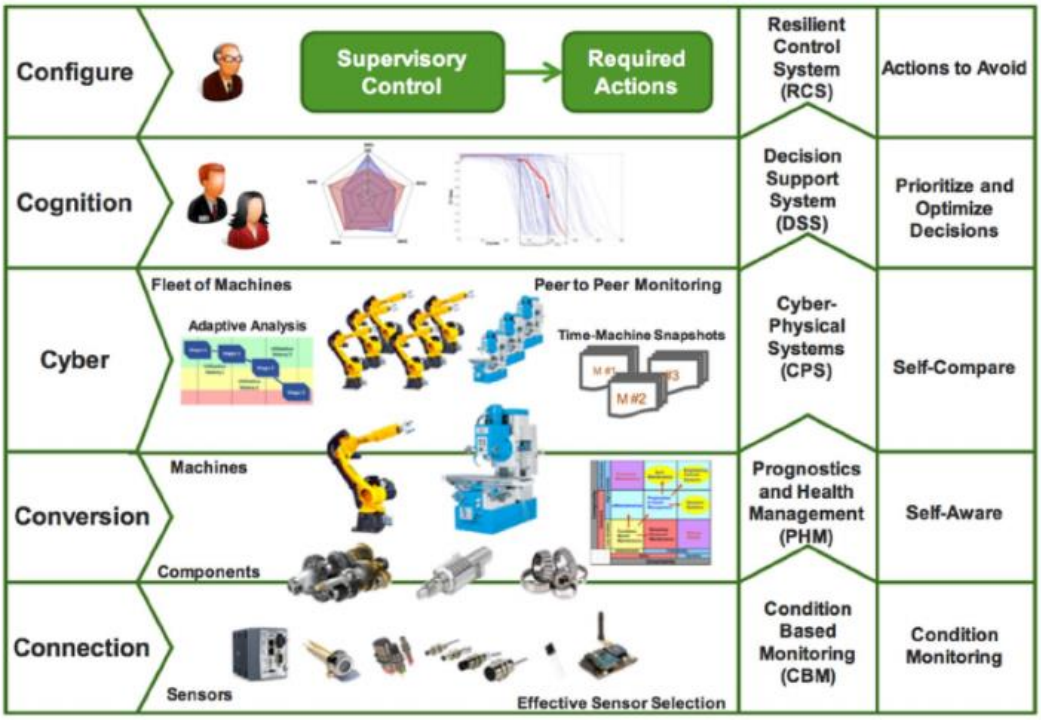


Figure 2.13 Cyber-physical equivalent structure[281]

The CPE concept is defined as a virtual representation (a virtual replica) of a production system completely synchronised with the physical one in all aspects: geometry, function, and behaviour, as shown in ***Figure 2.13***. Because CPE is defined by the networking and interaction of computing and Multiphysics systems, physical systems may be mechanical or electrical. Control systems, planning, or even signal processing could be considered computational; the interaction of these systems with their environments, humans, or each other results in CPSs.

CPE and DTs are related concepts that are connected by sensors and networking. On the other hand, the DTs are limited to the digital model. Simultaneously, CPSs are defined by their DTs and physical assets, implying that they serve as foundations for creating CPE [282], as shown in ***Table 2.7***, summarising the misconception and clarification between DTs and CPS.

Table 2.7 Summary of the misconception and clarification between DTs & CPS

Misconceptions and Clarifications	
Simulative vs. Interactive Nature	**Misconception**: Both DT and CPS are primarily concerned with simulating physical entities. **Clarification:** While DT is heavily rooted in simulation and analysis, CPS focuses more on real-time interaction and control between physical and cyber components
Purpose and Application	**Misconception:** DT and CPS serve identical purposes and applications in industries. **Clarification:** DT leans towards enabling simulation, analysis, and insight generation, whereas CPS predominantly deals with real-time control, interaction, and automation of physical systems.
Operational Complexity	**Misconception:** The operational complexities of DT and CPS are synonymous since they merge physical and digital elements. **Clarification:** DT often involves complexities related to detailed simulation, data analytics, and lifecycle management, while CPS grapples with challenges related to real-time control, synchronization, and communication between physical and cyber entities.
Dependency and Operation	**Misconception:** DT and CPS have similar dependencies on physical and cyber elements. **Clarification:** DT can conduct simulations and analyses even with disruptions in the physical entity's operation, while CPS usually requires seamless operation of both cyber and physical entities to maintain functionality.

6.3.3 *Digital Models (DMs)*

A DM is a digital representation of a physical thing that does not involve automated data exchange between the physical and digital objects; the two-way manual data flow characterises the DM, as shown in ***Figure 2.14*****.** A DM can represent a physical object that exists or will exist in the future. There is a possibility that the digital representation will include a description of the actual object that is more or less exhaustive. ***Table 2.8*** summarises the misconception and clarification between DTs and DMs.

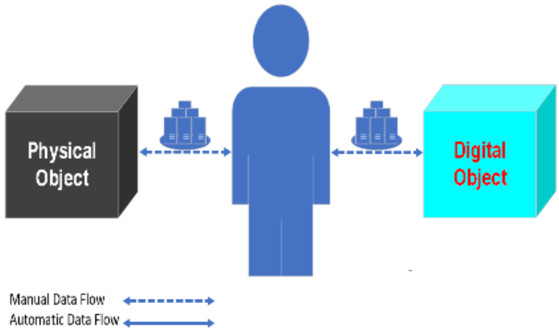


Figure 2.14 DM process where the two ways data transferred manually.

These models may include simulation models of proposed factories, mathematical models of new products, or any other models of a physical thing that do not involve automatic data integration. The DM focused on "what if" or what might happen in the real world. However, the DTs are much more than DM because the DTs continuously monitor, control, and diagnose what is happening in RT to predict and optimise situations and systems [283]. While DMs have a close definition or description of the DTs, there are significant distinctions between the two DTs having automatic data flow and DMs having manual data flow. Nevertheless, this is not a comprehensive list of the models under this category.

Table 2.8 Summary of the misconception and clarification between DTs &

Misconceptions and Clarifications	
Static vs. Dynamic Nature	**Misconception:** DMs and DTs are similar due to their digital representation of physical entities. **Clarification:** While DTs usually present a static representation, DTs are dynamic, incorporating RT data and interactions with the physical world.
Data Utilization and Interaction	**Misconception:** Both utilize data and similarly have interactive capabilities. **Clarification:** DTs involve continuous data exchange and interactions with their physical counterparts, while DMs generally lack real-time data integration and interactive functionality.
Complexity and Application	**Misconception:** Their applications and complexities are analogous since they represent physical entities digitally. **Clarification:** DTs are often more complex due to their RT, interactive, and analytical capabilities, and they find applications in advanced use-cases like predictive maintenance and operational optimization. In contrast, DMs might be utilized for simpler applications like design visualization and documentation.
Purpose and Functionality	**Misconception:** DMs and DTs serve identical purposes in digital representation. **Clarification:** DMs primarily serve purposes related to visualization, design, and documentation, whereas DTs extend to functional aspects like simulation, analysis, and control, providing actionable insights and facilitating decision-making.

6.3.4 ***Digital Shadows (DS)***

DS often pertains to the digital footprint left by an individual or entity across the online sphere. This can encompass everything from social media interactions and transaction histories to publicly accessible personal information and generated content. ***Table 2.9*** summarises the misconception and clarification between DTs and DMs. A deeper analysis of the digital shadow can unveil nuanced insights into various domains, including privacy, security, digital identity, and personal branding. According to the concept of a DM, if there is also an automated data flow in only one direction between the state of an actual physical object and a digital object, one may call the combination of these two things a DS, as shown in ***Figure 2.15***. A shift in the state of the PO will cause a corresponding shift in the state of the digital object, but not the other way around.

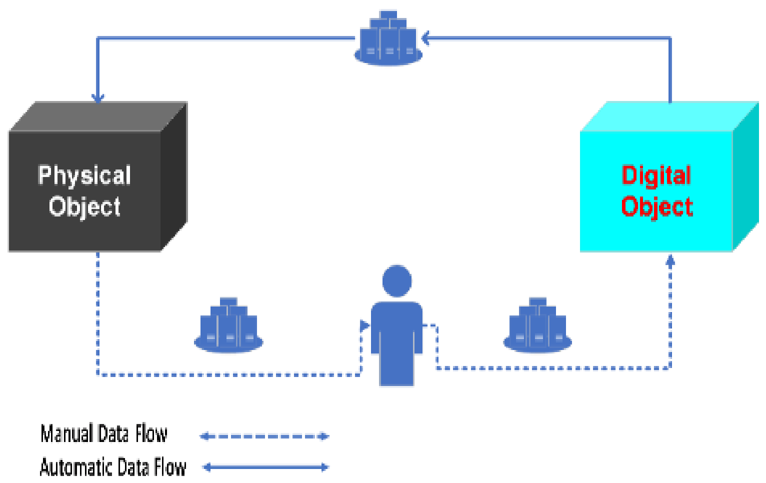


Figure 2.15 DS only moves in one direction between the PO and DO

Instead of the reverse, a change in the PO's state causes a change in the digital object. Two similar physical and computational systems can be considered DTs, a more direct depiction of any PS in computer form, referred to as a PAv. Cyber-physical equivalent (CPE) is the relationship between interconnected computers and physical systems. Until the beginning of 2008, the PAv dominated the manufacturing world. However, by the end of 2010, the literature indicated that engineering and manufacturing had adopted DTs as their domain. The concepts of DS and DTs often find themselves shrouded in a mist of misconceptions, primarily due to their capabilities in providing digital representations of PO or systems. The nuanced differences in their functionalities, applications, and complexities provide a robust framework for analysis. Let us dissect and explore these concepts to uncover their distinctive features and clarify prevalent misconceptions:

Table 2.9 Summary of the misconception and clarification between DTs & DS.

Misconceptions and Clarifications	
Real-Time Interaction and Control	**Misconception:** DS and DTs are sometimes misinterpreted as having real-time interaction and control capabilities. **Clarification:** While DTs establish RT interaction and control with the physical entity, DS predominantly provides a static data visualization without interactive functionalities.
Data Analytics and Simulations	**Misconception:** They are often perceived as similar in their data analytics and simulation capabilities. **Clarification:** DTs facilitate advanced data analytics and simulations based on real-time data, whereas DS lacks dynamic analytics and predictive simulations.
Complexity and Applications	**Misconception:** DS and DTs are occasionally viewed as comparable in complexity and applicable scenarios. **Clarification:** DTs involve higher complexity due to their dynamic, interactive, and analytical capabilities and find applications in advanced use cases like predictive maintenance and real-time monitoring, while DS is simpler and utilized for basic data visualization and documentation.

6.3.5 *Digital Twin WEB (DTW)*

DTs and DTW are concepts deeply embedded within digital transformation and smart technologies, often confusing due to seeming similarities in their terminologies. These two entities diverge significantly in their scopes, functionalities, and applications. Below is a succinct analysis exploring these terms and elucidating prevalent misconceptions, as shown in ***Table 2.10*** shows the summary of misconceptions and clarifications between DTs and DTW. The term DTW, sometimes known as "Twinweb", was defined as "an ongoing development effort for constructing a global network of DTs in a similar internet-native and user-friendly manner as the World Wide Web (WWW) gives information to people as shown in ***Figure 2.16***." [284]. DTW prioritises Readability for humans and machines, which describes their relationship with the other twins in the series, creating a knowledge network based on the real world. DTW typically encompasses an interconnected virtual representation of the physical world within the digital realm, merging cyber and physical entities to facilitate enhanced system monitoring, analysis, and control. This concept blends IoT, AI, and data analytics aspects to simulate, predict, and visualize scenarios in a digital format that closely mirrors reality.

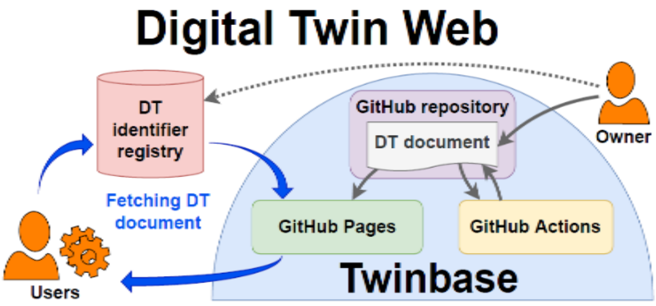


Figure 2.16 DTW distributing of DTs from owners to users [285]**.**

DTs and DTW are concepts deeply embedded within digital transformation and smart technologies, often confusing due to seeming similarities in their terminologies. These two entities diverge significantly in their scopes, functionalities, and applications. Below is a succinct analysis exploring these terms and elucidating prevalent misconceptions.

Table 2.10 Summary of misconceptions and clarifications between DTs and DTW

Misconceptions and Clarifications	
Scope and Interaction	**Misconception:** DTs and DTW are often misperceived as synonymous due to their similar nomenclatures. **Clarification:** While a DTs refers to the digital replica of a singular physical entity, the DTW refers to a network of multiple DTs, enhancing the scope from a singular entity to an interconnected ecosystem.
Functional Capabilities	**Misconception:** Their data analysis, simulation, and control capabilities are sometimes considered equivalent. **Clarification:** DTW extends the functionalities of individual DTs by facilitating data sharing and collective decision-making among the interconnected entities, thereby providing an additional layer of collaborative functionality.
Application Domain	**Misconception:** DTs and DTW applications and deployment domains are often conflated. **Clarification:** While DTs find diverse applications across various sectors for individual entity monitoring and control, DTW is particularly pertinent in scenarios where interconnected data exchange and collaborative decision-making among multiple entities are required.

6.3.6 ***Physical Twins (PTs)***

In digitalization and smart technologies, concepts such as DTs and PTs often become subjects of exploration and, sometimes, misconceptions due to their intertwining functionalities in replicating real-world entities. Analysing these concepts with a focus on their distinct functionalities, applications, and scopes is paramount to clarifying misconceptions. ***Table 2.11*** summarises the misconceptions and clarifications between the DTs and PTs. PTs are not a widely-acknowledged term in technological and industrial literature. Consequently, it does not have a standard definition or recognized application. However, if the term PT was to be interpreted straightforwardly, it could refer to a physical replica or model of an object or system used to analyse, study, or test scenarios in a tangible, real-world context without impacting the original entity. Such physical replicas might be employed in various scenarios like prototyping, testing, simulating physical conditions, or studying structural and material properties in a controlled environment. This is speculative and extrapolated from the term without a standard definition or application in technical fields.

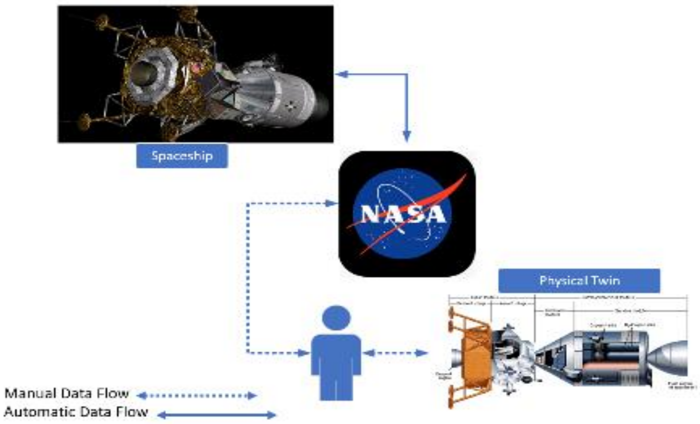


Figure 2.17 NASA's first concept of the Physical Twin

NASA first introduced the concept of the PT in the aerospace industry during the Apollo programme, when two identical space shuttles were built to use one in space. A second person will be on the planet to study the shuttle's behaviour in the area and keep track of its conditions [65], [68].

Table 2.11 Misconceptions Summary and clarifications between the DTs and PTs.

Misconceptions and Clarifications	
Form and Interaction	**Misconception:** The physical and digital representations might be perceived as similar due to their "twin" nomenclature. **Clarification:** A DT involves digital representation and virtual interaction, while a PT (hypothetically) involves tangible representation and manual physical interaction.
Analytical Capabilities	**Misconception:** DTs' and PTs' analytical and simulative capabilities might be conflated. **Clarification:** DTs enable digital simulations, predictive analytics, and remote control, while PTs enable tangible analyses and manual testing.
Scope and Application	**Misconception:** The scope and application of Digital and PTs might be perceived as interchangeable. **Clarification:** DTs find extensive application across varied sectors for digital monitoring and analysis, while PTSs (hypothetically) would be more constrained to contexts requiring tangible analyses and physical testing.

6.3.7 *Industrial Internet of Things (IIoT) / IoT*

Navigating through the technologically intensive concepts of IoT and DTs could sometimes lead to misunderstandings, given their interlaced functionalities in digital transformation and smart technologies. Both concepts revolve around enhancing connectivity, data utilization, and smart operations, yet they are distinctly different in their purposes, functionalities, and implementations. ***Table 2.12*** briefly analyses unravelling the misconceptions between IoT and DTs. The IoT is a collective term that refers to all the many devices connected to the Internet. It is about giving so-called 'things' the ability to think for themselves and gather information about the environment in which they find themselves via AI. When Kevin Ashton developed his plan for the IoT in the late 1990s, the term IoT was first used in a publication according to [286]; in this hypothetical situation, a programme would connect a Coca-Cola vending machine to the internet to check whether the beverage had adequately cooled down and was in a state where it could be purchased and enjoyed by a customer. Due to the numerous sensors available today, as shown in ***Figure 2.18***, the IoT concept is critical for its implementation. While the DT are a vision of the future fully connected world, they cannot exist without sensors. An extensive benefit delivered by the advancement of the IoT brings the DT closer to realising its full potential. IoT can be defined as the infrastructure in the physical space used to connect physical assets [287].

Figure 2.18 Internet of things [288]

Thus, the IoT utilises networking and sensors, whereas DT technologies use networking and sensors; however, the DT utilises the digital model in cyberspace [289]. The number of IoT devices registered yearly demonstrates this technology's exponential growth. More than 17 billion people existed in the year 2018, according to [290]. By 2025, more than 75 billion devices will be operating, and [291] predicts the market will be valued at more than $5 trillion. Many linked gadgets help to make the dream of a completely connected world a reality. All elements of daily life, including the communication business, the healthcare industry, the building and transportation industries, smart cities, and manufacturing, are impacted favourably by the growth of IoT devices [292], [293].

Table 2.12 Misconception summary and clarification between IoT and DTs

Misconceptions and Clarifications	
Purpose and Functionality	**Misconception:** IoT and DTs might be perceived as identical due to their emphasis on connecting the physical and digital worlds. **Clarification:** While IoT focuses on interconnecting physical devices and sharing data, DTs primarily revolve around creating a digital replica of a physical entity for simulation, analysis, and control.
Data Utilization	**Misconception:** The data utilization in IoT and DTs might be misinterpreted as serving similar purposes. **Clarification:** IoT predominantly involves data collection and sharing among devices, while DTs focus on utilizing data for RT synchronization, simulation, and predictive analytics.
Implementation and Deployment	**Misconception:** IoT and DTs' implementation mechanisms and deployment strategies might be perceived as analogous. **Clarification:** IoT implementation enhances device connectivity and data exchange, while DT deployment primarily focuses on mirroring, monitoring, and controlling physical entities digitally.

6.4 *Characteristics of Integrating AI with DTs*

In the enthralling nexus of smart technologies, integrating AI with DTs emerges as a paradigm that exemplifies technological synergy, steering unprecedented advancements across myriad sectors. As virtual replicas of physical entities or systems, DTs interactively mirror RT conditions and changes, while AI introduces the capabilities of learning, reasoning, and self-correction to this dynamic digital replica. This amalgamation brings about enhanced predictive maintenance and operational efficiency and pioneers intelligent decision-making and autonomous actions in the digital replica.

A. **Universal connection and intelligent objects:** The manufacturing equipment should be outfitted with smart sensors capable of RT monitoring and data exchange with other network elements. A risk-free, dependable, quick platform must accommodate these nonstop data exchanges.
B. **Advanced analytics:** It is necessary to automate as much of the data preparation, perception, analysis, learning, and execution process as possible while minimising the amount of manual feature engineering and human intervention. It is now possible for production systems to self-configure, self-adapt, and self-learn, increasing productivity, speed, flexibility, and efficiency [294], [295].

C. **Hybrid decision-making:** RT data limitations and data from many sources must be considered to arrive at a globally optimal solution. Several orders will have their practicability, efficacy, and efficiency regarding implementation methodologies reviewed during this procedure [296].

D. **Autonomous model update:** RT control, optimisation, forecasting, and other similar activities necessitate the synchronisation of data and the use of complex modelling techniques to map between VS and PS.

E. **Self-regulating disturbance and resilience handling:** Smart robots are interdisciplinary technology that integrates sensing and analysing production information, representation of experience, and knowledge. One of the features of smart robots is intelligent decision-making based on information, data, experience, and prior knowledge. It can simulate, model, and autonomous operation.

F. **Fault diagnosis framework:** DTs are a living representation of a physical system backed by multi-physics simulation, machine learning, AR / VR, and cloud services. These multi-physics support results and enable constant environmental or operational adjustments for DTs [297].

6.5 *Types of Modelling*

The modelling types are shown and summarised in ***Table 2.13;*** as it embarks on the rich tapestry of modelling, one enters a realm where reality and hypothetical scenarios are dissected, analysed, and reconstructed to understand better, predict, and manipulate the physical and conceptual world. Modelling types, primarily characterized by their methodological approaches and application domains, encompass a vast array, each offering a unique lens through which real-world complexities can be decoded and visualized.

6.5.1 *Physical Modelling*

Deployed to simulate physical objects and processes in a controlled environment, physical models, such as architectural maquettes or engineering prototypes, furnish tangible, scaled representations. These models offer a palpable medium to analyse, test, and iterate designs and hypotheses in a risk-mitigated, controlled setting.

6.5.2 *Mathematical Modelling*

A theoretical framework wherein mathematical structures and notations delineate the characteristics and dynamics of systems, mathematical modelling becomes a pivotal tool in predicting and exploring various phenomena across sciences, engineering, economics, and more through computational simulations and analytical solutions.

6.5.3 *Statistical Modelling*

Using statistical methods and assumptions to emulate datasets' variability and underlying patterns, statistical modelling aims to infer relationships, predict outcomes, and understand the inherent structures within data, thereby enabling evidence-based decisions and predictions.

6.5.4 *Computational Modelling*

Harnessing the power of computational algorithms and simulations, computational models synthesize complex systems into digital replicas, enabling explorations and analyses that might be impractical, risky, or impossible to conduct in the real world, providing a playground for virtual experimentation and discovery.

6.5.5 *Conceptual Modelling*

Predominantly dealing with abstract concepts and relationships, conceptual modelling constructs frameworks that aid in understanding and exploring theories, ideas, or systems in a structured manner, thereby translating abstract concepts into comprehensible, actionable insights.

Table 2.13 Modelling types with physical or Digital integration

Modelling Types	Description	Physical / Digital
Mathematical /Analytical	Time characteristics validation	Only physical
	behavioural analysis of a physical object's	Only Digital
	(White-box design) with validation of algorisms	Physical & Digital
	Training employees	
	Control design of systems	
Graphical /Statistical	Reliability estimation	Physical & Digital
	Stability estimation	
Systematic /Functional	2-D design verification	Physical & Digital
	3-D design validation	
Diagrammatic Data Flow	Data representation of the system's logic	Only Digital
	No real-time data flow	Physical & Digital
Scale Modelling	System's design verification	Physical & Digital
	Considers all the previous descriptions	
	Time verification	
	System safety and security verification	
Digital Twins	System's design verification	Physical & Digital
	System's infrastructure validation and monitoring	
	Cybersecurity verification	
	Live system's condition monitoring	
	Actual data flow presentation	
	Includes all the previous modelling descriptions	
Advanced Digital Twins	Integrates the full description of digital twins with Artificial Intelligence	Physical & Digital

6.6 *Methods of Failure detection for Coiled Springs and Their Limitations*

The most recent failure analysis methods used in the literature and their limitations are shown in ***Table 2.14***. In light of these methods and limitations, a holistic approach that amalgamates various methods is often pivotal in ensuring a comprehensive failure analysis for coiled springs, thereby mitigating risks and enhancing reliability in numerous applications where springs are fundamental mechanical components. Failure detection methods for coiled springs play a crucial role in achieving this goal.

Table 2.14 Failure detection methods for coiled springs

Ref	Method	Limitations
[230] 2023	Effective-Strain damage and Probabilistic approach	ESD model estimated lower fatigue life than conventional models, and the coil springs had lower fatigue reliability with load sequence
[298] 2023	Development of a finite element model to justify and validate the outcomes of the study	The study is limited to the analysis of extension springs and does not cover other mechanical springs. Does not explore the effects of environmental factors, such as temperature or humidity, on the failure of extension springs. The study is based on a case study analysis and may not capture the full range of failure mechanisms and scenarios that can occur in industrial applications. It does not address the impact of external factors, such as vibrations or shocks, on the failure of extension springs.
[299] 2022	Acoustic method fault detection system and Batch sampling method for quality check (QC) inspections	The authors could not replicate the line density and noise peak observed in the reference experiment in their simulation. The complexity of the structure makes fault detection difficult, and Batch sampling method is ineffective for detecting faults.
[300]	Multiple linear regression (MLR) and Strain-life models	The evaluation of the proposed model is limited to comparing the predicted FL with measured strain FL models without considering other factors such as stress FL approaches or real-world validation.
[301]	Visual observations, optical and scanning electron microscopy and hardness test	Lacks detailed information on the specific conditions and factors that contributed to the FF of the valve springs. And lack of investigation into the root causes of the failure, such as the operating conditions, material properties, and design considerations
[302]	FE Method for stress concentration factor evaluation	Does not consider specific factors that caused the unexpected early FF of the component. Lacks information on the specific design modifications to address the fatigue failure and meet the customer requirements. The analysis is based on simplified simulations and may not fully capture the complex behaviour of the component under actual operating conditions.
[303]	Chemical composition analysis	It focuses primarily on the surface initiation of fatigue cracks and does not provide a comprehensive understanding of the

	and mechanical property analysis	underlying mechanisms and factors that led to the failure. Lacks information on the specific material properties and manufacturing processes of the spring diaphragm, which could have contributed to its susceptibility to fatigue failure.
[38]	Microstructural analysis and fractography by SEM and Inclusion rating by optical microscopy	The acquisition of a strain signal in traditional methods is constrained due to errors, time-consuming processes, and high costs. Proposes a new method for generating strain signals based on computer simulation, but it does not address the challenges of acquiring strain signals in real-world scenarios.

6.7 *Comparison of Methods Used for Predictive Maintenance*

Several comparisons have been made among various machine learning methodologies within scholarly discourse. ***Table 2.15*** summarises the recent methods used for PdM and data types: Real Data (RD) and Synthetic Data (SD). In the cited study [264], the researchers employed a selection of six ML algorithms, namely ANN, SVM, linear regression (LR), Gaussian Process Regression (GPR), ensemble bagging, and ensemble boosting algorithms. These algorithms were utilised to estimate the state of charge of lithium-ion batteries. The suggested ANN and GPR techniques demonstrated high performance compared to previous approaches, with a mean absolute error of 85%. Hence, using ANN and GPR might facilitate the development of an optimal battery management system for electric cars by leveraging State of Charge predictions. The authors of [304] suggested a hybrid data-driven approach that integrates the advantages of GPR and Long Short-Term Memory (LSTM) to enhance the precision of Remaining Useful Life (RUL) prediction for lithium-ion batteries while also ensuring dependable management of uncertainty.

In the study of [305], the authors provide a unique two-stage Wiener process model to effectively characterise the deterioration patterns shown by lithium-ion batteries throughout various degradation phases. Following the findings of reference [306], a comparative analysis was conducted on four distinct classifiers, namely SVM, Decision Trees (DeT), Random Forests (RF), and k-Nearest Neighbours (kNN). The findings indicate that all algorithms exhibit a high level of accuracy, with particular emphasis on the SVM classifier, which demonstrated superior performance across four distinct operating systems. The SVM model exhibited a minimum accuracy of 96.6% on the ignition and cooling systems, whilst the fuel system had the highest accuracy of 98.5%. The SVM classifier demonstrated superior performance across four distinct operating systems, with accuracy rates of 96.6%, 98.7%, 98%, and 96.6%, respectively.

The authors use distinct training and testing datasets of standardised driving cycles created using a simulation testbed. These datasets are employed for problem diagnostics in turbocharged petrol engine systems. The RF approach yields superior results to the SVM method, as seen by its minimum accuracy of 0.885, surpassing the second-highest accuracy of 0.806. However, it is feasible to enhance the precision of all methodologies by using low-pass filtering on the resulting outputs.

Table 2.15 Method's summary used for PdM and data types RD and SD

Ref	Year	Methods	Applications	Data Types
Digital Twins				
[307]	2021	Maintenance of the constant velocity joint of a car		SD
[308]	2019	Predictive maintenance of an automotive braking system		SD
[309]	2017	Prediction of brake pad wear in a car		SD
Deep Learning				
[310]	2021	Ensemble method	Health prediction for sensor systems	RD
[311]	2021	CNN	Multi-sensor Fault Detection	RD
[312]	2021	LSTM	Remaining fatigue life of automotive suspension	RD
[313]	2021	EFMSAE-LSTM	Prediction of mechanical fault time series	RD
[314]	2021	EBa, EBo	State of charge estimation of lithium-ion battery for electric vehicles	RD
[315]	2021	CAE+LSTM	RUL prediction for electric valves	SD
[305]	2020	Merged-LSTM	Time-between-failure (TBF) prediction modelling based on multisource data	RD
[316]	2020	LSTM, RF	Heavy medium lead-acid battery prognosis	RD
[317]	2020	AE	Prediction of upcoming failures in trucks	RD
[318]	2020	LSTM+GPR	RUL prediction for lithium-ion (Li-ion) batteries with reliable	RD
Machine Learning				
[319]	2021	SVM	Fault detection, identification, and prediction for autonomous vehicle controllers	SD
[320]	2021	ANN + k-NN	Vehicle health monitoring	RD
[321]	2021	ANN, SVM, LR, GPR	State of charge Estimation of lithium-ion battery for electric vehicles	RD
[322]	2020	LR	Failure's prediction of a given vehicle component	RD
[323]	2020	RF, SVM, ANN, GP	Fault diagnosis in turbocharged petrol engine systems	SD
[324]	2019	SVM	Fault diagnosis of vehicle suspensions	SD
[325]	2019	MLR	Fatigue life evaluation of automotive coil springs	RD
[326]	2018	DT, SVM, RF, k-NN	Monitoring and fault predicting system in the vehicle	RD
[327]	2018	DT	Identification of different fault types of axle box bearings	RD

[328]	2018	k-NN	Classification of vibration gravity to predict anomalies	RD
[329]	2017	GPR	RUL prediction for slow-speed bearings	RD
[330]	2017	MLR	Energy intensity of new automotive plants	RD
[331]	2016	LR, ANN	Diesel engine fuelled with biodiesel alcohol mixtures	RD
Physics-Based Models				
[332]	2019	Vibration-based machinery health monitoring techniques		RD
[304]	2018	Description of a compact angular head (roller hemming)		SD
Statistical and Stochastic Approaches				
[333]	2021	Identification of defects in a spur gear system		RD
[334]	2021	Description of lithium-ion batteries 'degradation		RD
[334]	2019	Description of degradation processes		RD
[335]	2018	Modelling of all possible causal relationships between sensor signals recorded directly from CAN bus in-vehicle networks		RD
[336]	2018	Diagnosis of the connection of lithium-ion battery in series		RD
[337]	2017	Diagnosis of battery faults		RD
Knowledge-Based Models				
[338]	2020	Fuzzy logic	Evaluation of vehicle state to prevent anomalies and malfunctions	RD

7 LITERATURE GAPS

This research literature embarked on an academic journey through the intricate realms of existing literature; researchers often encounter a pivotal element, known as the 'literature gaps,' which stands as an uncharted territory within a specific research domain. The literature gap section, an indispensable facet of scholarly writings, endeavours to illuminate areas where questions remain unanswered, theories untested, or applications unexplored. It lays the foundation for the justification of new research, highlighting the spaces where knowledge is scarce or absent, thereby signalling opportunities for further exploration and understanding. By meticulously examining and unravelling what is known and, crucially, what is not known within the body of literature, researchers carve out a niche for their studies, asserting the pertinence and necessity of their inquiries in the boundless ocean of existing knowledge. Within these gaps, the seeds of innovation and discovery are sown, cultivating advancements, insights, and novel perspectives within the scholarly community and beyond. This study has revealed three main literature gaps for DT technology and its usage in the automotive industry, in particular with suspension systems for mechanical springs as follows:

1. From the review and analysis carried out in ***Chapter 2,*** particularly from the literature analysis section, in particular from the theory and practice point of view, it is clear that the DTs technology concept is misunderstood and has a massive misconception across theory and practice. In short, no standardisation characteristics across theory and practice exist to leverage and seize the full potential benefits of implementing the actual DT technology.
2. From the review and analysis in ***Chapter 2***, there is very little to no scientific paper showing how to implement actual DTs for a suspension system. From the literature analysis section, it is clear that all the current methods used up to date (2023) do not consider the current time as the fourth dimension of their strategies; the data they collect might be RT data but not CRT, which is very important to consider the degradation of the mechanical springs over time.
3. From the review and analysis carried out in ***Chapter 2***, it is clear and obvious that the methods used for failure analysis of coiled springs or PdM still have many limitations, especially when dealing with the dynamic load during operation.

8 CHAPTER SUMMARY

Although the study in this review was carried out in line with [75], the study has many restrictions. Despite this, it is impossible to ensure complete coverage of all aspects of DT technology, primarily due to the many concepts developed in theory and practice. On the other hand, the review ensures no ambiguity in understanding and that decisions are transparent. The guarantee of the study took place along the study in line with [74].

This systematic review is organised around two main research questions and is structured around DT technologies in theory and practice settings and the condition monitoring, diagnosis and predictive maintenance for suspension systems. In response to the research questions, the study presented comprehensive concepts, followed by a review of state of the art, discussion of research issues classifications, and new directions for future research. Additionally, the review went in-depth analysis regarding. This review improved and enhanced the transparency for understanding DTs concepts and highlighted the benefits of DTs in various applications. This review benefits the theory and practice by providing new avenues for future research and suggestions for improvements and enhancements. Therefore, the contribution of the evaluation is rich in information for both theory and practice.

This review deeply examined DTs' concept, maturity, creation, values, applications, techniques, and technology and created the most suitable way to implement DTs in theory and practice through 500 publications. This review guides the status of DT's development and application in today's theory and practice environment. This review also outlined the current challenges and possible future work directions. This review consolidated the different types of DTs and definitions throughout the literature to easily identify DTs from the rest of the favourable terms, such as PAv, DTh, DM, DS, CPS, and CPE.

The review and analysis carried out in ***Chapter 2*** identified four characteristics/dimensions of the actual DT technology to be standardised and implemented across theory and practice as follows:

5- Physical Asset / Entity (PE)
6- Virtual Replica/ Entity (VE) (3D modelling)
7- Connections between the PE and its VE
8- Current Real Time (CRT) data

Therefore, this research proposes these characteristics or dimensions to standardise the concept of DTs technology across theory and practice and identifies DTs as a "***Four dimensions virtual replica that continuously simulates the entire behaviour of anything.***"

CHAPTER 3

Physics-Based Digital Twins for Vibration Fatigue Analysis and Modelling from Theory to Concept Implementation

1 CHAPTER OVERVIEW

Industry 4.0 introduced Digital Twins (DT), but defining or conceptualising the DT is still challenging. Many academics and industries still use old technologies, named DT. This young technology is in danger of reaching the plateau despite its immense benefit to sectors. This chapter proposes a novel and unique mathematical DT concept for the coil springs used in suspension systems. The uniqueness of the meaning is that it is suitable and adaptable wherever it applies in theory and practice.

The novel concept of the DT for this study is based on numerical analysis using Euler's theory. The Euler method is a first-order numerical procedure for solving ordinary differential equations (ODEs) with a given initial value. The Euler method is used to conceptualise the DTs models physically, which is novel and unique to this case study. This concept of the DTs models based on the Euler method will approximate solutions by iteratively computing the value of the function at discrete time steps. The Euler method is named after the mathematician Leonhard Euler, who first described the technique in the 18th century. It is considered the simplest and most basic method for numerical ODEs. A successful numerical DT model developed and validated the proposed concept of the DT based on Euler's method. The numerical testing verified the accuracy and efficiency of the DT model through the exact representation of the internal and external behaviours of the vibrating system in all situations. The model still has some limitations and is open for further research; further research depends on the type of application.

This chapter explains the process of developing:

- A novel analytical approach to conceptualise DTs
- The concept is computationally fast, easy to implement and cost-effective.
- The DT model continuously visualises and evaluates parts' conditions
- The proposed DT model applies to all theories and practices.
- The proposed DT enhances condition monitoring in current real-time.
- The proposed technique improves predictive and proactive maintenance

2 INTRODUCTION

There has been a noticeable upward trajectory in the prevalence of vibration fatigue analysis within the automotive sector. An investigation was carried out by [339] to analyse the fatigue caused by vibrations on a vehicle body. The Dirlik technique was used, together with experimental wheel hub accelerations, in order to minimise both development costs and time. Furthermore, [340] conducted a study in which they analysed the impacts of load input directions on the fatigue life of a car bracket using vibration fatigue analysis. Based on the extant literature, it is evident that the load component plays a pivotal role in the study of Fatigue Life (FL). Researchers have undertaken efforts to ascertain the real loadings in order to get a comprehensive understanding of this phenomenon. [341] conducted a further investigation into the importance of loading signals, positing that the stationarity and Gaussian characteristics notably influence the FL.

However, when it comes to actual vehicle applications, the loading signals are always non-stationary, which adds complexity to the analysis [342]. The inherent frequencies of automotive components would probably fall within the frequency spectrum of road excitations. The time domain fatigue study did not consider these dynamic effects [343]. The study examined the dynamic impacts of structure, specifically focusing on lower arm [344], [345] and door weather strip seals [346]. Modal analysis has traditionally been used to investigate the dynamic behaviour of structures. Modal analysis was conducted on a car's crankshaft [347] and drum brakes [348] in the automotive sector. The modal analysis encompasses the data on the response of a structure, which may be acquired using an experimental methodology, including a shaker table, modal hammer, and pressure sensor [349]. Additionally, it is possible to get a structure's modal analysis outcomes through Finite Element Analysis (FEA) [350]. FEA has also been utilised within the automotive sector to model the dynamic response of a bus [351].

Through an exhaustive review of the literature, it has been shown that random vibration signals have significant impacts on the FL. The study by [352] included examining vibration fatigue in engine structures. The researchers used random loadings to investigate the impact of the damage summation rule across various load sequences. In the context of the vibration fatigue study, it has been shown that when the loading signals align with the structural frequencies, the resulting vibrations experience amplification [353]. Therefore, modal analysis was suggested as a means to ascertain the structure's resonant frequency prior to doing the study on vibration fatigue. The fatigue numerical analysis involves using vibration excitation using Frequency

Response Functions (FRFs) to determine the stress or strain tensor distribution in the automotive structure's frequency domain[339].

However, there is ongoing debate over the accuracy of FL prediction in the frequency domain, particularly when dealing with diverse non-stationary loadings. The significance of effectively managing information and data within the industrial sector has steadily increased and now plays a more substantial role in determining the competitiveness of firms compared to the management of material or financial flows [354]. The modelling, simulation, and corporate information systems fields have seen significant advancements, resulting in their integration and the subsequent emergence of DTs. These DTs serve as virtual representations of actual assets. [355], [356] [357], [358] DTs at greater levels of maturity are used in industries such as automotive and aviation. These DTs go beyond basic visualisation or access to machine IoT data and facilitate various product processes throughout their lifespan. Mature DTs can access and use diverse data sources [359], therefore integrating and contextualising data within their operational context [360]. Furthermore, they facilitate decision-making processes by using RT simulation [361].

The primary objective of the scientific discipline of RT simulation is to progress towards the singularity point, characterised by the seamless integration and synchronisation of virtual and physical assets. The statement above suggests that there will be a significant restructuring of industrial business practises [362]; this restructuring will include the utilisation of DTs as a fundamental framework for facilitating the exchange of information across different organisations. Additionally, DTs will enable joint efforts in data collecting, processing, analytics, and exploitation on a larger scale within the ecosystem. There is a noticeable rise in the adoption of virtualization in the realm of work. This refers to executing tasks within virtualized environments [363], [364].

Additionally, the utilisation of DTs in the domains of product development and production is becoming increasingly prevalent [356], [365], [366]. Furthermore, there is a growing implementation of advanced industrial automation and collaborative robotics [367]. Lastly, novel approaches are being developed to enhance collaboration and facilitate industrial design, planning, and implementation [368]. The concept of DTs has transformed, progressing beyond simple simulation models to become powerful instruments that allow the examination of authentic product behaviours inside virtual settings. The use of physics-based simulation allows for the creation of virtual prototypes that adhere to real-world physical limitations [369].

Additionally, the incorporation of Real-Time (RT) capacity expands the application of simulation to various phases within the product lifecycle. Using computationally efficient dynamics modelling presents opportunities for several applications, such as fault and condition identification, issue root source debugging, and predictive maintenance [370]. Cutting-edge simulation models can include RT system hydraulics [370], enabling them to effectively adapt to user inputs in the context of the mobile heavy machinery sector.

The use of DTs is seeing an upward trend in several industries, sectors, and methods aimed at improving organisational effectiveness [371], [372]. According to reference [373], the use of DT technology in virtual learning, the establishment of standardised working environments, resource optimisation, and operational efficiency can provide significant benefits to both the users and staff members of the organisation. Companies increasingly utilise DT to improve operational flexibility and obtain insights into their performance and operating conditions through RT data [371]. This data can facilitate improved decision-making in various operational aspects, including condition monitoring, function simulation, evolution simulation, dynamic scheduling, predictive maintenance, and quality control [371]. Moreover, the utilisation of RT data provided by DTs enables the surveillance and enhancement of operations [371], [373], the advancement of novel products, the implementation of more efficient service programmes [374], the expansion of business models, and the achievement of more effective value generation [374], [375].

The DT methodology utilises information from diverse perspectives, which is then disseminated throughout many departments and stakeholders using systematic approaches. This technique facilitates the automation of operations at an advanced level. From a technological perspective, the primary obstacle is facilitating and using data transfers across several interconnected systems to achieve high-level automation of goods and processes. Data interoperability concerns may be resolved; nevertheless, effectively utilising the data and analytics necessitates a comprehensive comprehension fostered across many levels. In order to effectively derive value from data within business processes, several key factors must be considered. Firstly, the information must be appropriately disseminated to the relevant teams and individuals in a timely manner, ensuring that it is presented in a practical and comprehensible format. Secondly, the organisation must support cross-functional teams, facilitating collaboration and cooperation across different departments.

2.1 *Euler Method (EM)*

The EM is a numerical technique for solving ordinary differential equations (ODEs) with a given initial value. It is a first-order method, meaning that it uses the function's derivative at a single point rather than the function itself to estimate the value of the function at future points. The EM is relatively simple to implement and can quickly approximate the solution to an ODE. However, it can be less accurate than other methods, particularly for ODEs with rapidly changing solutions or problems with multiple solutions. It is important to note that the Euler method is straightforward to approximate the solution of ODEs.

This chapter integrates the EM with the DT model to monitor the mechanical behaviour of the coiled springs used in suspension systems; the prediction of DT models has a solid mathematical background for their concept. At this stage, the CPS was formed based on the advent of the materials and capabilities of the sensor. In other words, the IoT became the backbone of the fourth industrial revolution [376], [377]. This industrial revolution changed how models behave in companies, businesses, and academia; the competition rules between them altered to adapt the IoT ideas and concepts. IoT pushed the industrial revolution to the digitalisation stage [378]–[380]. From the industrial point of view, digital technology solutions offer better opportunities for industrial companies and consumers, saving time, reducing unnecessary costs, reducing downtime, and increasing the availability of services.

2.1.1 *Euler Method Characteristics*

The EM is a numerical technique for solving ordinary ODEs, and it has several characteristics:

1. It is a first-order method: The EM uses the function's derivative at a single point, rather than the function itself, to estimate the value of the function at future points. It means it is based on the slope of the solution at one point.
2. It is relatively simple to implement: The EM is relatively straightforward, making it a good choice for quickly approximating solutions to ODEs.
3. It is sensitive to step size: The accuracy of the Euler method depends on the step size used. The method becomes more accurate as step size decreases, but the computational cost increases.
4. It is not always appropriate: The EM is less suitable for problems with stiff equations or chaotic dynamics.
5. It can be used for long-time predictions: As the EM is relatively fast and easy to implement, it can be used for long-term predictions of the solution of the differential equation.
6. It is a single-step method, which means that each step-in time uses the information from the previous step to calculate the solution for the next step.

2.1.2 *Implementation of Euler Method with Digital Twins*

The EM can approximate the solution to an ODE of the form $y'(x) = f(x, y)$, where x is the independent variable, y is the dependent variable, and f is a given function. The basic idea behind the EM is to use the function's derivative at a single point (x0, y0) to estimate the value of the function at a future point (x1, y1).

Here is the algorithm used in the EM:

1. Start with an initial value for and y, e.g., x0 and y0.
2. Given the step size h, then calculate x1 = x0 + h,
3. Using the ODE to calculate the approximate value of y1: y1 = y0 + h * f(x0, y0)
4. Repeating steps 2 and 3, updating xn and yn with each iteration
5. Repeating this process until the desired x value or the number of iterations is chosen.

It is important to note that the EM's solution is not always accurate, and the error will increase as the step size h is decreased. Therefore, it should be used with care, and it is important to use the step size h appropriate for the problem to be solved.

This chapter offers physical modelling conceptualising the DTs technology with the concept of springs modelling. The idea introduced in this study is cost-effective and straightforward to implement in theory and practice. While the aim is only to conceptualise the DT, the mechanical behaviour of the coil spring is used to validate the proposed concept based on EM.

The rest of this chapter is organised as follows: ***Section 3*** Describes the methodology; ***Section 4***, Results and Discussion; ***Section 5*** summary.

3 METHODOLOGY

This section covers the theoretical and analytical methods used for behaviour prediction of the springs, as shown in ***Figure 3.1***. This research uses the EM in DTs to monitor, characterise, and predict the safety and faults of the primary springs used in suspension systems. Coil springs are mechanical devices used in various applications, such as automotive suspension systems. The following approach is used to integrate the Euler method with DTs for coil springs condition monitoring and Predictive Maintenance (PdM):

1. Starting with a DT of the coil spring, including a model of the spring's dynamics. The spring's behaviour can be modelled using a set of ordinary ODEs that describe the spring's deflection as a function of time and applied force.

2. Using the EM to integrate the ODEs and simulate the spring's behaviour over time. The ODE Hooke's law can define F= -k x, where k is the spring constant and x is the deflection.

3. Using the EM to calculate approximate solutions for the ODEs at a series of discrete time steps and update the DT's parameters (e.g., the spring constant, initial spring length, and the applied force) with this information.

4. Comparing the simulation results with the RT or historical data of the physical spring. Use the comparison results to optimize the DT's accuracy by tuning the model's parameters.

5. Repeat steps from 2 to 4 to continuously update the DT model and improve its accuracy.

3.1 *Materials*

Table 3.1 Load, geometric measurement, and materials properties

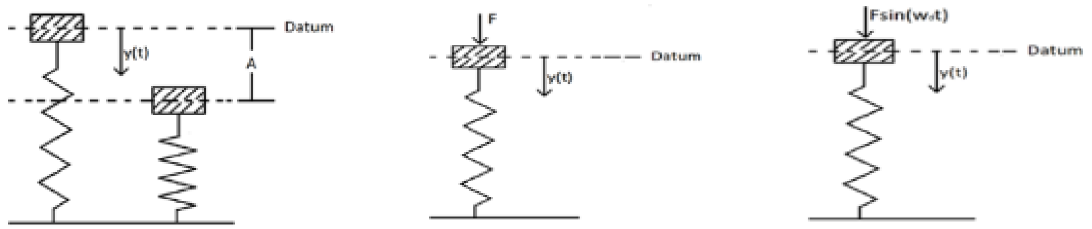
LOAD PROPERTIES	
Mass/kg	1
STEADY APPLIED FORCE (N)	100
TRANSIENT APPLIED FORCE	500
GEOMETRIC PROPERTIES	
FREE LENGTH (Lf)	100
HOLE DIAMETER (D)	70
WIRE DIAMETER (d)	6
OUTER DIAMETER (D3)	66.5
MEAN DIAMETER (D2)	60.5
SPRING INDEX (C)	10.08
COIL DIAMETER (D1)	54.5
NUMBER OF ACTIVE COILS	9
NUMBER OF TOTAL COILS	11
SOLID LENGTH (Ls)	66
TO DETERMINE THE EXACT INDEX	5.1

STRESS CORRECTION FACTOR (KW1)	1.14
MAXIMUM LOAD(Fs)	198.98
MAXIMUM TORSIONAL STRESS (Ss)	162.52
CLEARANCE	3.025
PITCH HEIGH	9.11
SOLID DEFLECTION (delta x)	34
MATERIALS PROPERTIES	
YOUNG'S MODULUS (E) MPa	190000
SHEAR MODULUS MPa	72000
SPRING RATE (K) N/mm	5.85
SPRING COMPLIANCE m/N	0.17
Density () Kg/mm^3	0.0000079
Poisson Ratio	0.3
TENSILE STRENGHT MPa	1500
TORSIONAL STRESS Mpa	750
yield strength (Mpa)	1230
kc	313186.81
Wahl Factor	1.14
Alpha (coefficient of initial relative velocity)	0.08

It is important to note that, as the EM may not be the most accurate method for spring modelling due to the presence of non-linearity, it is important to evaluate the result of the EM and compare them with a real-life experiment. Also, remember that simulation accuracy depends on the model's accuracy and the step size, and it is also important to use the appropriate step size and ODE solvers depending on the system's complexity. The analysis is subject to the other operating conditions, incorporating the output responses, strains, normal, maximum induced shear, and shear Von-mises stress within the oscillating spring.

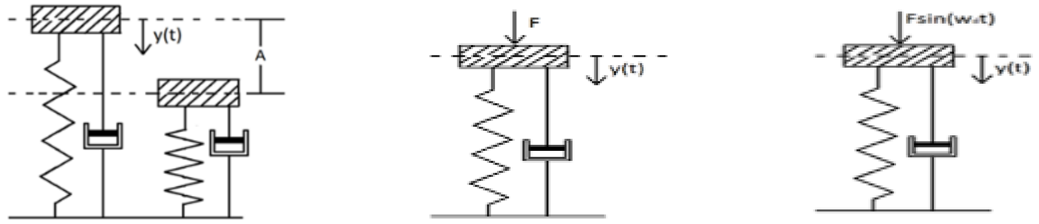
Two main vibration systems included throughout this section are (i) Linear and (ii) Non-Linear systems. These two cases involve Undamped (i) and (ii) Damped cases. Each one of the mentioned cases is subjected to three different conditions, which are (i) Free-Vibration (FV) in the absence of the applying external force, (ii) Steady-Forced Vibration and (iii) Transient-Forced Vibration.

Linear and Non-Linear Schematics Used in the Analysis (Undamped)



(A) Free Forced (B) Steady Forced (C) Transient Forced

Linear and Non-Linear Schematics Used in the Analysis (Damped)



(D) Free Forced (E) Steady Forced (F) Transient Forced

Figure 3.1 Schematics used in the analysis

3.2 *Linear Vibration Systems (Undamped)*

This section investigates the analytical solutions for the output response, normal strain, and normal and maximum induced shear stress within each of the three different linear-vibration operating conditions as a function of time in detail, where the damping effect is ignored.

3.2.1 *Free Forced-Vibration (FFV) System:*

Figure 3.1 (A) displays the construction of a simple FFV system (where the weight of an oscillating object and damping forces are not considered) consisting of the spring and the object. ***Figure 3.1 (A)*** shows that the object was displaced by an amplitude A initially, where the general expression for the displacement of an oscillating object concerning the time is defined as shown in **Eq 1**. Therefore, the displacement y(t) based on the above equation is obtained as shown in **Eq 2**. And in **Eq 3** $\boldsymbol{\omega_n}$ Illustrates the natural frequency of the system.

$$m\ddot{y}(t) + ky(t) = 0 \tag{1}$$

$$y(t) = Acos(\omega_n t) \tag{2}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{3}$$

Where m and k denote the mass of an oscillating object and the stiffness (spring rate) of the spring within the system, the expressions for the generated normal strain, normal stress and the maximum induced shear stress for all cases concerning the time based on the above system are stated as follows:

$$\varepsilon = \frac{y(t)}{L_f} \tag{4}$$

$$\sigma = \frac{4ky(t)}{\pi d^2} \tag{5}$$

$$\tau_{max} = K_s \frac{8ky(t)d}{\pi D^3} \tag{6}$$

Where L_f, d, D are the free length, wire diameter and the mean diameter of the spring's coils. The Von Mises stress, often used in ductile material failure theories, provides a scalar value that effectively measures stress at a point, allowing comparison to material strengths given in terms of simple tension or compression tests. The Von Mises stress σ_v is given by:

$$\sigma_v = \sqrt{\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2} \tag{6*}$$

The term K_s Indicates the Wahl Stress factor, considering both the torsional and direct shear stresses and the curvature of the wire, as shown in **Eq 7**. Where C indicates the spring index, defined as a ratio of the mean wire diameter D_2 of the spring's coils to the wire diameter d as shown in **Eq 8**.

$$K_s = \frac{4C-1}{4C-4} + \frac{0.615}{C} \tag{7}$$

$$C = \frac{D_2}{d} \tag{8}$$

3.2.2 *Steady Forced-Vibration (SFV) System*

Figure 3.1 (B) illustrates the SFV oscillation system, where the steady external force is applied to an oscillating object. Therefore, the corresponding displacement would be defined as shown in **Eq 9**. The derived corresponding expression for the displacement of **Eq 9** is shown in **Eq10**. The results are shown in ***Figure 3.2*****.**

$$m\ddot{y(t)} + ky(t) = -F \tag{9}$$

$$y(t) = \frac{-F}{k}(1 - \cos(\omega_n t)) \tag{10}$$

3.2.3 *Transient Forced-Vibration (TFV) System*

Figure 3.1 (C) represents the TFV oscillation system, where the external transient force is applied to an oscillating object. Therefore, the equation of the motion that describes ***Figure 3.3*** would be as shown in **Eq 11**. Since ω_d Indicates the driving frequency of the system; therefore, a general analytical solution for the displacement of this system concerning the time and the given driving frequency is calculated from **Eq12**. The results are shown in ***Figure 3.3.***

$$m\ddot{y(t)} + ky(t) = -Fsin(\omega_d t) \tag{11}$$

$$y(t) = \frac{F}{m({\omega_n}^2 - {\omega_d}^2)}(\frac{\omega_d}{\omega_n}\sin(\omega_n t) - \sin(\omega_d t) \tag{12}$$

3.3 *Linear Vibration Systems (Damped)*

This section examines the analytical solutions for the output response, normal strain, and normal and maximum induced shear stress within the three different linear-vibration operating conditions as a function of time in detail and the damping effect.

3.3.1 *Free Forced-Vibration (FFV) System*

Figure 3.1(D) shows the construction of a simple FFV system consisting of the spring, damper and object. The following equation of motion characterises this system, as shown in **Eq 13**. Based on the initial conditions where at $t = 0$, $y = A$ and $\dot{y} = 0$, general expressions for the displacement of an oscillating object-based, assuming its corresponding response is underdamped ($\xi < 1$), would be as shown in **Eq 14**. Where ξ and ω_a Denote the damping ratio and actual frequency of an oscillating object within the system, determined by **Eq 15**.

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = 0 \tag{13}$$

$$y(t) = Ae^{-\xi\omega_n t}\cos(\omega_a t) \tag{14}$$

$$\xi = \frac{c_a}{c_{cr}} = \frac{c_a}{\sqrt{4mk}} \tag{15}$$

$$\omega_a = \omega_n\sqrt{1-\xi^2} \tag{16}$$

3.3.2 *Steady Forced-Vibration (SFV) System*

Figure 3.1 (E) illustrates the SFV oscillation system, including the damping effect. The next model attributes the equation of motion for this system as shown in **Eq17**. By using the initial conditions at $t = 0$, $y = 0$ and $\dot{y} = 0$, a general expression for an output response of an oscillating object for this given system obtained as shown in **Eq 18**. The results are shown in ***Figure 3.4.***

$$m\ddot{y}(t) + c_a\dot{y}(t) + ky(t) = -F \tag{17}$$

$$y(t) = \frac{F}{k}\left(\frac{\xi\omega_n}{\omega_a}e^{-\xi\omega_n t}\sin(\omega_a t) + e^{-\xi\omega_n t}\cos(\omega_a t) - 1\right) \tag{18}$$

3.3.3 *Transient Forced-Vibration (TFV) System*

Figure 3.1 (F) displays the TFV oscillation system, where the opted external transient force is applied to an oscillating object. The equation of motion is given as shown in **Eq 19**. The initial conditions of the steady-forced vibration system were applied to obtain the following expression of the object's displacement, as shown in **Eq 20**. Where B_1, B_2 , X_0 Moreover, ∅it is defined in **Eqs 21, 22, 23, and 24**, respectively. The results are shown in ***Figure 3.5.***

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = -F\sin(\omega_d t) \tag{19}$$

$$y(t) = B_1 e^{-\xi\omega_n t}(B_1 cos(\omega_a t) + B_2 sin(\omega_a t)) + X_0 sin\,(\omega_d t - \emptyset) \tag{20}$$

$$B_1 = X_0 sin\,(\emptyset) \tag{21}$$

$$B_2 = \frac{X_0\omega_d\,sin(\emptyset) - B_1\xi\omega_n}{\omega_a} \tag{22}$$

$$X_0 = \frac{(-F/k)}{\left(\left(1-\left(\frac{\omega_d}{\omega_n}\right)^2\right)^2 + \left(\frac{2\xi\omega_d}{\omega_n}\right)^2\right)^{\frac{1}{2}}} \tag{23}$$

$$\emptyset = tan^{-1}\left(\frac{2\xi\omega_d/\omega_n}{1-\left(\frac{\omega_d}{\omega_n}\right)^2}\right) \tag{24}$$

3.4 *Non-Linear Vibration Systems (Undamped)*

This section studies the analytical solutions for the output response, normal strain, and normal and maximum induced shear stress for the non-linear vibration system, consisting of four springs under three different operating conditions, excluding the damping effects throughout all the segments.

3.4.1 *Free Forced-Vibration (FFV) system*

Figure 3.1 (A) represents the construction of the Non-Linear FFV system composed of four springs and objects.

Determining the Natural Frequency (NF) for the system is shown in Figure 3.1 (A)

The equations of motion at node one within the system are in **Eq 25**. The equation of motion at node 2 in **Eq 26**. The equation of motion at node 3 in **Eq27**. The equation of motion at node 4 in **Eq 28**.

$$m\ddot{y}_1(t) + k_1\big(y_1(t) - y_2(t)\big) = 0 \tag{25}$$

$$k_1\big(y_1(t) - y_2(t)\big) = k_2\big(y_2(t) - y_3(t)\big) \tag{26}$$

$$k_2\big(y_2(t) - y_3(t)\big) = k_3\big(y_3(t) - y_4(t)\big) \tag{27}$$

$$k_3\big(y_3(t) - y_4(t)\big) = k_4 y_4(t) \tag{28}$$

Since no damping is taking place throughout the entire system, an expression that associates the displacements y_1, y_2, y_3 and y_4 is given below:

$$k_{eq}y_1(t) = k_1\big(y_1(t) - y_2(t)\big) = k_2\big(y_2(t) - y_3(t)\big) = k_3\big(y_3(t) - y_4(t)\big) = k_4y_4(t) \tag{29}$$

Using the relationships given in **Eqn (30)** to obtain the following matrix:

$$\begin{bmatrix} m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \\ \ddot{y}_3 \\ \ddot{y}_4 \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 + k_4 \end{bmatrix}\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{30}$$

Using the initial conditions were at

$\dot{y}_3 = 0, y_4 = A_4$ and $\dot{y}_4 = 0$. Where A_1 , A_2 , A_3 and A_4 are the initial displacements (amplitude) of the nodes. Based on the equations mentioned above, the proposed analytical expressions for the displacements of nodes y_1, y_2, y_3 and y_4 would be as follows: Using **Eqs 31 to 34** and associating them with the matrix relationship illustrated in Eqn **32** to obtain the following matrix relationship: Taking the determinant of the square matrix of **Eq 35** and equate it to zero to obtain the eigenvalue (square of NF)

$$y_1(t) = A_1cos(\omega_x t) \tag{31}$$

$$y_2(t) = A_2cos(\omega_x t) \tag{32}$$

$$y_3(t) = A_3cos(\omega_x t) \tag{33}$$

$$y_4(t) = A_4cos(\omega_x t) \tag{34}$$

$$\begin{bmatrix} k_1 - m{\omega_x}^2 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 + k_4 \end{bmatrix}\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{35}$$

$$\begin{vmatrix} k_1 - m{\omega_x}^2 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 + k_4 \end{vmatrix} = 0 \tag{36}$$

Based on the further derivation from the above determinant matrix, the expression for the $\omega_x{}^2$ (eigenvalue) is obtained as follows:

$$\omega_x{}^2 = \frac{k_1}{m}\left(1 + \frac{\begin{vmatrix} -k_1 & -k_2 & 0 \\ 0 & k_2+k_3 & -k_3 \\ 0 & -k_3 & k_3+k_4 \end{vmatrix}}{\begin{vmatrix} k_1+k_2 & -k_2 & 0 \\ -k_2 & k_2+k_3 & -k_3 \\ 0 & -k_3 & k_3+k_4 \end{vmatrix}}\right) = \frac{k_{eq}}{m} \tag{37}$$

k_{eq} The equivalent spring rate of the entire system is obtained from the following relationship. Since the spring segments are assumed to be connected in a series relationship shown in **Eq 38**. Therefore, the natural frequency of the system is in **Eq 39**.

$$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \frac{1}{k_4} \tag{38}$$

$$\omega_x{}^2 = \left(\frac{k_{eq}}{m}\right)^{1/2} \tag{39}$$

Since it is a free vibration, the initial displacement of node one can be decided or assumed, and by knowing this displacement at node 1 (A_1) then the instantaneous displacements of nodes 2, 3, and 4 (A_2, A_3, A_4) can be determined by making further derivation for **Eq 30** and further simplified by substituting some of the expressions obtained by X_1, X_2, and X_3 as shown in **Eqs 40 to 42** to obtain instantaneous displacements of nodes 2, 3, and 4 (A_2, A_3, A_4)

$$X_1 = \frac{k_1 - k_{eq}}{k_1} \tag{40}$$

$$X_2 = \frac{k_2 X_1 - k_{eq}}{k_2} \tag{41}$$

$$X_3 = \frac{k_{eq}}{k_4} \tag{42}$$

$$A_2 = X_1 A_1 \tag{43}$$

$$A_3 = X_2 A_1 \tag{44}$$

$$A_4 = X_3 A_1 \tag{45}$$

3.4.2 *Steady Forced-Vibration (SFV) System*

Figure 3.1 (B) represents the Non-Linear SFV, including applying a steady external force on the object. The equations of motion, including the oscillating object at node one, are expressed in the following equation from the above diagram.

$$m\ddot{y}_1(t) + k_1\big(y_1(t) - y_2(t)\big) = -F \quad (46)$$

The equations of motion at nodes 2, 3, and 4 will be the same as expressed in the previous system from **Eqs 26 to 28**. Since the initial displacements at nodes 1, 2, 3 and 4 are taken to be zero at time zero, the analytical solutions for the displacements of y_1, y_2, y_3 and y_4 concerning the time can be derived using a second-order differential equation between equations of motions expressed in **Eqs 27 to 29 and Eq 46** to obtain the following equations, and the results are shown in ***Figure 3.6***.

$$y_1(t) = \left(\frac{-F}{k_{eq}}\right)(1 - cos(\omega_x t)) \quad (47)$$

$$y_2(t) = \left(\frac{-FX_1}{k_{eq}}\right)(1 - cos(\omega_x t)) \quad (48)$$

$$y_3(t) = \left(\frac{-FX_2}{k_{eq}}\right)(1 - cos(\omega_x t)) \quad (49)$$

$$y_4(t) = \left(\frac{-FX_3}{k_{eq}}\right)(1 - cos(\omega_x t)) \quad (50)$$

3.4.3 *Transient Forced-Vibration (TFV) System*

Figure 3.1(C) represents the Non-Linear TFV applying external transient force on the object. The equations of motion of an oscillating object within the system would be:

$$m\ddot{y}_1(t) + k_1\big(y_1(t) - y_2(t)\big) = -Fsin(\omega_d t) \quad (51)$$

The equations of motion at nodes 2, 3, and 4 will be the same as expressed in the previous system from **Eqs 26 to 28**. Since the initial displacements at nodes 1, 2, 3 and 4 are taken to be zero at time zero, the analytical solutions for the displacements of y_1, y_2, y_3 and y_4 concerning the time derived using second-order differential equation between equations of motions expressed in **Eqs 26 to 28 and Eq 51** to obtain the following equations and the results are shown in ***Figure3.7.***

$$y_1(t) = \left(\frac{F}{m((\omega_x)^2-(\omega_d)^2)}\right)\left(\left(\frac{\omega_d}{\omega_x}\right)\sin(\omega_x t) - \sin(\omega_d t)\right) \quad (52)$$

$$y_2(t) = \left(\frac{FX_1}{m((\omega_x)^2-(\omega_d)^2)}\right)\left(\left(\frac{\omega_d}{\omega_x}\right)\sin(\omega_x t) - \sin(\omega_d t)\right) \quad (53)$$

$$y_3(t) = \left(\frac{FX_2}{m((\omega_x)^2-(\omega_d)^2)}\right)\left(\left(\frac{\omega_d}{\omega_x}\right)\sin(\omega_x t) - \sin(\omega_d t)\right) \quad (54)$$

$$y_4(t) = \left(\frac{FX_3}{m((\omega_x)^2-(\omega_d)^2)}\right)\left(\left(\frac{\omega_d}{\omega_x}\right)\sin(\omega_x t) - \sin(\omega_d t)\right) \quad (55)$$

3.5 *Non-Linear Vibration Systems (Damped)*

This section studies the numerical solutions for the output response for the non-linear vibration system using the Euler method, consisting of three active springs under three different operating conditions, including the damping effect within the first spring only.

3.5.1 *Free Forced-Vibration (FFV) System*

Figure 3.1 (D) represents the construction of the Non-Linear FFV system, consisting of three active springs, an object and damping throughout the first spring. The equation of motion of an oscillating object (node 1) within the system is shown in **Eq 56**. The equation of motion at a junction point (node 2) between spring one and spring two within the system would be defined as shown in **Eq 57**.

$$m\ddot{y}_1(t) + c_1(\dot{y}_1(t) - \dot{y}_2(t)) + k_1\big(y_1(t) - y_2(t)\big) = 0 \quad (56)$$

$$c_1\big(\dot{y}_1(t) - \dot{y}_2(t)\big) + k_1\big(y_1(t) - y_2(t)\big) \\ -c_2\big(\dot{y}_2(t) - \dot{y}_3(t)\big) - k_2\big(y_2(t) - y_3(t)\big) = 0 \quad (57)$$

The equation of motion at a junction point between spring two and spring 3 (node 3) within the system is described as follows:

$$c_2\big(\dot{y}_2(t) - \dot{y}_3(t)\big) + k_2\big(y_2(t) - y_3(t)\big) - c_3(\dot{y}_3(t) - \dot{y}_4(t)) - k_4\big(y_3(t) - \\ y_4(t)\big) = 0 \quad (58)$$

The equation of motion at a junction point between spring three and spring four (node 4) within the system is described as follows:

$$c_3(\dot{y}_3(t) - \dot{y}_4(t)) + k_3\big(y_3(t) - y_4(t)\big) - c_4\dot{y}_4(t) - k_4 y_4(t) = 0 \quad (59)$$

Analytical Solutions for y_1, y_2, y_3 and y_4 within **Eqs 57 to 60** concerning time cannot be achieved directly. Therefore, the numerical solutions for these displacements were obtained using the Euler Method, taking initial conditions at $t = 0$, $y_1 = A_1$, $\dot{y}_1 = 0$, $y_2 = A_2$, $\dot{y}_2 = 0$, $y_3 = A_3$, $\dot{y}_3 = 0$, $y_4 = A_4$, $\dot{y}_4 = 0$. The equation relationship is achieved by initially making the acceleration at node1($\ddot{y}_1(t)$) as a subject from **Eq 56**.

$$\ddot{y}_1(t) = \frac{-c\big(\dot{y}_1(t) - \dot{y}_2(t)\big) - k_1\big(y_1(t) - y_2(t)\big)}{m} \quad (60)$$

$$\dot{y}_1(t) = \ddot{y}_1(t - \Delta t)\Delta t + \dot{y}_1(t - \Delta t) \quad (61)$$

To find the acceleration at node 1 ($\ddot{y}_1(t)$) the values of the velocities at nodes 1 and 2 ($\dot{y}_1(t)$ and $\dot{y}_2(t)$) and displacements at nodes 1 and 2 ($y_1(t)$ and $y_2(t)$) must be known in advance, where the velocities are equal to zero at time zero. However, the displacements at time zero are equal to A_1, and A_2 respectively. Since the acceleration is now known, the Euler method is used to determine the velocity at node 1 in the following time step Δt explicitly, as shown in **Eq 61**. Assuming the acceleration between the two-time steps is constant, the velocities in these two-time steps are known. Therefore, taking the average of the velocities and multiplying it by the change of time (time-step) will result in the change in displacement for node 1. Adding this change of displacement to the initial displacement will result in displacement at the end of the given time step. Therefore, the displacement $y_1(t)$ It will be determined using the following equation.

$$y_1(t) = \left(\frac{\dot{y}_{1(t-\Delta t)+}\dot{y}_{1(t)+}}{2}\right)\Delta t + y_1(t-\Delta t) \quad (62)$$

By rearranging **Eq 58** to obtain the velocity at the node two at a given time (t)

$$c_1\dot{y}_2(t) + c_2\dot{y}_2(t) = k_1y_1(t) + c_1\dot{y}_1(t) + \ k_2y_3(t) + c_2\dot{y}_3(t) - k_1y_2(t) - k_2y_2(t) \quad (63)$$

Making $\dot{y}_2(t)$ As a subject from **Eq 58,** obtain the following equation:

$$\dot{y}_2(t) = \frac{k_1y_1(t)+c_1\dot{y}_1(t)+\ k_2y_3(t)+c_2\dot{y}_3(t)-k_1y_2(t)-k_2y_2(t)}{c_1+c_2} \quad (64)$$

Since the velocity at node two is known, using the same technique as for node 1 to obtain the displacement at node two at a given time (t), which results in the following equation:

$$y_2(t) = \left(\frac{\dot{y}_{2(t-\Delta t)+}\dot{y}_{2(t)+}}{2}\right)\Delta t + \ \ y_2(t\ \Delta t)$$
(65)

By rearranging **Eq 59** to obtain the velocity at node three at a given time (t)

$$c_2\dot{y}_3(t) + c_3\dot{y}_3(t) = k_2y_2(t) + c_2\dot{y}_2(t) + \ k_3y_4(t) + c_3\dot{y}_4(t) - k_2y_3(t) - k_3y_3(t) \quad (65)^*$$

Making $\dot{y}_3(t)$ As a subject from **Eq 59**, obtain the following equation:

$$\dot{y}_3(t) = \frac{k_2y_2(t)+c_2\dot{y}_2(t)+\ k_3y_4(t)+c_3\dot{y}_4(t)-k_2y_3(t)-k_3y_3(t)}{c_2+c_3} \quad (66)$$

Since the velocity at node three is known, using the same technique as for node 1 to obtain the displacement at node three at a given time (t) results in the following equation.

$$y_3(t) = \left(\frac{\dot{y}_{3(t-\Delta t)+}\dot{y}_{3(t)+}}{2}\right)\Delta t + y_3\ \ (t-\Delta t) \quad (67)$$

By rearranging **Eq 60** to obtain the velocity at node four at a given time (t)

$$c_3\dot{y}_4(t) + c_4\dot{y}_4(t) = k_3y_3(t) + c_3\dot{y}_3(t) - k_3y_4(t) - k_4y_4(t) \tag{68}$$

Making $\dot{y}_4(t)$ As a subject from **Eq 59**, obtain the following equation:

$$\dot{y}_4(t) = \frac{k_3y_3(t)+c_3\dot{y}_3(t)-k_3y_4(t)-k_4y_4(t)}{c_3+c_4} \tag{69}$$

Since the velocity at node four is known, using the same technique as for node 1 to obtain the displacement at node four at a given time (t) results in the following equation.

$$y_4(t) = \left(\frac{\dot{y}_{4(t-\Delta t)+}\dot{y}_{4(t)+}}{2}\right)\Delta t + y_4(t-\Delta t) \tag{70}$$

3.5.2 *Steady Forced-Vibration (SFV) System*

Figure 3.1 (E) illustrates the same system for the Non-Linear SFV system, considering the application of external steady force on the object. The equation of motion of the constant forced oscillating object for node 1

$$m\ddot{y}_1(t) + c_1\big(\dot{y}_1(t) - \dot{y}_2(t)\big) + k_1\big(y_1(t) - y_2(t)\big) = -F \tag{71}$$

The equation of motion at nodes 2, 3 and 4 will be the same as in **Eqs 58 to 60**. Going through the same procedure as that within the free-vibration system by determining the numerical solutions for the displacements y_1, y_2, y_3 and y_4 using the Euler Method. The only difference between this system and the free-vibration system is the expression of $\ddot{y}_1(t)$ Due to the inclusion of the steady external force, defined as shown in **Eq 72**, the results are shown in ***Figure 3.8.***

$$\ddot{y}_1(t) = \frac{-F-c\big(\dot{y}_1(t)-\dot{y}_2(t)\big)-k_1\big(y_1(t)-y_2(t)\big)}{m} \tag{72}$$

3.5.3 *Transient Forced-Vibration (TFV) System*

Considering the TFV system will lead to the following equation of motion of a steady forced oscillating object within the system:

$$m\ddot{y}_1(t) + c_1\big(\dot{y}_1(t) - \dot{y}_2(t)\big) + k_1\big(y_1(t) - y_2(t)\big) = -Fsin(\omega_d t) \tag{73}$$

The equation of motion at nodes 2, 3 and 4 will be the same as in Eq **58 to 60.** Going through the same procedure as that within the free-vibration system by determining the numerical solutions for the displacements y_1, y_2, y_3 and y_4 using the Euler Method. The only difference between this system and the free-vibration system is the expression of $\ddot{y}_1(t)$ Due to the inclusion of the transient external force, defined as shown in **Eq 74**, the results are shown in ***Figure 3.9***.

$$\ddot{y}_1(t) = \frac{-Fsin(\omega_d t) - c(\dot{y}_1(t) - \dot{y}_2(t)) - k_1(y_1(t) - y_2(t))}{m} \quad (74)$$

3.6 *Stiffness and Compliance Matrix*

The potential function is a mathematical function defined by the group of rigid body movements. It captures the changes in potential energy that occur when the body undergoes translations or rotations [381]. The force and moment may be integrated to form one coil to another in a spring. The force exerted on each coil due to the potential is expressed as the potential gradient. In this case study, the stiffness matrix equals the sum of spring rates in the coils.

$$k = \frac{G * d^4}{8 * D_2^3 * Na} \quad (75)$$

Where K is the Spring rate

G is the Shear modulus (MPa)

d is the Wire diameter

D is the Mean diameter

Na is the Number of the active coils

Compliance Matrix

Is the inverse of the stiffness matrix = 1/k

4 **RESULTS AND DISCUSSION**

The presented ***Figures 3.2 to 3.9*** serve as evidence of the comprehensive range of potential damage scenarios for which the proposed DT model will account in relation to the springs. Failure to consider all potential damage scenarios would constitute a limitation of the model. For instance, the model's ability to anticipate or respond to an unconsidered potential scenario that manifests in a user's experience would be compromised. Hence, the model must incorporate all possible scenarios of potential damage that may occur with the spring. This research makes a significant contribution in this regard, as it addresses a gap in the existing literature. Specifically, ***Table 3.4*** demonstrates that many physics-based DT models discussed in prior studies fail to account for all potential damage scenarios. Furthermore, these models exhibit limitations or lack validation.

Figures 3.2 to 3.9 depict the dynamic behaviour of mechanical springs under transient loads in real-time conditions. These ***Figures 3.2 to 3.9*** confirm the model's correctness by evaluating the entire compliance matrix. The significance of ***Figures 3.2 to 3.9*** lies in their ability to provide visual representation. This is exemplified in ***Figure 3.10*****,** which allows us to determine the safety or potential failure of the springs. Specifically, it enables us to obtain and compare stresses with the failure stress of the materials that influence the spring at the present moment.

The complexity of capturing the dynamic load exerted on springs arises from the extensive range of people, vehicles, and environmental conditions involved. Nevertheless, the recently developed Digital Twin Physics model can accurately capture and represent the dynamic load, enabling the creation of a real-time model. ***Figures 3.2 to 3.9*** depict the many probable situations that may arise during the operation of the springs. These scenarios are relevant to all users and are distinct for each user. As seen in ***Table 3.4*****,** the preceding methodologies used physics-based modelling techniques, although they were all subject to certain limitations. However, this research endeavour has successfully addressed or mitigated these limitations by implementing a physics-based model. Moreover, prior literature is scarce using this particular methodology, thus demonstrating its innovation. The stiffness matrix shown in ***Table 3.2*** and the compliance matrix displayed in ***Table 3.3*** support and confirm the proposed model's correctness.

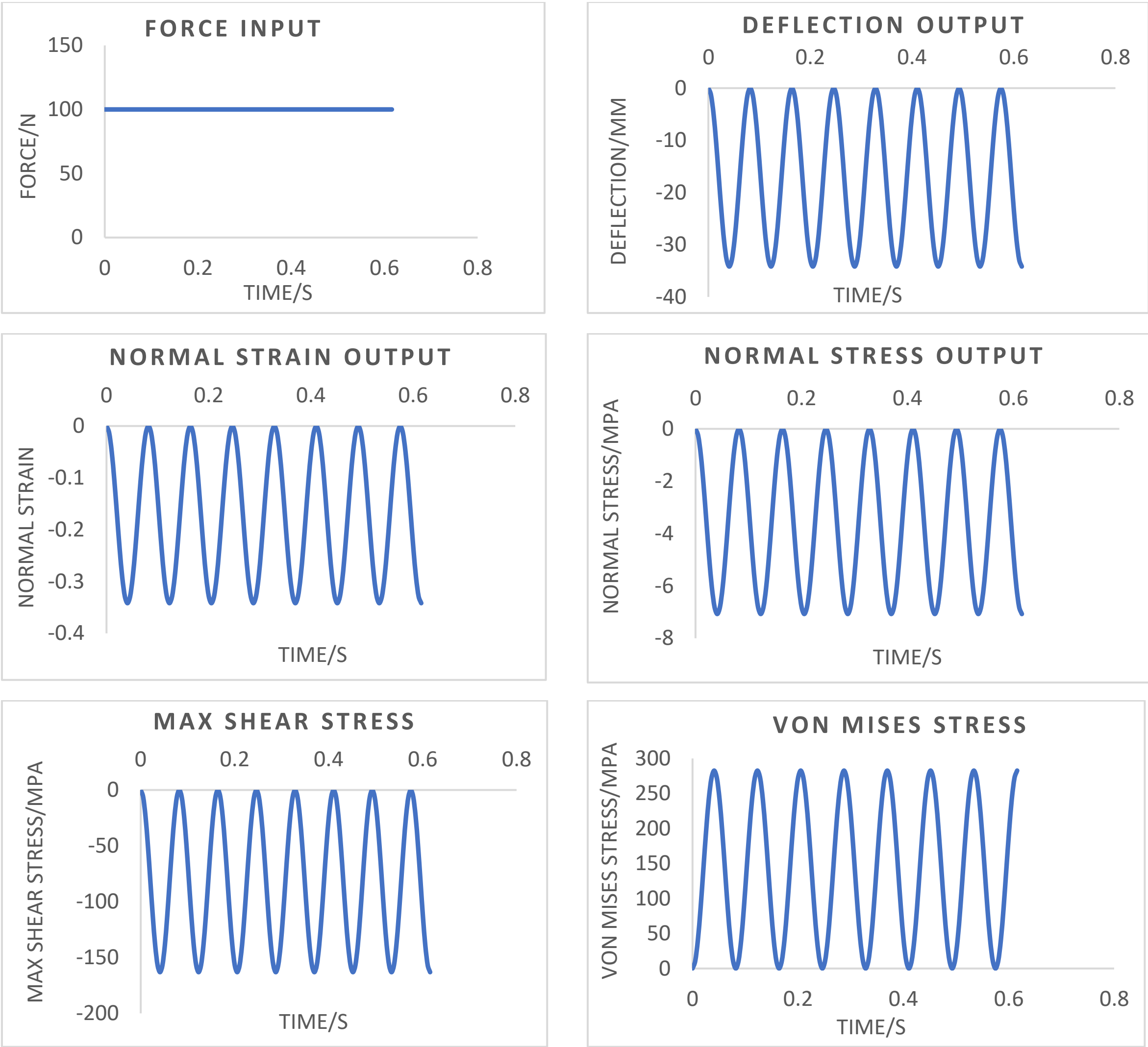


Figure 3.2 Six resulting figures from linear SFV (Undamped)

4.1 ***Linear Transient-Forced Vibration Systems (Undamped)***

using ***Figure 3.1 (C)*** to derive the deflection equation resulting in the output deflection from the derived **Eq 12**, this resultant deflection can be used as an input into **Eqs 4, 5, 6, and 6*** to produce normal strain and stress output, maximum induced shear stress, and Von Mises stress. It is noticed in ***Figure 3.2*** that the variations of the normal and maximum induced shear stress to behave similarly concerning the time are irregular compared to the behaviour of the linear-steady forced vibration system. **Eq 12** does not resemble the behaviour stated by **Eq 10** due to including the driving frequency within the applying external force. Overall, the deflection and strain responses perform similarly to the stresses. Suppose the spring obeys isotropic behaviour. The given force and driving frequency of 1000N and eight rad/s on the system led to the maximum normal and induced shear stress under these operating conditions to 42.6 MPa and 1251.35 MPa. This result characterises the spring's failure to occur due to induced shear stress since the shear-yielding stress for this spring is about 410MPa.

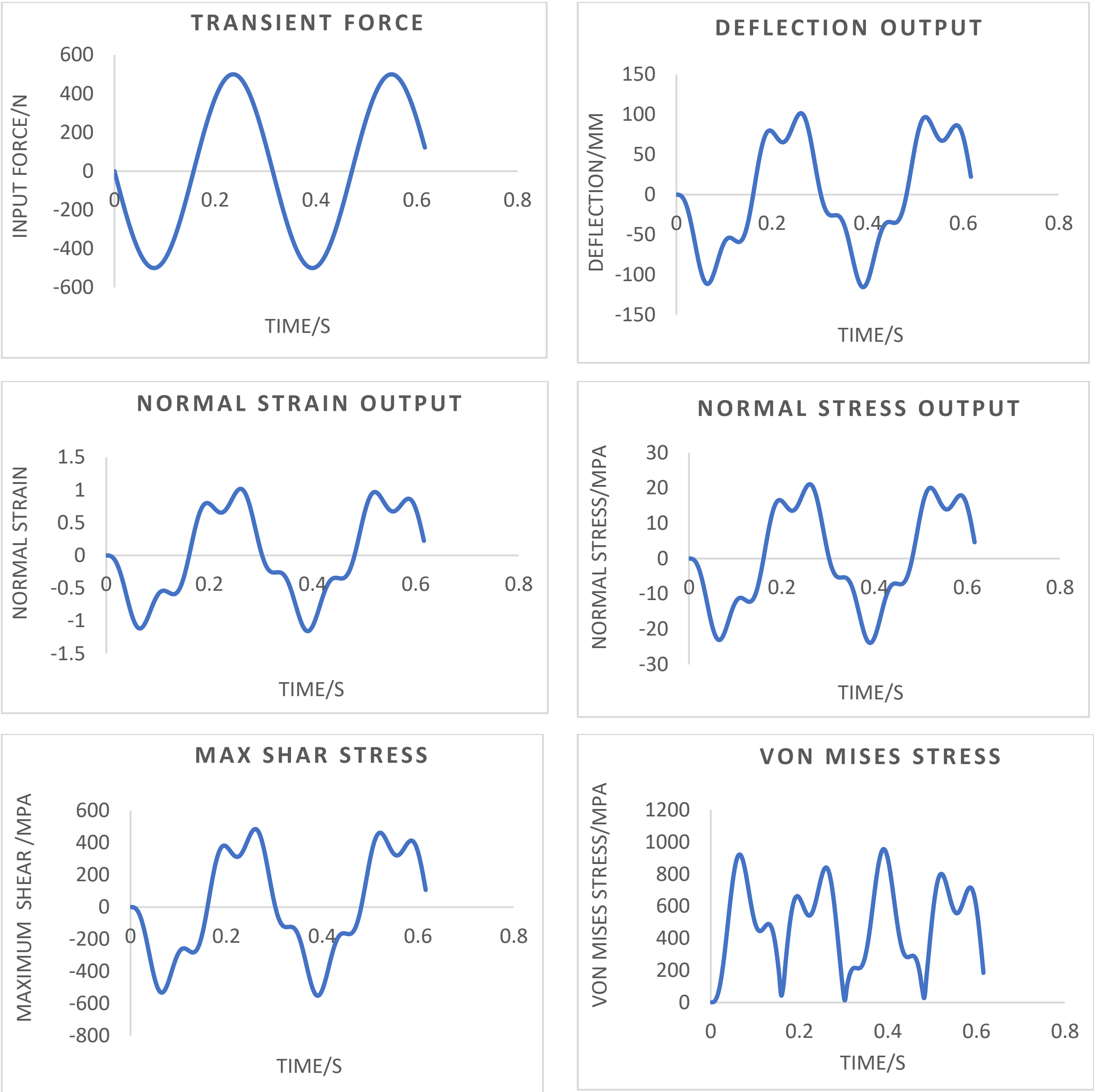


Figure 3.3 Six resulting figures from linear TFV (Undamped)

4.2 *Linear Steady-Forced Vibration Systems (Damped)*

using ***Figure 3.1 (E)*** to derive the deflection equation resulting in the output deflection from the derived **Eq 18**, this resultant deflection can be used as an input into **Eqs 4, 5, 6, and 6*** to produce normal strain and stress output, maximum induced shear stress, and Von Mises stress According to the results from ***Figure 3.3***, the damping effect is considered, leading the variation of the stress responses to get damped concerning the time compared to that described in ***Figure 3.2*** since the opted damping coefficient of the spring is lower than the critical damping of the entire system. Using the same given operating parameters as that provided within the undamped case (where applying steady force is 1000N) and by taking the selected damping coefficient of the spring to be about 100Ns/m, resulting in the obtained values for the maximum normal and induced shear stresses to be about -22.64MPa and -609MPa. Once again, this signifies that failure would occur due to shearing mode since the obtained shear stress is greater than the shear yield stress.

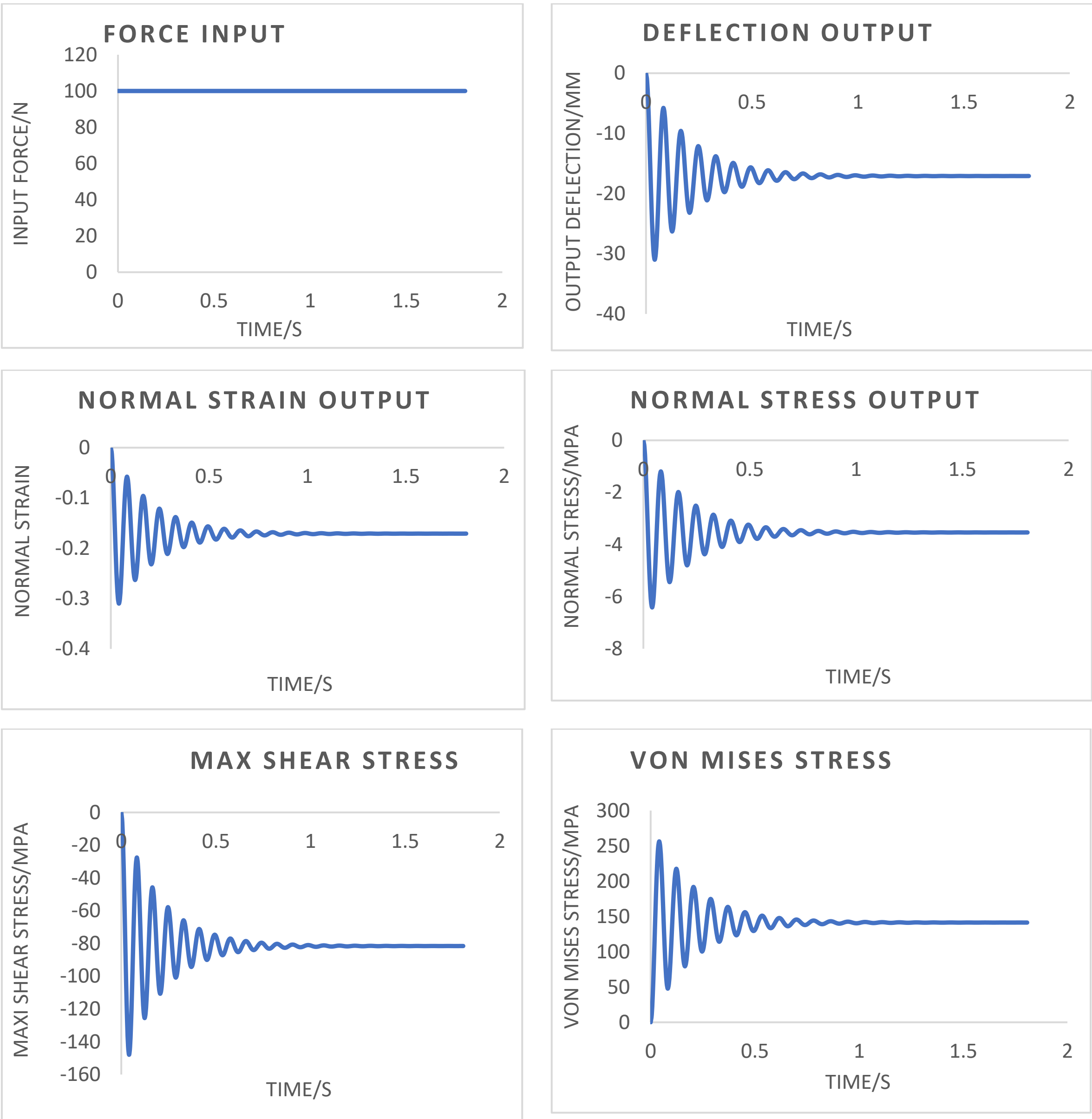


Figure 3.4 Six resulting figures from linear SFV (Damped)

4.3 ***Linear Transient-Forced Vibration Systems (Damped)***

using ***Figure 3.1 (F)*** to derive the deflection equation resulting in the output deflection from the derived **Eq 20**, this resultant deflection can be used as an input into **Eqs 4, 5, 6, and 6*** to produce normal strain and stress output, maximum induced shear stress, and Von Mises stress The damping effect in the system mentioned in the section of the undamped linear transient-forced vibration system leads to the output response being slightly distorted compared to the rest of the spring's motion within the first few seconds of the spring's motion movement observed. The spring's motion's movement observation is interpreted as the transient response throughout this duration, which has gotten damped quite rapidly. The entire system's overall response is the same as the steady-state response. Incorporating the damping effect into the system leads the overall response to behave similarly to the simple harmonic motion response. Using the same transient force has been mentioned within the undamped linear transient-forced vibration system. They obtained values for the maximum normal and induced shear stresses of about -14.78MPa and -433.90MPa. Once again, this signifies that failure would occur due to shearing mode since the obtained shear stress exceeds the shear yield stress.

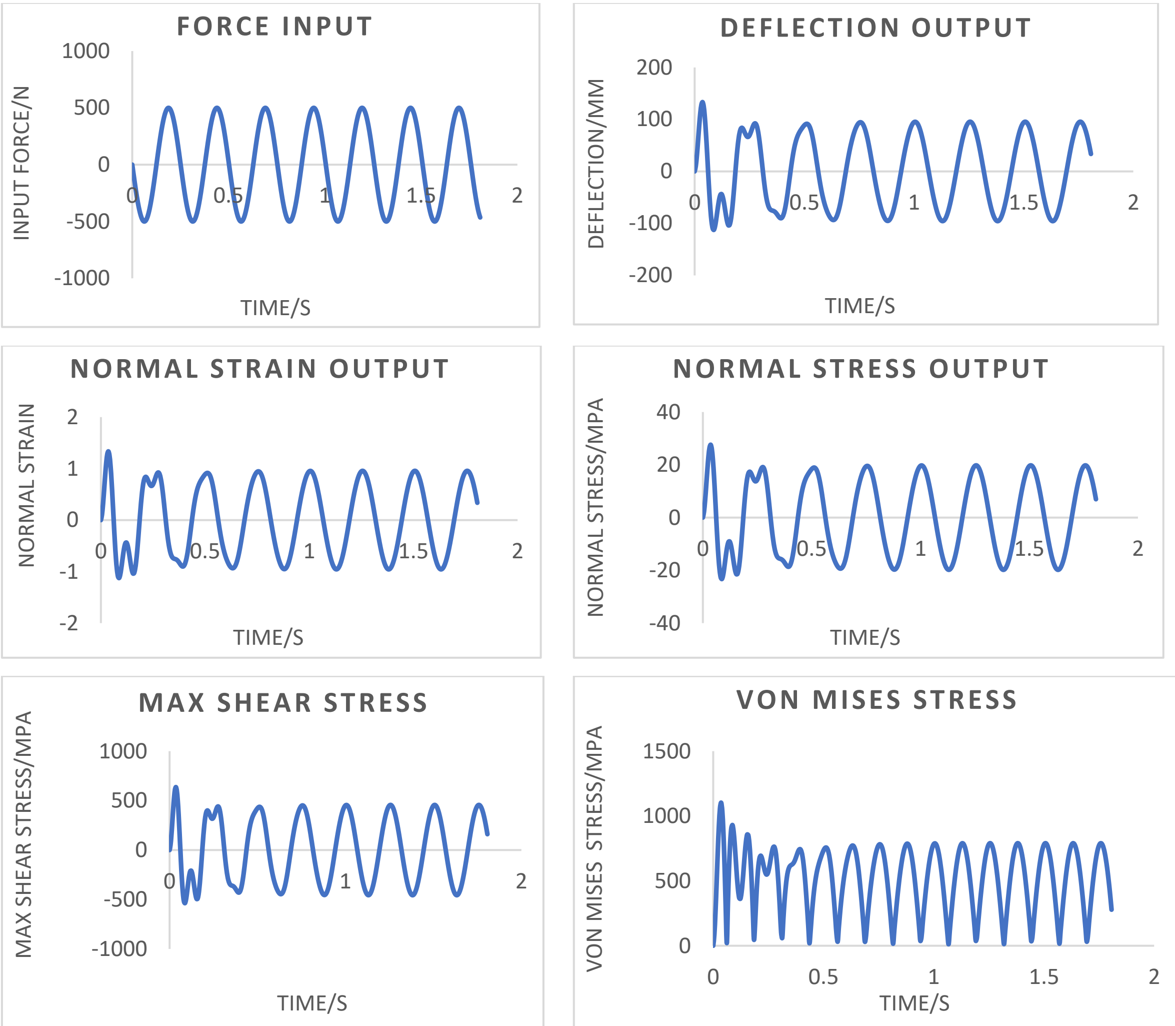
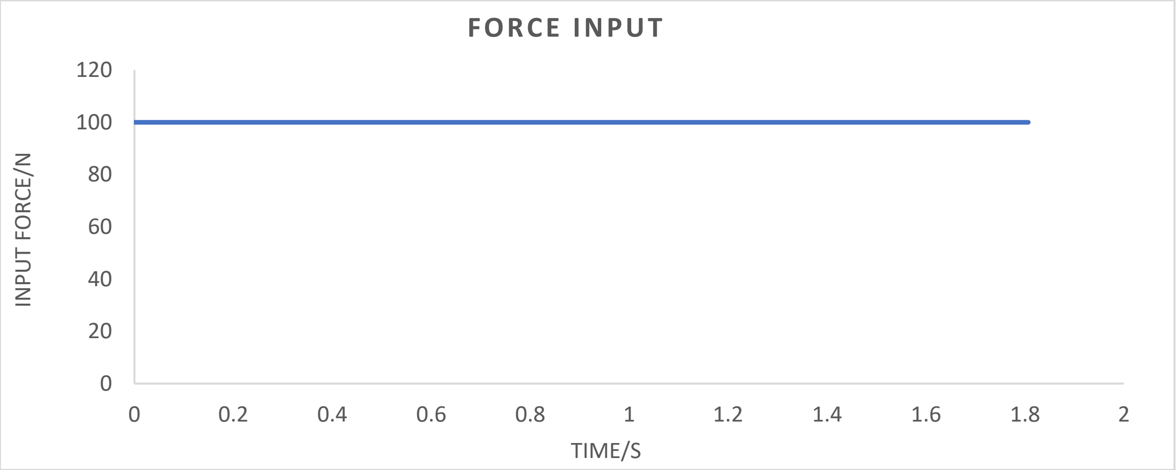


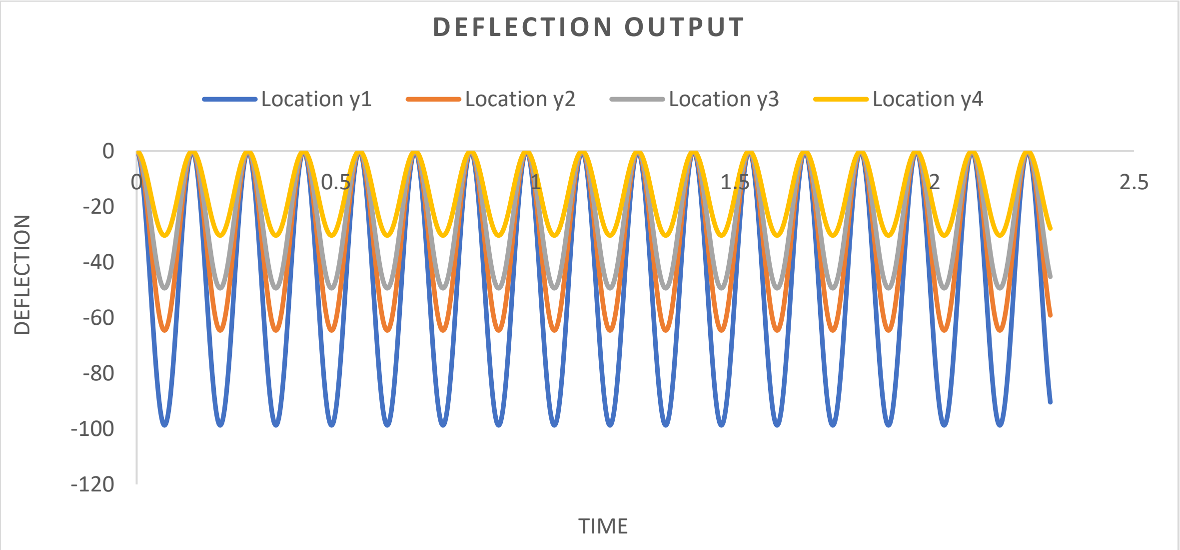
Figure 3.5 Six resulting figures from linear TFV (Damped)

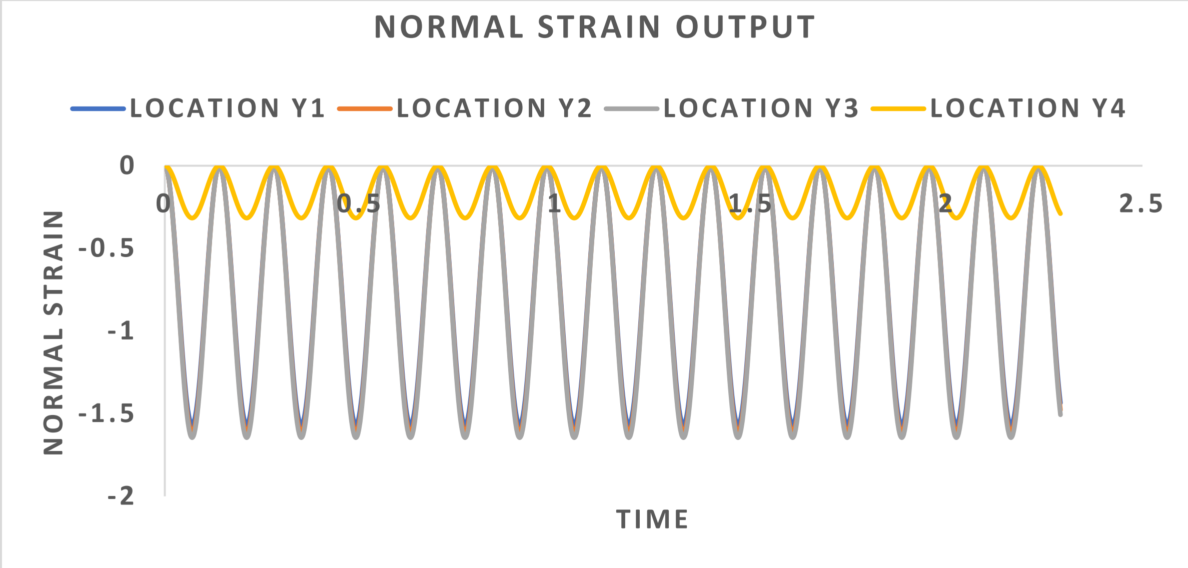
4.4 *Non-Linear Steady-Forced Vibration Systems (Undamped)*

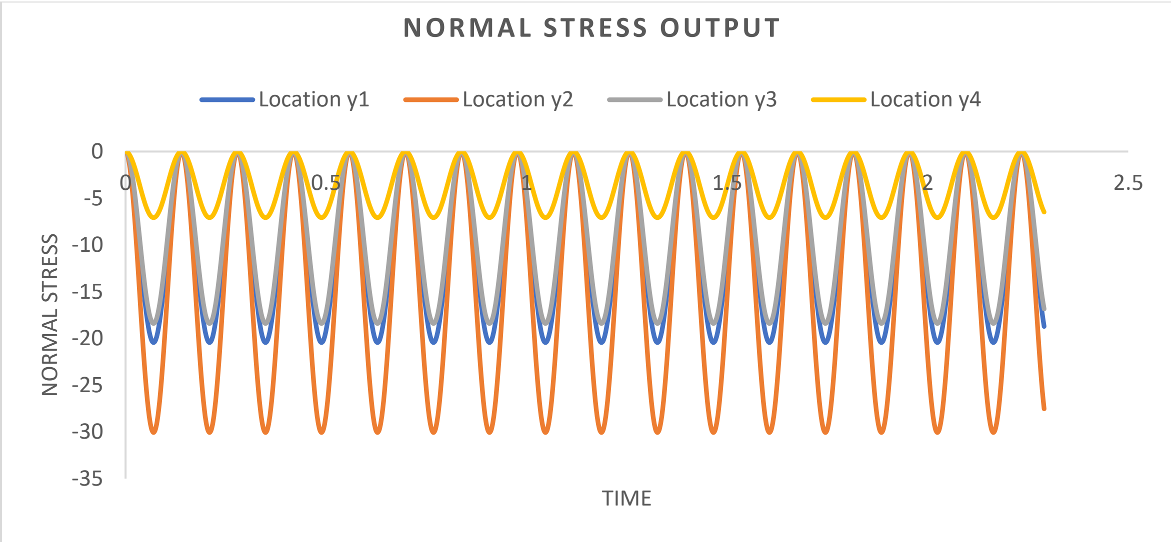
using ***Figure 3.1 (B)*** to derive the deflection equation resulting in the output deflection from the derived **Eqs 47 to 50**, this resultant deflection can be used as an input into **Eqs 4, 5, 6, and**

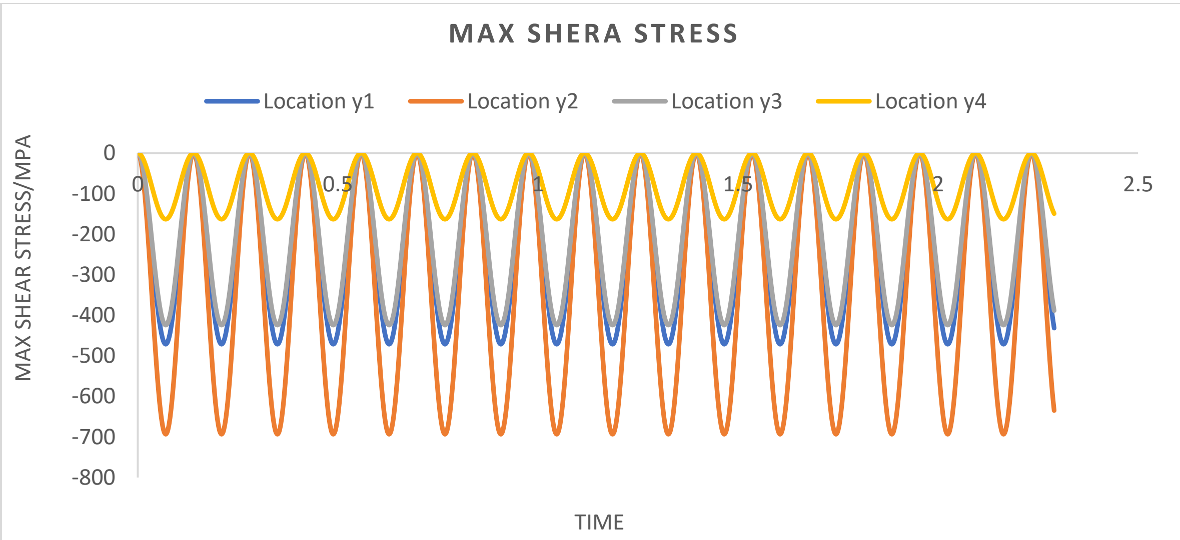
6* to produce normal strain and stress output, maximum induced shear stress, and Von Mises stress The non-linear steady-forced vibration in the un-damped case illustrates all measurements' output response (deflection, strain, maximum normal and induced shear stresses). The output for each of the four springs behaves harmonically with the same natural frequency, with different values concerning the time due to the other geometric properties of each spring. Based on the assumption that all the springs within this vibration system obey the isotropic behaviour, and using the applying force of 1000N, they obtained values for the maximum normal and induced shear stresses to be about -70.02MPa and -2055.5MPa for spring **1**, -59.42MPa and -1744.06MPa for spring **2**, -101.86MPa and -2989.82MPa for spring **3**, -25.47MPa and -747.45MPa for spring **4**. These values indicate that springs **1**, **2** and **3** will fail due to their high shear stresses (where spring three will be the first among them), while spring **four** will be the least likely to fail since its shear stress has not reached yielding shear stress.






NORMAL STRAIN OUTPUT
LOCATION Y1
LOCATION Y2
LOCATION Y3
LOCATION Y4
NORMAL STRAIN
0
-0.5
-1
-1.5
-2
0
0.5
1
1.5
2
2.5
TIME


NORMAL STRESS OUTPUT
Location y1
Location y2
Location y3
Location y4
NORMAL STRESS
0
-5
-10
-15
-20
-25
-30
-35
0
0.5
1
1.5
2
2.5
TIME


MAX SHERA STRESS
Location y1
Location y2
Location y3
Location y4
MAX SHEAR STRESS/MPA
0
-100
-200
-300
-400
-500
-600
-700
-800
0
0.5
1
1.5
2
2.5
TIME

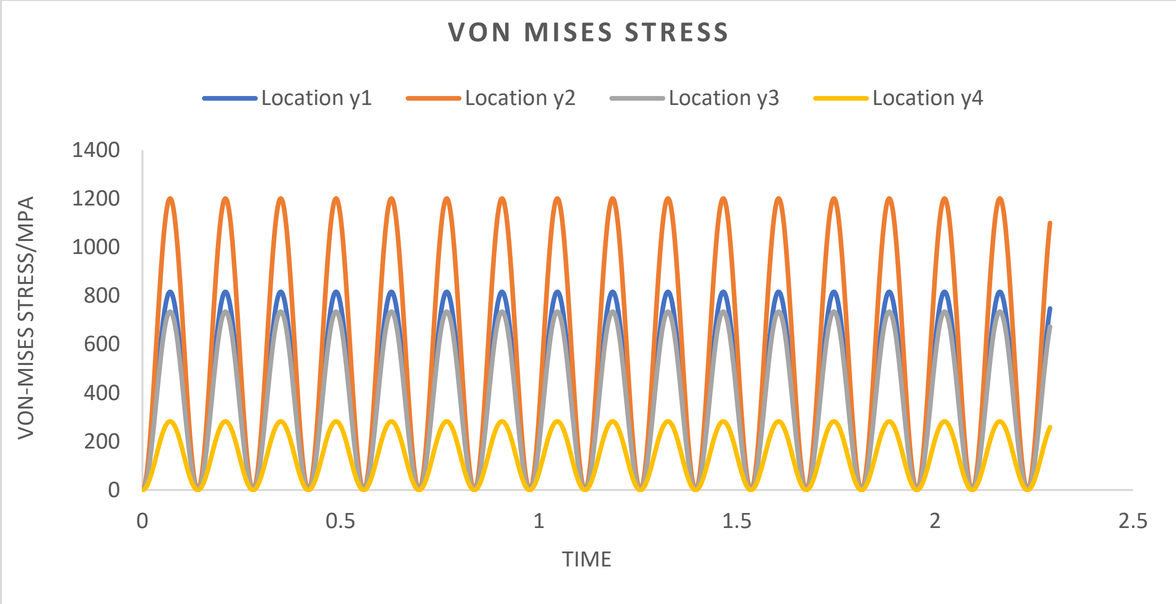
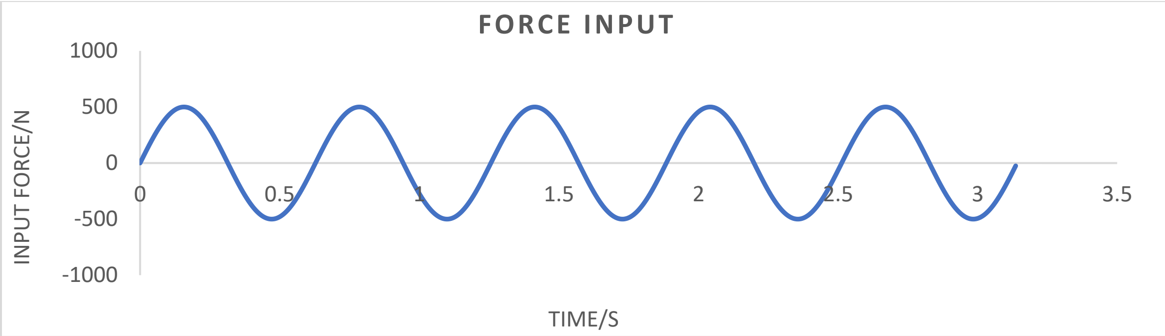
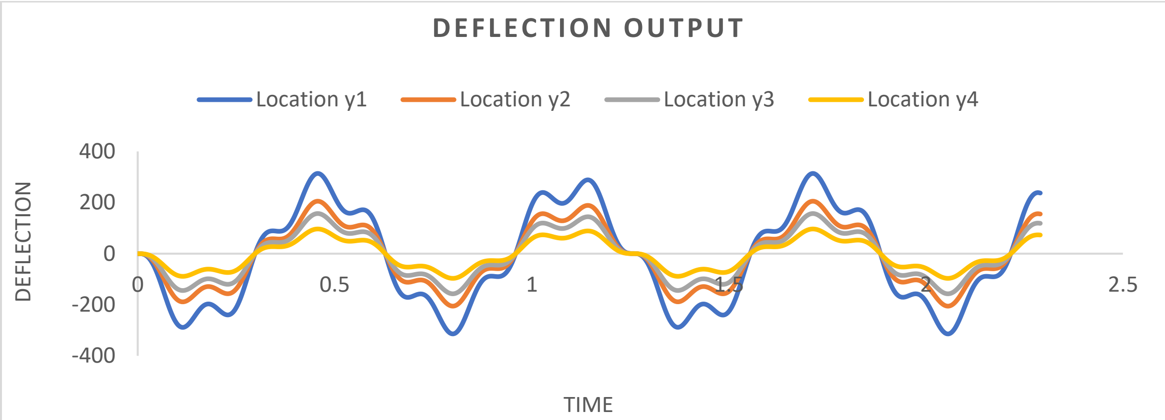


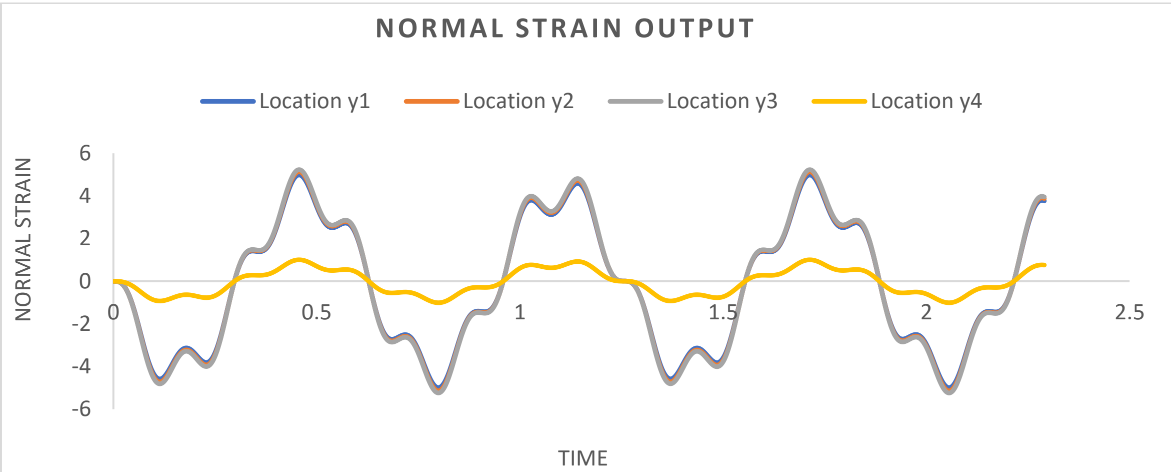
Figure 3.6 6 resulting figures of Non-Linear SFV (Undamped)

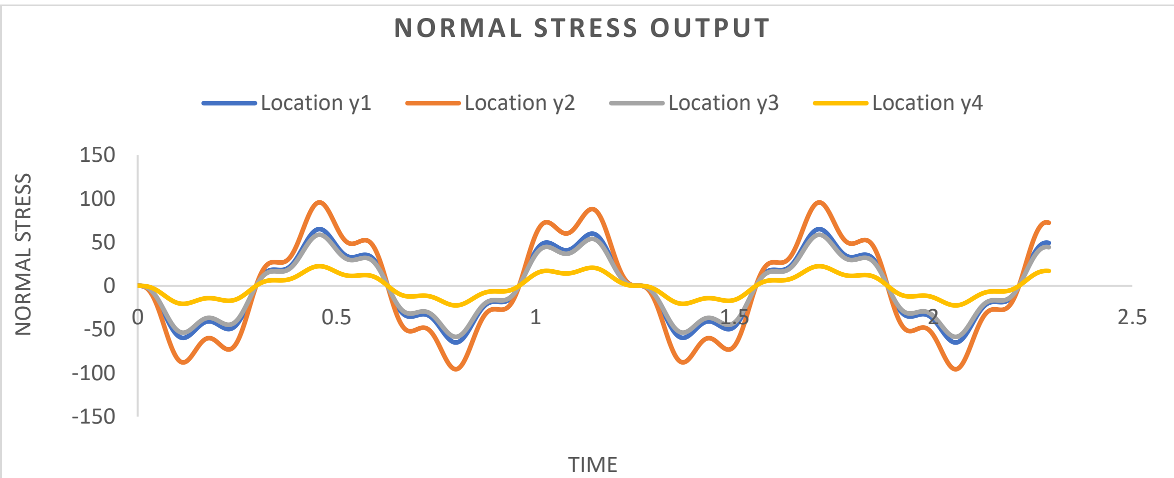
4.5 ***Non-Linear Transient-Forced Vibration Systems (Undamped)***

using ***Figure 3.1(C)*** to derive the deflection equation resulting in the output deflection from the derived **Eqs 52 to 55**, this resultant deflection can be used as an input into **Eqs 4, 5, 6, and 6*** to produce normal strain and stress output, maximum induced shear stress, and Von Mises stress. The non-linear transient vibration un-damped case shows the output response of all measurements (deflection, strain, maximum normal and induced shear stresses). The output for each of the four springs behaves with the same natural frequency, where the amplitude of each operating spring changes throughout their motions since the type of force acting on the oscillating object is transient force, incorporating the driving frequency parameter. Based on the selected value 1000N at a driving frequency of 8 rad/s, the resultant maximum normal and shear stresses are about 70.66MPa and 2074.11MPa, respectively. For spring **1**, 59.96MPa and 1759.85MPa for spring **2**, 102.78MPa and 3016.89MPa for spring **3**, 29.69MPa and 754.22MPa for spring **4**. These values indicate that springs **1**, **2** and **3** will fail due to their high shear stresses (where spring three will be the first among them), and spring **four** will be the least likely to fail since its shear stress has the lowest value among all the springs.


FORCE INPUT
1000
500
0
-500
-1000
INPUT FORCE/N
0
0.5
1
1.5
2
2.5
3
3.5
TIME/S


DEFLECTION OUTPUT
Location y1
Location y2
Location y3
Location y4
400
200
0
-200
-400
DEFLECTION
0
0.5
1
1.5
2
2.5
TIME


NORMAL STRAIN OUTPUT
Location y1
Location y2
Location y3
Location y4
6
4
2
0
-2
-4
-6
NORMAL STRAIN
0
0.5
1
1.5
2
2.5
TIME


NORMAL STRESS OUTPUT
Location y1
Location y2
Location y3
Location y4
150
100
50
0
-50
-100
-150
NORMAL STRESS
0
0.5
1
1.5
2
2.5
TIME

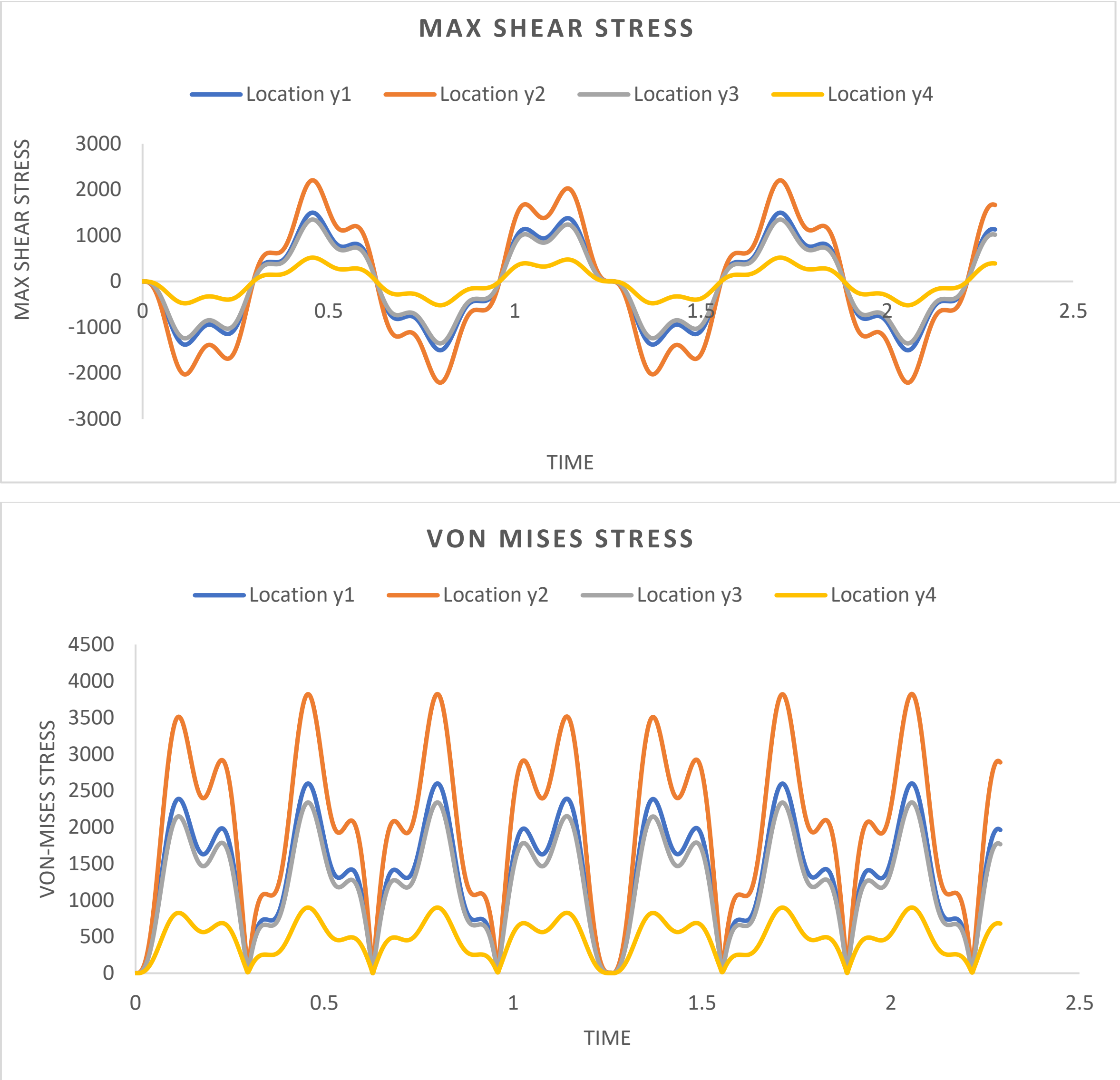
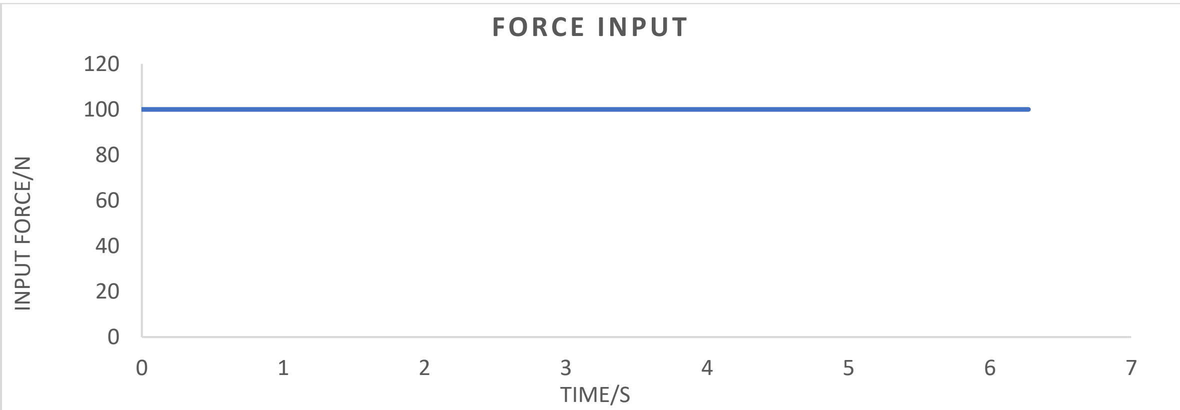


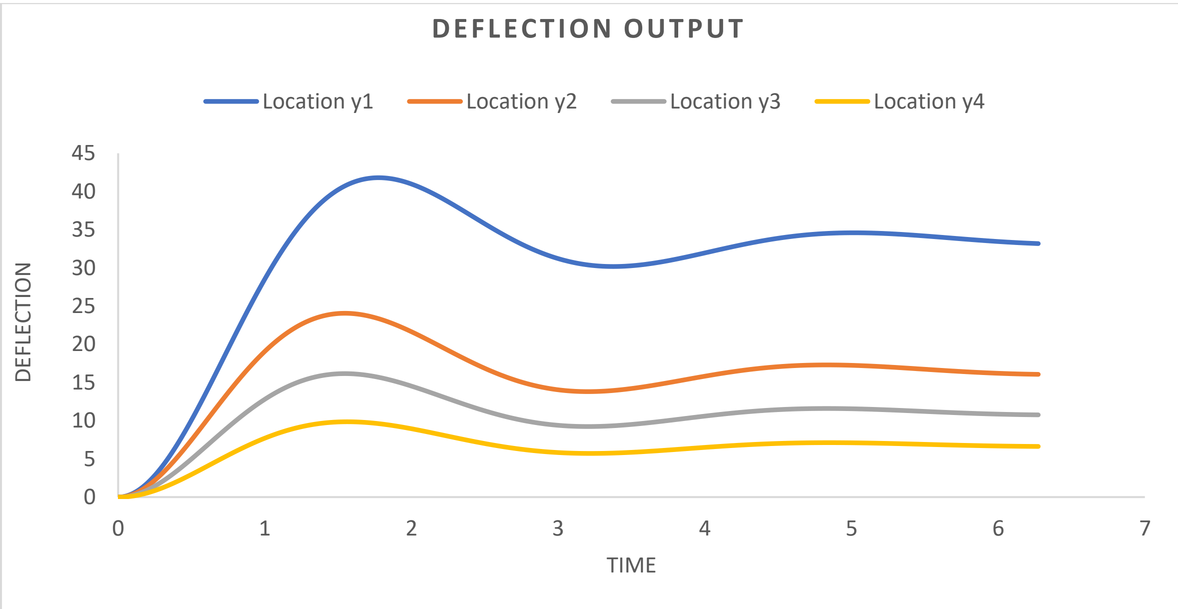
Figure 3.7 Six resulting figures from Non-Linear TFV (Undamped)

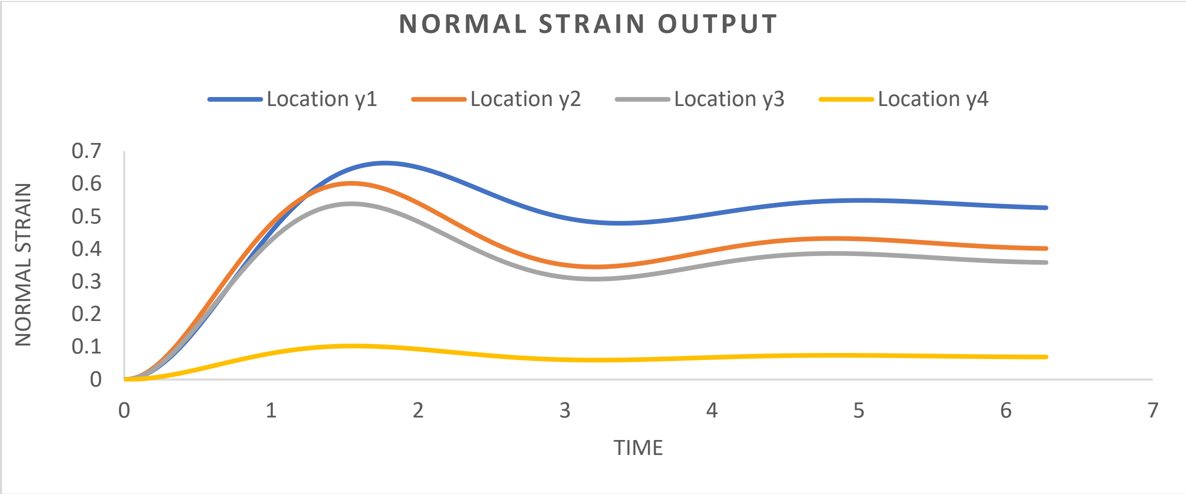
4.6 ***Non-Linear Steady-Forced Vibration Systems (Damped)***

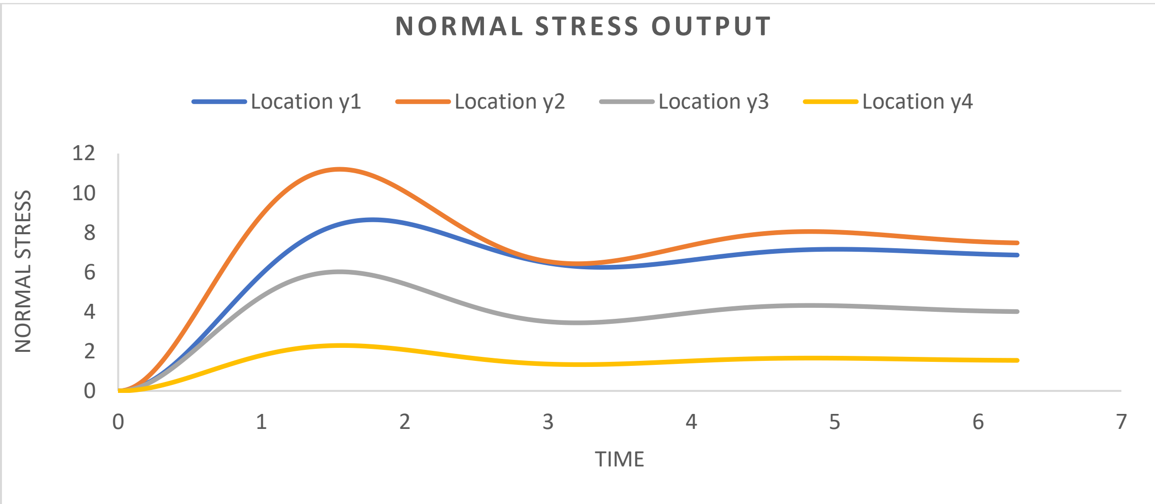
using ***Figure 3.1 (E)*** to derive the deflection equation resulting in the output deflection from the derived **Eqs 71 and 72**, this resultant deflection can be used as an input into **Eqs 4, 5, 6, and 6*** to produce normal strain and stress output, maximum induced shear stress, and Von Mises stress. The construction of this system would be similar to that mentioned within the section of the un-damped non-linear steady-forced vibration systems; the only difference is throughout the analysis of springs' motions within the system, which is attached to the base gets extended nor compressed. In the theoretical studies section, the numerical solutions using the Euler method for the displacements of y_1, y_2 and y_3 The time, based on the given applying the steady force of 1000N and a damping coefficient of 100Ns/m (takes place only through the first spring). Therefore, this method leads the maximum generated normal and induced shear stresses within these springs to be as follows:

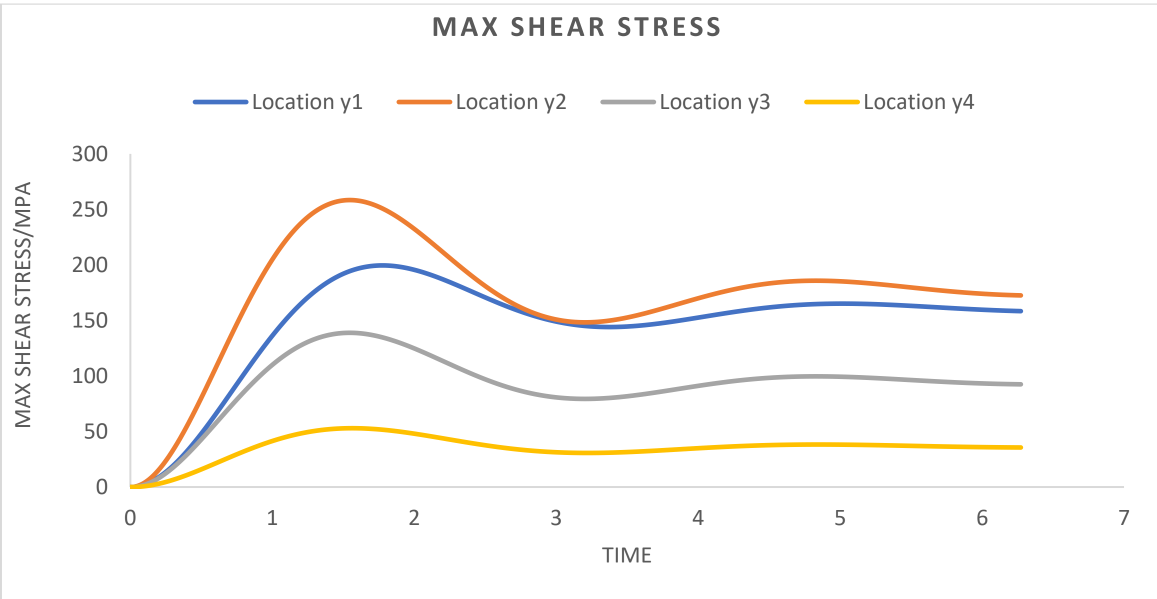
Spring 1: -50.62 MPa (Maximum Normal Stress) and -1485.7MPa (Maximum induced shear stress). Spring 2: -33.80MPa (Maximum Normal Stress) and -992.15MPa (Maximum induced shear stress). Spring 3: -25.35MPa (Maximum Normal Stress) and -744.11MPa (Maximum induced shear stress). These values show that the shear failure would occur among these springs since their shear stresses exceeded the yielding shear stress.






NORMAL STRAIN OUTPUT
Location y1
Location y2
Location y3
Location y4
NORMAL STRAIN
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
TIME


NORMAL STRESS OUTPUT
Location y1
Location y2
Location y3
Location y4
NORMAL STRESS
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
TIME


MAX SHEAR STRESS
Location y1
Location y2
Location y3
Location y4
MAX SHEAR STRESS/MPA
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
TIME

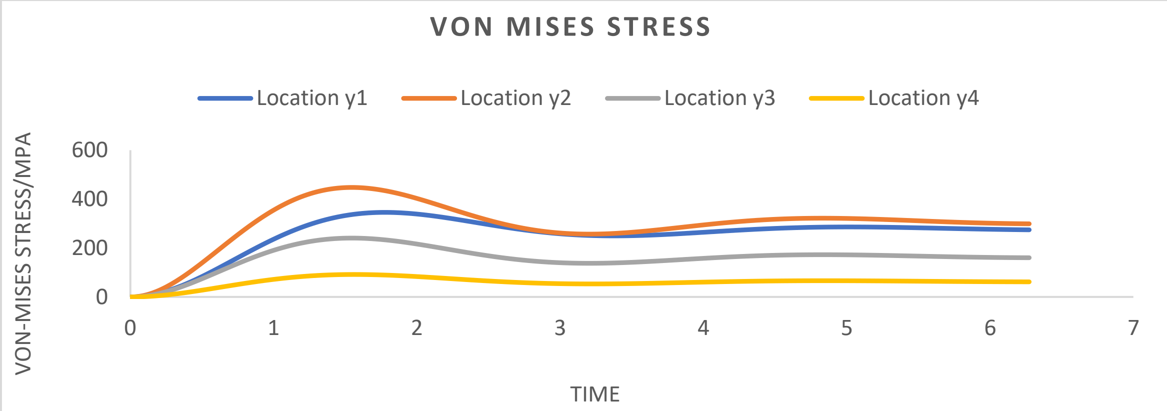
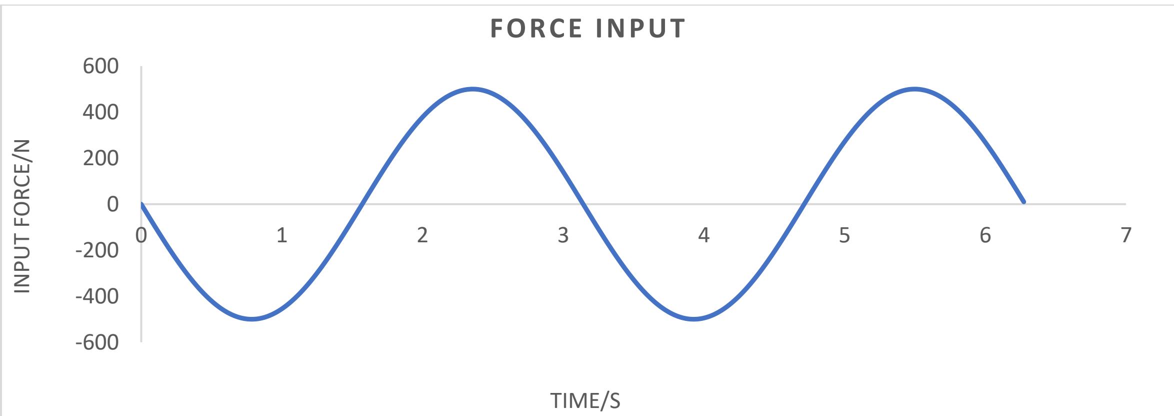
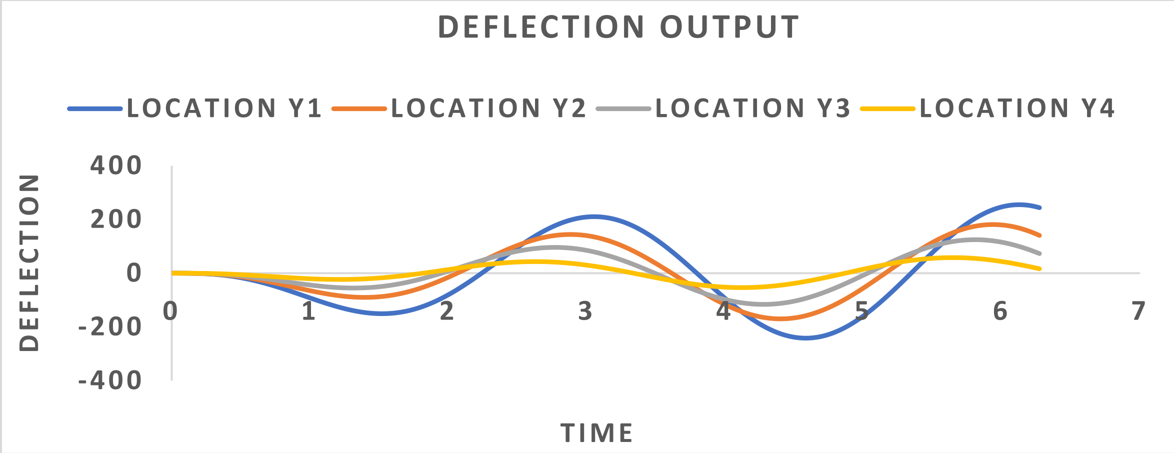


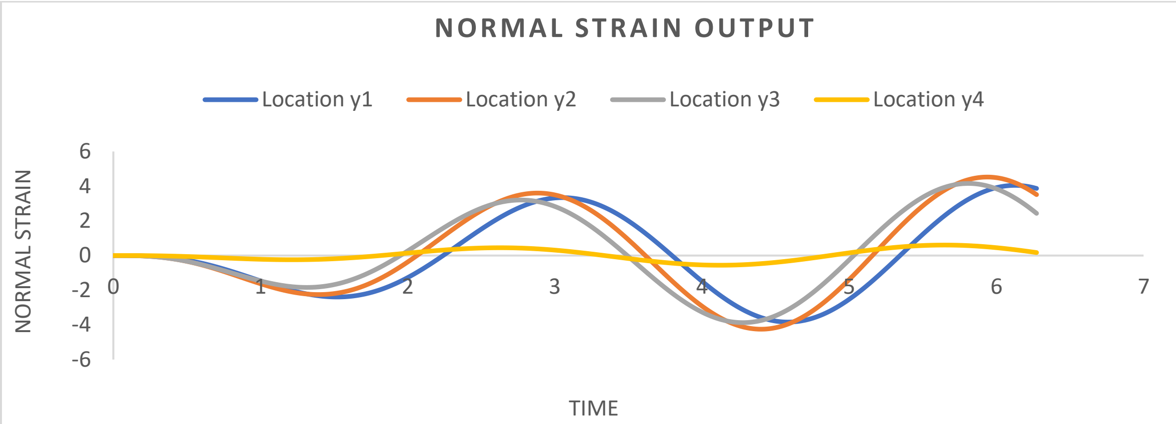
Figure 3.8 Six resulting figures from Non-Linear SFV (Damped)

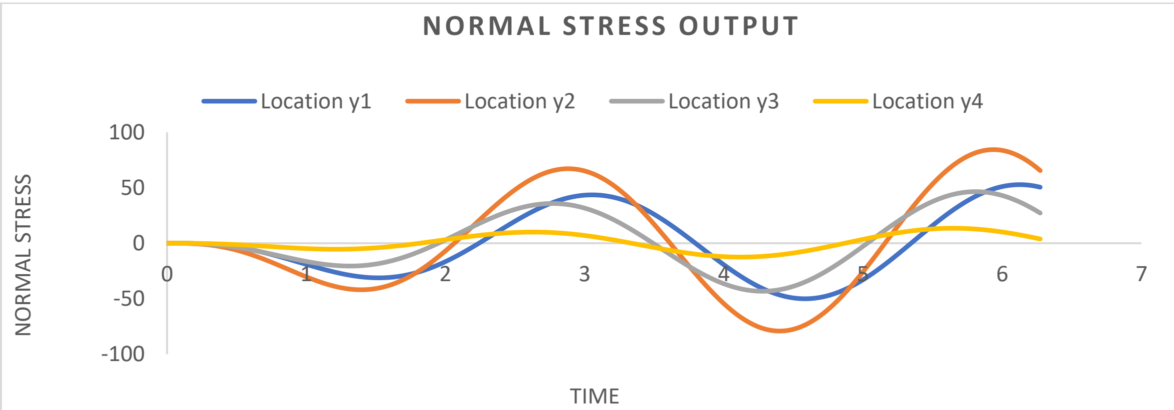
4.7 ***Non-Linear Transient-Forced Vibration Systems (Damped)***

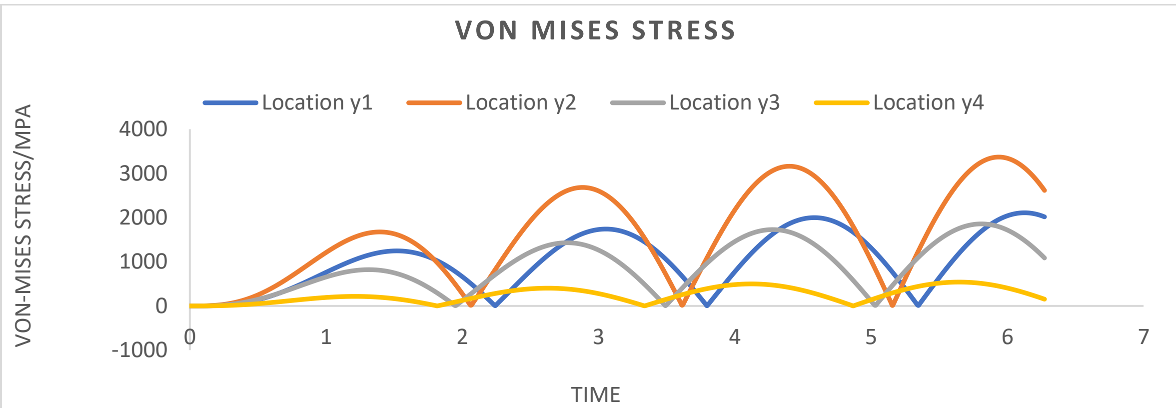
using ***Figure 3.1 (F)*** to derive the deflection equation resulting in the output deflection from the derived **Eqs 73 and 74**, this resultant deflection can be used as an input into **Eqs 4, 5, 6, and 6*** to produce normal strain and stress output, maximum induced shear stress, and Von Mises stress. Based on the system's construction comprising three active springs (as mentioned for the damped non-linear steady-forced vibration system), replacing the steady force with the transient force having a magnitude of 1000N with a driving frequency of 8 rad/s. The conditions mentioned led to the maximum generated normal and induced shear stresses (again based on the Euler Method) within these springs to be as follows: **Spring 1**: -153.227MPa (Maximum Normal Stress) and -4497.58MPa (Maximum induced shear stress). **Spring 2**: -101.57MPa (Maximum Normal Stress) and -3010.01MPa (Maximum induced shear stress). **Spring 3**: -76.91MPa (Maximum Normal Stress) and -2257.51MPa (Maximum induced shear stress). These values illustrate that shear failure would occur among these springs since their shear stresses exceeded the yielding shear stress.




DEFLECTION OUTPUT
LOCATION Y1
LOCATION Y2
LOCATION Y3
LOCATION Y4
DEFLECTION
400
200
0
-200
-400
0
1
2
3
4
5
6
7
TIME


NORMAL STRAIN OUTPUT
Location y1
Location y2
Location y3
Location y4
NORMAL STRAIN
6
4
2
0
-2
-4
-6
0
1
2
3
4
5
6
7
TIME


NORMAL STRESS OUTPUT
Location y1
Location y2
Location y3
Location y4
NORMAL STRESS
100
50
0
-50
-100
0
1
2
3
4
5
6
7
TIME


VON MISES STRESS
Location y1
Location y2
Location y3
Location y4
VON-MISES STRESS/MPA
4000
3000
2000
1000
0
-1000
0
1
2
3
4
5
6
7
TIME

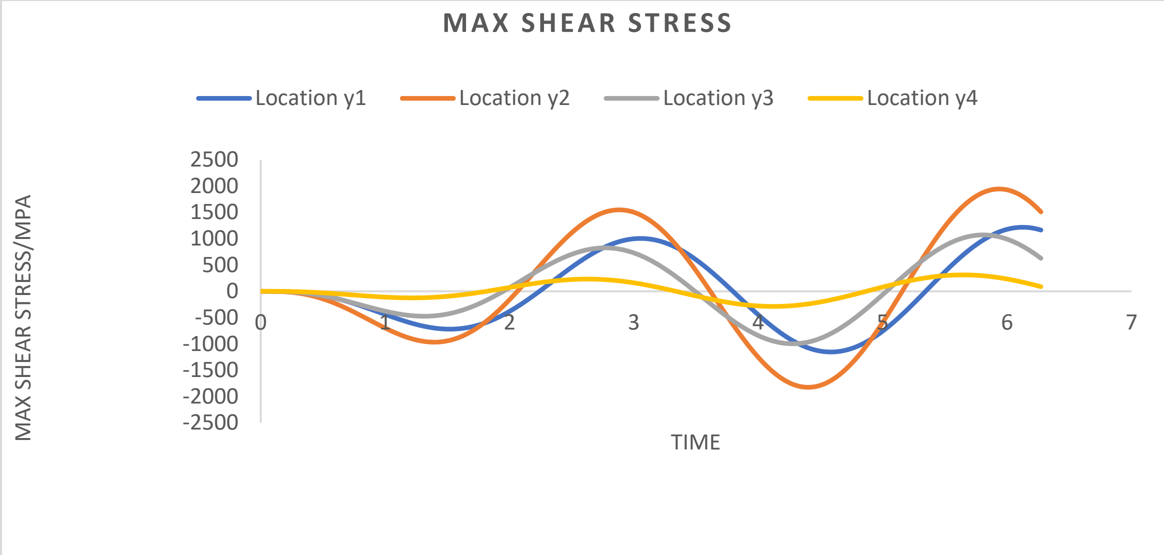


Figure 3.9 Six resulting figures from Non-Linear TFV (Damped)

4.8 *Overall Stiffness Matrix*

Using equation 75 for each coil in the spring, then adding them all to make the overall stiffness matrix

Table 3.2 Overall achieved stiffness matrix of the DT model using Eq 75

5.852466	-5.85247	0	0	0
5.852466	19.02051	-13.1680478	0	0
0	-13.168	23.70248611	-10.5344	0
0	0	-10.5344383	17.11846	-6.58402
0	0	0	-6.58402	6.584024

4.9 *Overall Compliance Matrix*

By taking the inverse of the stiffness matrix, this will result in the compliance matrix

Table 3.3 Overall compliance matrix of the DT by using the inverse of Eq 75

0.085434	0.085434	0.085434076	0.085434	0.085434
-0.08543	0.085434	0.085434076	0.085434	0.085434
-0.08543	0.085434	0.161375477	0.161375	0.161375
-0.08543	0.085434	0.161375477	0.256302	0.256302
-0.08543	0.085434	0.161375477	0.256302	0.408185

4.10 *Digital Twin Model (DTM)*

Figure 3.10 represents the physics-based discrete-time model, which provides a graphical representation of the current real-time mechanical behaviour of the vibrating system (more precisely, the Coil Spring). The load that is being applied to the spring is the sole input that this model takes into consideration. ***Figure 3.10*** presents a visual representation of the facts behind the assertion that. As a result of recent developments in the physics-based model, it is now possible to compute the maximum Von Mises Stress with a greater degree of precision than ever before. As a consequence of this, it is now much simpler to determine if the spring will break during operation or whether it will maintain its structural integrity throughout the process. It indicates that the spring will fail if its applied stress is greater than the yield failure stress. On the other hand, under typical operating conditions, the spring may be considered safe if the applied stress is maintained at a lower level than the yield failure stress.

The present model accounts for the dynamic load placed on the springs when the mechanism operates. Specifically, there are eight mechanical springs, each weighing five hundred Newtons (N) applied to it. Only six of these springs are considered risk-free for use in the system. However, two of the springs broke due to the maximum Von Mises stress exceeding the yield failure stress of the material, causing the springs to fail.

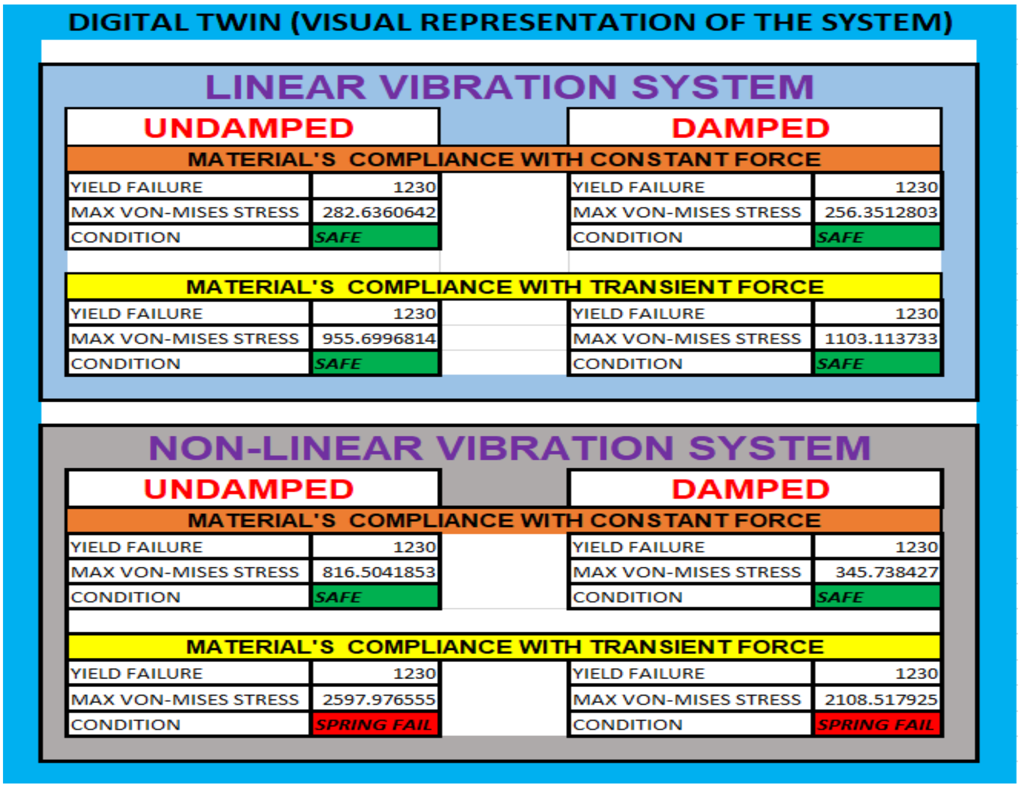


Figure 3.10 Resulting DTM based on the numerical analysis.

4.11 *Comparison of Physics-Based Models in the Literature and this Research*

Table 3.4 Comparison of physics-based models in the literature and this research

Ref	Method	Limitation
[382]	Physics-based dynamic simulation AI methods for analysing performance	**1-** Lack of addressing potential issues related to accuracy and reliability. **2-** Low performance. **3-** Lack of considering real-time data **4-** Practical implication of using AI with the physics-based model is not considered. **5-** No compliance matrix
[383]	physics-based models and integration of physics-based models with machine learning	**1-** Lack of validation process or evaluation metrics. **2-** Lack of consideration of different damage scenarios. **3-** The classifiers are missing. Lack of compliance matrix
[384]	physics-based methodology and engineering simulation approach combining mathematics and field data	**1-** Data used are near-real time but not the current real-time. **2-** Lack of information on the specific mathematical models and algorithms. **3-** Lack of any validation processes.
[385]	Component-based reduced-order modelling and Bayesian state estimation for data-driven model adaptation	**1-** The methodology's applicability to different systems or structures is not discussed, limiting its generalizability. **2-** The paper does not address the potential impact of measurement errors or sensor noise on the performance of the digital twin. **3-** The practical implications are missing
[386]	Model order reduction, co-simulation & hardware-in-the-loop, model-based control, model-based diagnostics	**1-** Lack of mathematical detailed approach. **2-** Limited to only one damage scenario. **3-** Based on estimation and not actual and accurate data. **4-** No compliance matrix to assess the accuracy and reliability of the DT model
Features		
This Research	Physics-Based Euler Method for solving ODE	**1-** Considered Current time operating conditions and real-time data **2-** Considered all possible damaged scenarios **3-** Provided detailed mathematical and algorithm modelling **4-** Provided the practical implications **5-** Addressed all the impact of potential errors by considering all scenarios **6-** Applicable to any coiled springs used in suspension systems across practice **7-** The model is capable of providing overall stiffness and compliance matrices **8-** Simple and cost-effective to use 9- No visualisation of the physical asset (Mechanical Springs)

5 CHAPTER SUMMARY

This chapter proposed a novel numerical concept of the DT based on EM. The DT model successfully replicated the mechanical behaviour and virtually represented the mechanics of materials for the physical coiled spring. This study successfully developed a numerical way to validate the proposed idea of the DT. The technique suggested still has limitations and is subject to further research. This chapter proves that DT is a virtual replica of anything, where the replication must mirror the entire internal and external mechanical behaviour of the replicated thing in the Current Real Time (CRT) with four dimensions. The DT model virtually represented all stresses acting internally on the spring. While the resulting strains and stresses are accurate based on EM, this paper proposed a novel concept for DT.

The DT model captured all the variations of the normal and maximum induced shear stress in CRT. Additionally, the model showed the instant representation of the system's behaviour and showed that vibration behaved similarly concerning the rough time compared to the conduct of the Linear SFV system in the case of free force. The damping effect in the system mentioned in the undamped linear TFV system section leads the output response to be slightly distorted compared to the rest of the spring’s motion within the first few seconds of the spring’s motion movement observed. The Non-Linear steady and transient forced vibration used in the un-damped case illustrates all measurements’ output response (deflection, strain, maximum normal and induced shear stresses). The output for each of the four springs behaves harmonically with the same NF, with different values concerning the time due to the other geometric properties of each spring. Non-Linear SFV Systems (Damped) are the same as the undamped system. The only difference is that throughout the analysis of springs’ motions within the system, which is attached to the base, neither gets extended nor gets compressed.

The model shows the overall displacement of the coils and the displacement between each coil. The model still has some limitations and is open for further research; fatigue analysis is one of the types of failure that accrues to mechanical systems. Since all the stresses shown in the model’s interface are in the current real-time, improving the model further for fatigue analysis is essential.

CHAPTER 4
Digital Twins for Fatigue Damage and Lifecycles of Coil Springs Used in Suspension Systems

1 CHAPTER OVERVIEW

This chapter validates the proposed physical modelling method used in Digital Twins (DTs) of the coil springs introduced in ***Chapter 3***. This chapter uses an experimental design for the validation through a cost-effective and straightforward DT model for Live Condition Monitoring (LCM) and Predictive Maintenance (PdM) based on three dimensions instead of five. The first dimension is the Digital Entity (DE); DE is the Digital Model (DM) of the system we are interested in (digital primary springs used in suspension systems). The second dimension is the Physical Entity (PE); the PE is the primary physical springs used in an existing suspension system and the integrated intelligent sensors (load and strain). The third dimension is the Connection Entity (CE) between the PE and the sensors, sensors and Internet of Things (IoT) platforms, IoT platforms and the DE.

The experimental validation in this chapter contributes to the knowledge as follows:

- Fatigue analysis is based on Current Real Time (CRT) data that considers the impact of specific factors that cause systems' deterioration throughout a given period. Compared to the existing methods to analyse Fatigue Lifecycles (FL) where factors of systems' deterioration are based on predetermined empirical calculations, estimation or not considered.
- DT method is used to improve systems' empirical predetermined loads and lifecycles.
- The entire mechanical behaviours of systems are visualised in CRT.

The proposed DT model improves the empirical predetermined average load for simulation and experiment by 35.7 % (1.6 times more). Based on the actual load that the system experiences in the real-life case study, the DT model improves the empirical predetermined average lifecycles of the system by 12 times compared to the simulated results and nine times more compared to the experimental results. The proposed DT model still improves the average lifecycles of the system by 19.7% (1.2 times more) compared to the wireless DT model results based on the actual load applied to the system. A real-life case study of a suspension system in a Peugeot 3008 is used to demonstrate the proposed DT model's high accuracy and efficiency.

2 INTRODUCTION

The previous chapter is a physics-based method with a DT model capturing all the mechanical behaviour in Current Real-Time (CRT) data/or capturing all the stress acting on springs in the current time, which enables us to get von Mises stress, and we can compare it with the yield stress or failure stress. Since the stresses acting on the spring are uniaxial, von Mises was the best type of stress to compare with the failure stress to know if the springs are safe or will fail. One of the limitations of the physics-based method in ***Chapter 3*** was no visualisation of the physical asset; ***Chapter 4*** not only considers a physics-based model in the previous chapter (computational/simulation) but also considers the experimental and the proposed actual Digital Twin model, which provides full visualisations and overcoming the limitation in ***Chapter 3***.

The main focus of this work is on the use of coil springs in the suspension systems of passenger cars. However, the same approaches may be used to evaluate springs in many applications by adapting them to account for their inherent differences. The previous chapter is a Physics method with a DT model capturing all the mechanical behaviour in current time using real-time data / or capturing all the stress acting on springs in the current time, enabling us to get Von Mises stress and compare it with the yield or failure stress. Since the stresses acting on the spring are uniaxial, von Mises was the best type of stress to compare with the failure stress to know if the springs are safe or will fail. This chapter considers a physics-based model in the previous chapter (computational/simulation) and experimental and the proposed actual DT model.

Regular maintenance is critical for the reliability and safety of mechanical services, where engineers must keep operating parts in good working order. Although preventive maintenance is costly, replacing the failing parts after failure or having parts serviced earlier than required causes unnecessary delays and more expenses [387]. Applying simple models using fixed data (traditional simulation methods) is good but is insufficient for effective maintenance because current time parts' dynamic deterioration is not considered. However, Current Real Time (CRT) data will enable more profound insight into conditions. Industry 4.0 introduced the DTs as a new informatics technology dependent on the Internet of Things (IoT); since then, many authors referenced [127] to [163], as shown in chapter two ***Sections 5.2***, ***5.3***, and ***5.4***, have yet to define and conceptualise the DT [388] [389], [390]. Although many DT concepts exist, DT based on a live simulation is not yet used to enhance Condition Monitoring (CM) and maintenance.

DTs technologies have gained wide publicity; however, despite the significant work done and discovery that promises a prospering IoT in integrating DTs in industries, the research needs to be more transparent [391]. The concept of DT needs to be better understood, which impacts the future development of DT technology. Large industries like automotive [392] and oil and gas [393] were forced to discover their DT concepts and develop them for their products and services. Moreover, the systems' geometry and behavioural parts are still not visualised in Real Time (RT), where the parts of the system's aspects are used as an access point to monitor the system.

2.1 *Condition Monitoring (CM)*

CM [394] monitors the performance of industrial machinery and equipment over time to detect signs of wear and tear or malfunction [394]. CM aims to identify potential problems before they result in equipment failure or downtime. This CM helps to prevent costly repairs and unplanned downtime, increase equipment life, and improve overall system performance [395]. Overall, CM aims to detect potential problems early so that maintenance and repairs can be scheduled before the equipment fails, resulting in lower maintenance costs, increased equipment availability and prolonged equipment life [394].

2.2 *Current Condition Monitoring Methods*

1. **Vibration analysis:** This involves measuring the vibration levels of equipment and comparing them to known levels to detect changes that may indicate a problem.
2. **Oil analysis:** This involves analysing the oil used in equipment to detect signs of wear or contamination that may indicate a problem.
3. **Temperature monitoring:** This involves monitoring the temperature of equipment to detect changes that may indicate a problem.
4. **Ultrasonic testing**: involves using ultrasonic waves to detect changes in equipment structure that may indicate a problem.
5. **Current analysis:** This is a technique of monitoring electrical parameters such as current, voltage, power, and power factor to detect changes in equipment performance.
6. **Predictive Maintenance (PdM):** PdM helps improve maintenance activities' performance by using advanced monitoring techniques, such as vibration analysis and oil analysis, to predict when equipment will need maintenance before it fails.

2.3 *Real-Time Condition Monitoring (RTCM)*

RTCM is a method of condition-based monitoring that uses real-time data and analytics to monitor the condition of machinery and equipment continuously. RTCM aims to detect and diagnose equipment problems as they occur to minimise downtime and prevent equipment failure[395]. In RTCM, sensors and other monitoring equipment are used to gather data on the performance of machinery and equipment in RT. The data is then analysed using advanced algorithms and analytics to detect any changes or anomalies that could indicate a problem. This real-time analysis allows for early detection of problems, and prompt action can be taken to address the issue before it leads to equipment failure [394]. The data from RTCM is used to create equipment's DTs, which can be used to simulate and analyse the behaviour of the equipment over time and to detect any pattern that may indicate a problem.

RTCM is particularly useful in critical industries such as power generation, aviation, and transportation, where even a short equipment downtime can cause significant disruption and financial losses. It also provides the RT status of the equipment, which can be used to optimise the performance and maintenance of the equipment and improve overall system performance [394]. It is important to note that while RTCM provides increased visibility into equipment performance, it also requires significant infrastructure and resources, including advanced sensors, data collection and analysis tools, and skilled personnel.

2.4 *Types of Maintenance*

Maintenance is essential to any facility or system, as it helps keep equipment running efficiently and safely, prevent downtime, and prolong equipment life [396]. However, the best approach to maintenance depends on the specific equipment, usage, environment, and industry. Maintenance keeps equipment, machinery, and facilities in good working order by performing regular inspections, repairs, and replacements. There are several types of maintenance [304]:

- **Preventive maintenance (PvM)** is a proactive approach involving regular inspections and repairs to prevent equipment failure and downtime. PvM schedules are often based on time or usage, such as performing maintenance on equipment every six months or after a certain number of operating hours.
- **Predictive Maintenance (PdM)** is an advanced approach that uses condition-based monitoring (CBM) to detect equipment problems before they occur. By continuously monitoring equipment and identifying potential problems before they occur, PdM can help avoid unplanned downtime, reduce maintenance costs, and extend the life of the equipment.
- **Corrective Maintenance** is fixing equipment and machinery after it has failed or broken down. This method is a reactive approach, as the maintenance is performed after the problem has occurred, resulting in downtime and disruption.

- **Proactive Maintenance** goes beyond preventive maintenance by continuously monitoring equipment condition, environmental factors and other variables affecting the equipment's performance and predicting when a failure will occur.
- **Condition-Based Maintenance (CBM)**: It uses data and analytics to monitor equipment conditions and predict when maintenance is needed. By focusing maintenance activities on the equipment that needs it most, condition-based maintenance can help to reduce maintenance costs and improve equipment uptime.

2.5 *Coil Springs Maintenance*

Coiled springs are an essential component of the suspension system in a vehicle, and proper maintenance of these springs is important for ensuring that the vehicle rides smoothly and handles properly [302]. The main types of maintenance for coiled springs include visual inspections, spring rate checks, preload checks, alignment checks, lubrication and replacement. During a visual inspection, any signs of damage or wear, such as cracks, chips, or rust on the surface of the springs, should be checked; if they are severely damaged, they should be replaced. The force required to compress the spring rate should be checked to ensure it is within the right range; if it is too high or too low, it will affect the vehicle's handling and ride comfort. Preload, which is the amount of tension applied to the spring when it is installed, should also be checked; if it is too much or too little, it will affect the handling and comfort of the vehicle. The alignment of the suspension spring should be checked to ensure it is aligned correctly with the rest of the components. Additionally, lubrication can be added to the springs to reduce friction and wear, and if the springs are worn or damaged, they should be replaced[324], [381], [397]. Regular maintenance of the coiled springs can help extend the life of the suspension system, improve the vehicle's performance and ensure the driver's and passengers' safety[312].

2.6 *Fatigue and Remaining Useful Life (RUL) Analysis*

Fatigue analysis is the process of evaluating the ability of a structure or component to withstand cyclic loading over time. It is used to predict a system or component's life under repeated loads and identify potential failure points before they occur [301]. Fatigue is the leading cause of the failure of the coiled springs; however, many factors impact the fatigue life, such as surface roughness, material decarburisation, and material defects like inclusions. The cold coiling method of manufacturing coiled springs causes residual stress distribution, impacting fatigue life. It is evident in [398] that the fatigue limit of the helical springs depends on the residual stress field through experimental investigation. The traditional methods to estimate fatigue life cycles for mechanical coiled springs are based on fatigue strength with torsion. Modal analysis is a computational method that studies the dynamic properties of suspension systems in the frequency domain. The modal analysis ignores the forces acting on the coil spring; however, it depends on its mass and stiffness [399].

RUL of coiled springs in a vehicle can be calculated by comparing the current usage of the spring with its estimated life, considering the operating conditions, stress and loads it has undergone [329], [400]. There are a few methods to calculate the RUL of the coiled springs in the vehicle, depending on the amount and type of data available [259]. One method is to use a cumulative damage model, which considers the stress cycles and amplitude the spring has undergone and compares it with the material properties and FL predicted by the manufacturer [318], [329], [401]. This method requires data on the loading history of the spring, and it can be used to estimate the remaining useful life of a spring based on the number of cycles and the amplitude of the applied stress.

Another way is to use prognostics and diagnostics (PdM) techniques, which track the component's health over time by monitoring its vibration, temperature, and other parameters using sensors, which can be used to calculate the RUL of a spring [333], [401]. This method requires regular monitoring of the spring condition and can be used to estimate the RUL of a spring based on the current health of the component. It is important to note that even if the remaining useful life of a coiled spring is calculated, it is not a guarantee that the spring will fail at that specific moment, but it can be used to plan for maintenance, replacement or any other action that will ensure the safety and proper functioning of the vehicle[315], [333], [400]. These types of analysis can provide valuable insights into the behaviour of the coiled spring and can be used to optimise the design of the spring, improve its performance, and extend its service life.

2.7 *Fatigue Analysis Methods*

1. Endurance limit is based on the idea that a material can withstand a limiting number of cycles without failure. Beyond that, the material will continue to hold up to cyclic loading.
2. The stress-lif (S-N) method is based on the relationship between the stress amplitude and the number of cycles to failure. The S-N curve is determined experimentally and can be used to predict the life of a structure or component under a specific stress amplitude.
3. The strain-life (SL) (ε-N) method is based on the relationship between the strain amplitude and the number of cycles to failure. It is used when the material's properties change, such as with plastic deformation.

4. Finite Element Method (FEM): FEM can simulate the cyclic loading on a structure or component and predict its behaviour over time. The results can be used to identify potential failure points and

2.8 *Fatigue and Remaining Useful Life Parameters*

Several parameters are used to calculate the fatigue RUL of a coiled spring in a vehicle, [259], [315], [318], [401], including:

1. **Material properties:** The material properties of the spring, such as the yield strength, tensile strength, and fatigue limit, play a key role in determining the RUL of the spring. These properties can be obtained from the spring manufacturer or material supplier. These materials' properties are manual setup input inside the used software for the 3D design.
2. **Loading conditions:** The loading conditions of the spring, including the amplitude and frequency of the applied stress, must be known to calculate the spring's RUL. Loading conditions will be generated from the sensors, such as force sensors on the physical asset (coiled springs) at the current time.
3. **Stress analysis:** Stress analysis, such as the S-N curve (also known as the Wöhler curve), can determine the maximum stress the spring will experience and the number of cycles it can withstand before failing. Once the actual loading of the spring is generated, the sensors will record it and send it to an IoT plat form (in this research is the ThingSpeak) to be analysed and deduce stresses acting on the spring from it, as shown in the previous chapter; for example, Von Mises stress can be calculated and compared with the failure stress.
4. **Current usage:** The current usage of the spring, including the number of cycles and the amplitude of the applied stress, must be known to calculate the RUL of the spring. The current spring usage will show how weak the spring becomes through displacement generated between the free length of the spring and the solid length.
5. **Operating conditions:** The vehicle's operating conditions, such as the environment in which the vehicle is used and the type of loads it carries, can affect the RUL of the spring. Each user has a different applied load and driving environment, which impacts the coiled springs differently. Each user is unique to the impact of springs; this will be recorded from the different types of sensors positioned on the spring to report the unique data and send it to the IoT platform for analysis.

Considering these parameters, it is possible to calculate the fatigue life of a coiled spring and determine how long it is expected to last before it needs to be replaced [402]. It is important to note that the method of calculating fatigue life can vary depending on the loading condition and the material properties [230], [403]. It is a good practice to consult experts in mechanical engineering or the spring manufacturer; they may have their methodology and software to provide more accurate results.

2.9 *Finite Element for Fatigue Analysis*

FEM is a numerical technique for solving problems in engineering and physics [404]. It approximates the solution to a Partial Differential Equation (PDE) over a complex domain by breaking it into many smaller, simpler elements. The method is widely used to analyse structures, fluids, and other physical systems[405]. FEM is based on breaking down the problem domain into many smaller elements, each of which is assumed to have a simple, known solution. The solution for the entire domain is then obtained by solving for the unknowns at the nodes where the elements meet [406]. The FEM is widely used in mechanical engineering, aerospace engineering, civil engineering, biomedical engineering, and many more, as it can handle complex geometries, loading conditions, and material properties [407].

It is also useful for simulating nonlinear and time-dependent problems, it can be used for static and dynamic analysis, and it can handle both deterministic and probabilistic models [408], [409]. High Cycle Fatigue (HCF) is well-known and researched for fatigue testing. However, the testing was done with constant loads. The FL for helical springs was examined based on the critical plane using constant loading. [398] evaluated the multiaxial strength coiled springs used in suspension systems by applying Von Mises and critical plane criteria. [410] investigated the HCF life using start-stop conditions aligned with the analysis of fractured surfaces using failure analysis. [411] performed the same research as [410], despite the similarities between their results' outcomes, both results gave the exact estimation for the fatigue calculation. [399] did not just examine the fatigue strength with the HCF; however, he did combine the impact of the axial and torsional loading on the fatigue strength. [412] examined the stress distribution and all the parameters that impact the stress distribution.

The automotive industry is now seeing an increasing need to speed up the process of implementing novel ideas. In vehicle design, several conflicting objectives must be addressed, including lightweight construction and the imperative of assuring ideal longevity. There is now an increasing need within the car industry to accelerate the process of converting novel ideas into tangible manufacturing [48], [247], [413]. It is essential that the vehicles now being developed contain the necessary attributes, such as durability and lightweight construction, in order to maintain a competitive edge [246]–[248], [250], [414].

The automotive business relies on creating innovative and improved designs, which may provide a significant competitive edge and determine the success or failure of various goods [250]. The primary function of the suspension system is to effectively mitigate the impact of shock loads resulting from disturbances encountered on the road [252], [253], [413], [415]. The system consists of three discrete components: the spring, which acts as the force-bearing element; the damper, which serves as the oscillation-damping component; and the structural member. The issue of Fatigue Failure (FF) has substantial importance in the design of suspension systems. To fulfil the prerequisite requirements, a design must exhibit the capacity to withstand FF under pre-set design loading circumstances [253]. The spring comprises SAE 9254, a steel alloy often used to manufacture coil springs. The technical drawings cover the comprehensive design specifications for the spring [416].

This study includes an analysis of fatigue utilising the strain-life methodology, emphasising scenarios involving variable amplitude loading. The loading history was first obtained from the fatigue test data included in the spring design. The loading history was shown by a triangular waveform characterised by a frequency of 25 Hz. Furthermore, an alternative loading history, known as the standard SAESUS, was used. The historical data were subject to adjustments and modifications, which followed the highest and lowest deflection values found throughout the design process. The scaling and trimming procedures were used to guarantee that the recordings correctly depicted the whole bump and subsequent rebound deflection. This work aims to use the FEA approach to predict the fatigue properties of springs utilised in automobile suspension systems.

The rest of this chapter is organised in the following ways: ***Section 3*** shows the materials used and their properties; ***Sections 4*, *5*, and *6*** show the different methods used in this study, which are three different methodologies (Experimental, Computational, and Digital) are used and compared; ***Sections 7*, *8*, and *9*** includes the results and discussion, ***Section 10*** is for the conclusion.

3 MATERIALS AND EQUIPMENT

Table 4.1 Monotonic and cyclic properties of the spring's SAE9254 wire

Monotonic Properties	
Young's Modulus (E) MPa	2.e+005
Poisson's Ratio	0.3
Bulk Modulus MPa	1.6667e+005
Shear Modulus MPa	76923
Tensile Yield Strength (σ_y) MPa	2270
Tensile Ultimate Strength (σ_u) MPa	2950
Fracture Strain (ε_f)	4.08%
Fracture Stress (σ_t)	2483
Strain Hardening Component (n)	0.0418
Strength Coefficient MPa	2916
Strength Exponent	-0.106
Ductility Coefficient	0.213
Ductility Exponent	-0.47
Cyclic Properties	
Cyclic Strength Coefficient (K) MPa	3322
Cyclic Strain Hardening Exponent (n)	0.088
Cyclic Yield Strength (σ_y) MPa	1922
Fatigue Strength Coefficient (σ_t) MPa	4108
Fatigue Strength Exponent (b)	-0.109
Fatigue Ductility Coefficient (ε_t)	1.13
Fatigue Ductility Exponent (c)	-0.954
Geometric Properties	
Wire Diameter / mm	11.5
Mean Diameter of the spring/ mm	110
Coil's Free Length / mm	400
Number of coils	8
Coil's Pitch / mm	43.00
Wire diameter / mm	11.5
Mean diameter of the spring/ mm	110

Table 4.2 Structural steel > S-N curve and stress properties

Alternating Stress (MPa)	Cycles
400	1000
350	10000
260	1.e+005
160	1.e+006
100	1.e+007

4 EXPERIMENTAL METHOD

This section describes the practical investigation conducted based on experimental testing for fatigue analysis. Two experimental tests are available to analyse fatigue and predict the systems' life cycle: the constant amplitude test (fixed forced) and the programmed test. The programmed test was used; the empirical testing is based on the block cycle loading, where the coiled spring rate, strain and stress are measured. The experiment used in this paper aimed to analyse the suspension system's fatigue life, determine the system's lifecycle and compare the results with the DTM.

4.1 *Theory*

Figure 4.1 (a), the helical spring is exposed to an axial load denoted as F to ascertain the stress induced in the spring. Consider the scenario where the spring is divided into four sections or four groups representing the four springs used in a suspension system in an automotive vehicle at a certain location, as seen in ***Figure 4.1 (b)***. these four springs, or four groups, are treated with heat. The heat treatment was conducted on an electrical furnace with automatic temperature control as follows or divided into groups as follows: Group (1) heated at 200 C^o for 10 minutes, Group (2) heated at 300 C^o for 15 minutes, Group (3) heated at 400 C^o for 20 minutes, Group (4) heated at 500 C^o for 25 minutes. Internal forces are produced to establish and sustain equilibrium inside the remaining section, as seen in ***Figure 4.1 (b)***. A direct shear force, denoted as F, and a torque, denoted as T, are present. The maximum shear stress on the wire can be determined using the following equation [417], [418].

$$\tau_{\max} = \pm \frac{Tr}{J} + \frac{F}{A} \tag{1}$$

Eq 1 represents the maximum shear stress (τ max) in a material subjected to torsion and axial loading where:

- ± represents the sign of the shear stress, which can be either positive or negative.
- *T* is the applied torque.
- *r* is the radius of the shaft.
- *J* is the polar moment of inertia of the shaft cross-section.
- *F* is the axial force applied to the shaft.
- *A* is the cross-sectional area of the shaft.

The equation is important in mechanical engineering as it helps determine the maximum shear stress in a material subjected to torsion and axial loading. This information is crucial in designing and analysing various mechanical components such as shafts, gears, and springs, and in this project is used for the spring.

$$\tau = \frac{8FD}{\pi d^3} + \frac{4F}{\pi d^2} = K\frac{8FD}{\pi d^3} \qquad (2)$$

Where D is the mean coil diameter, K is the Wahl factor, C is the spring index defined by

$$K = 1 = \frac{0.5}{C}, \qquad C = \frac{D}{d} \qquad (3)$$

When the external force, F, is in a transient mod, the induced stress is also the variable. Therefore, the mean stress τ_m and the amplitude τ_a are defined by:

$$\tau_m = K_s \frac{8F_m D}{\pi d^3} \qquad (4)$$

$$\tau_a = K_b \frac{8F_a D}{\pi d^3} \qquad (5)$$

K_s and K_b are the correction factors [418], [419]due to curvature and F_m and F_a are the mean load and the load amplitude, respectively.

4.2 *Experiment Description for Relaxation and Fatigue Tests*

The objective of the relaxation test is to examine the change in the spring constant after a sequence of load cycles. The fatigue testing equipment seen in ***Figure 4.1*** comprised springs exposed to cyclic load and the Free Body Diagram (FBD) in (b). The spring constant, denoted as $K = \frac{F}{\delta}$, represents the ratio between the force exerted, F, and the resulting deflection of the spring δ. This study performed a series of relaxation tests to quantify the force, denoted as F, required to induce a deflection of 20 mm. The fatigue testing equipment was configured with preload and load amplitude values of 30 mm displacement and 25 mm, respectively. The spring constant was determined after doing 50,000 cycles. The primary aim of the experiment was to find the fatigue life cycles and to analyse the impact of cyclic loading in an ambient setting on spring relaxation, with a specific focus on the changes in the spring constant.

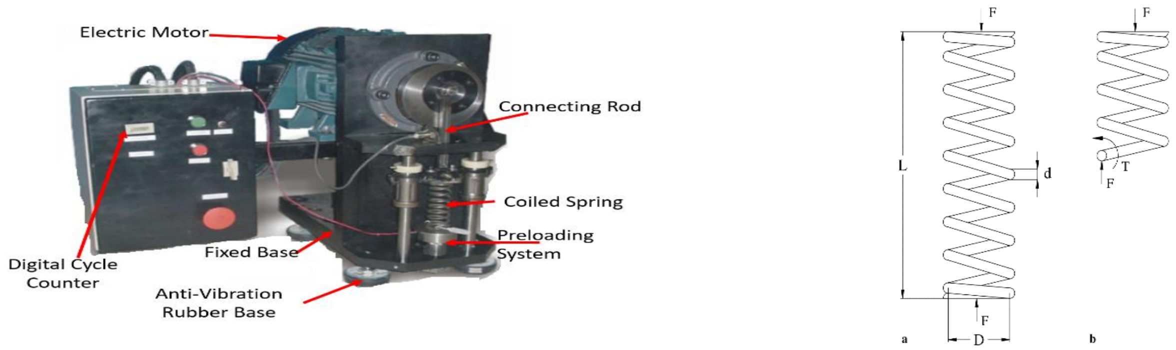


Figure 4.1 Fatigue testing setup; (a) Helical spring with axial load, and (b) FBD

A fatigue testing apparatus has been developed with the purpose of determining the S-N curve for helical compression springs, as seen in ***Figure 4.1***. The mechanism facilitates the application of force in alignment with the spring axis. The specialised equipment designed specifically for this purpose was used to conduct these tests. The fatigue testing equipment is seen in ***Figure 4.1.*** Using a slider-crank mechanism facilitates the conversion of rotational motion from a motor into rectilinear alternating motion, ultimately applying cyclic strain to the tested spring. The machine is equipped with a 7.5 HP electric motor that generates the required driving power to induce deformation in the active coils of the spring at a frequency of 25 Hz. In the event of a spring failure, the fatigue testing equipment ceases operation immediately, while a digital cycle counter records the fatigue life of the spring.

The experiment included conducting fatigue tests with constant mean stress τ_m of 300 MPa while varying the stress amplitude τ_a. In order to do this, the preload and amplitude displacement of the connecting rod were modified for each test, resulting in the attainment of the required values τ_m, and τ_a as outlined in **Eqs 4 and 5**. At this stage, the testing time will be long and need a significant reduction; one way to accelerate the testing time is to preload the spring with a specific force. In this case, the spring was preloaded with three different loads (0.7, 0.8, and 1) KN, respectively, with an average of 0.8 KN. The potential damage resulting from the accelerated testing was the same as the one done in actual fatigue testing; based on the regular practice for accelerated testing, the conditions of preloading and the frequency of loading is 25 Hz used when choosing the block load cycles, which resulted in testing the spring for 9*10^6 cycles (12.2 hours =12 h and 12 minutes).

The spring constant was determined before each experimental trial. Once the spring has been affixed to the equipment at a predetermined value of τ_a. The experiment was conducted till the occurrence of a spring fracture. Upon the failure, the number of cycles was duly recorded, followed by the execution of another test using a distinct parameter value τ_a. The S-N curve (stress amplitude – Number of cycles at failure) was constructed following the prescribed technique. If the initial stiffness value was reduced by 50% at the beginning of the trial, then the spring was considered to have failed, even if no physical crack occurred. The stiffness of the spring was determined after the static test, yielding a value of 20.03 N/mm. The observed value closely approximates the theoretical value of 41.34 N/mm; therefore, the spring is considered to have failed under the fatigue test.

5 COMPUTATIONAL METHOD

In this study, Ansys software is used to analyse FL. The SL approach is also elected because its suitability for the load sequence and mean stress impact is essential for fatigue analysis [420].

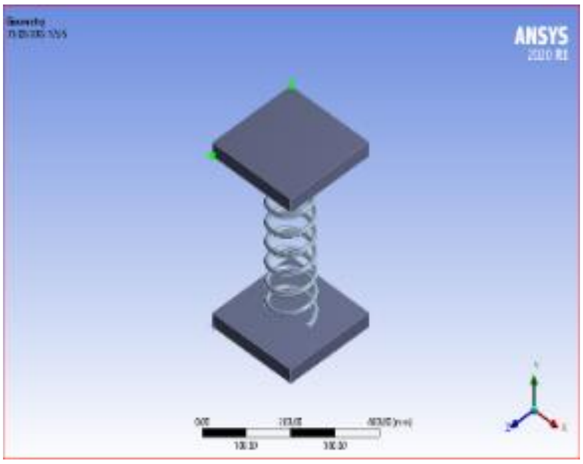
5.1 *Modelling*

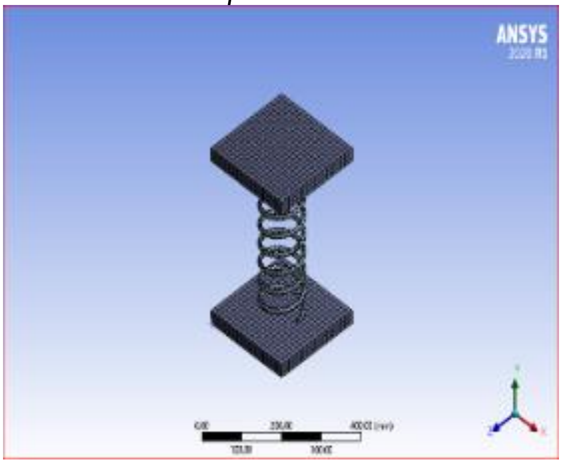
The ANSYS analysis code is used to build both the structural and FE models. The FE model and boundary conditions of the springs in a suspension system are shown in ***Figure 4.2***. The compression load is exerted through two inflexible surfaces, while the spring is integrated with 20-node brick pieces. Hence, the accurate circular wire and coil shape can be achieved by appropriately meshing the compressing surfaces using shell elements [413]. The load is imposed as a displacement, resulting in the spring's deformation from its initial length of 400 mm (without any load) to the specified height of 220 mm in the design [421].

The stresses and strains obtained from the structural analysis are used to depict the stress field inside the spring during the fatigue study. The simulation is configured so that the contact definition involves a bonded contact between the compression surface and the spring. The deformation is incrementally applied to ease a solution's convergence. The stress analysis findings are then inputted into fatigue analysis software to forecast the spring's fatigue characteristics when subjected to repeated loads [416]. The selection of material properties is contingent upon the specific analytical approach used. The material under consideration is regarded as exhibiting both elastic and isotropic properties. ***Table 4.1*** presents the spring characteristics of the SAE 9254 spring steel alloy [422].

A mesh sensitivity analysis was conducted on the finite element (FE) model in order to determine the optimal mesh size that achieves a suitable trade-off between accuracy and computational cost, as documented in references [41], [249], [423], [424]. The investigation involves monitoring particular variables and assessing structural error in the fixed effects solution. The hexahedral meshing strategy is used for the meshing of the spring geometry, while the tetrahedral meshing technique is also examined to compare the two mesh types [413]. The use of hexahedral elements (HEX20) and tetrahedral elements (TET10) is shown in ***Figure 4.2***.

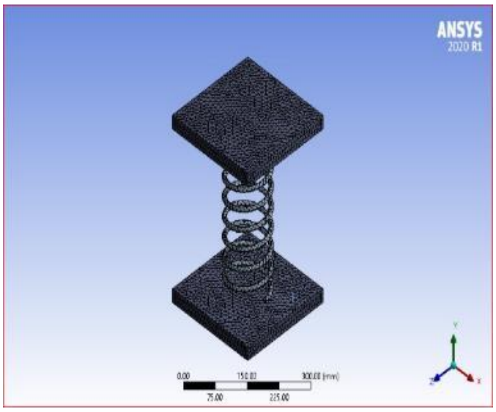
3D model *Refined mesh*





(A) (B)

Final mesh



(C)

Figure 4.2 (A) initial 3D model (B) meshing of the 3D and (C) final meshing FE

5.2 *Boundary Conditions*

ANSYS software was used to analyse the mechanical behaviours of the coil spring created as parts. Since this analysis is static, using ANSYS modelling, apply the boundary conditions, and ***Figure 4.3*** shows the boundary conditions applied on the upper ring of the coil spring while the lower part is treated as a fixed end**,** the rigid top surface is treated as the dynamic surface where the load is applied. The lower rigid surface is treated as a fixed support, and the load acts axially downwards on the top surface. A limited amount of force is applied downwards on the rigid top surface of the helical spring to carry out the static analysis. Engineers decide on a load based on their design calculations. The load is applied at a static position or when the coil spring is stationary. The static analysis does not have the actual varying force applied concerning the times; instead of having variable loads applied, the fixed inertia and time-varying loads are used as equivalent static loads. The static analysis resulted in damping and inertial effects, and different types of stress were obtained without applying any external forces.

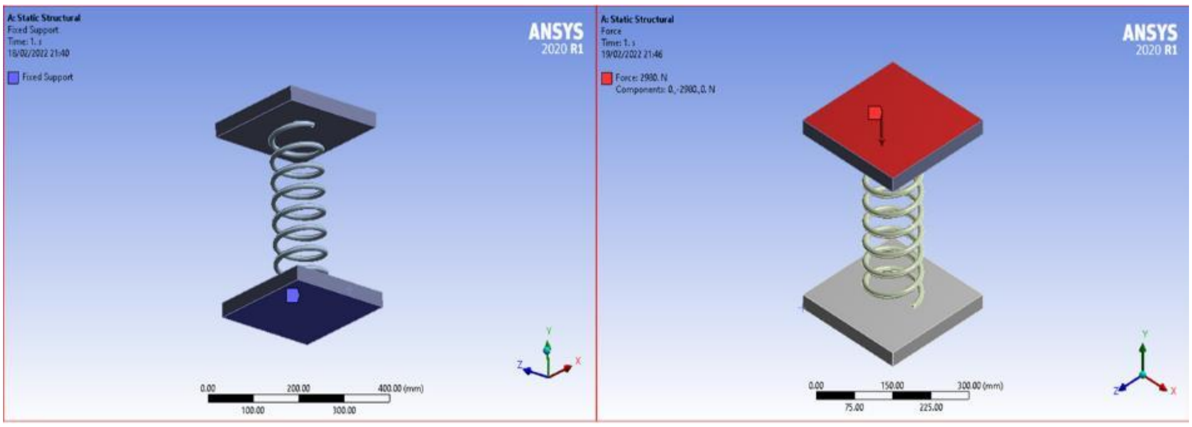


Figure 4.3 Fixed lower and upper ends of the coil spring where the force is applied

5.3 *Strain Life (SL) Approach*

The local SL technique is warranted when the loading history is characterised by randomness and where the influence of mean stress and load sequence effects is deemed significant. The methodology used in this study encompasses many methodologies aimed at transforming the loading history, geometry, and material properties (both monotonic and cyclic) into a prognostication of fatigue life [425]. The stress and strain inside the crucial zone are initially evaluated using the Rainflow cycle counting approach [426] to minimise the load-time history.

The subsequent procedure involves using the finite element technique to transform the diminished load-time history into a strain-time history and determine the stress and strain within the region experiencing significant stress. Subsequently, the fracture initiation procedures are used to forecast the FL. Fatigue damage accumulation is facilitated using the simple linear theory, as presented by Palmgren [427] and Miner [428]. Ultimately, the cumulative damage values of each cycle are aggregated until a predetermined threshold of critical damage is attained, which serves as the failure criterion. This research used the strain life analysis methodology to determine the FL. The characterization of the fatigue resistance of metals may be accomplished via the use of a strain-life curve. The mathematical expression of the link between the total strain amplitude ($\Delta\varepsilon/2$) and the number of reversals to failure ($2N_f$) is given by the Coffin Manson Model [425], as shown in **Eq 6**.

$$\varepsilon_a = \frac{\sigma_f}{E}\left(2N_f\right)^b + \varepsilon_f\left(2N_f\right)^c \qquad (6)$$

Where the meaning of each term is shown in ***Table 4.1.***

The absolute maximum principal strain method is used to combine component strains

$$\varepsilon_{AMP} = \varepsilon_3 \text{ if } \left|\varepsilon_3\right| > \left|\varepsilon_1\right| \text{Else } \varepsilon_{AMP} = \varepsilon_1 \qquad (7)$$

ε_{AMP} is the maximum principal strain, and ε_1 and ε_3 are the principal strains.

The Morrow model is used for mean stress (σ_m) corrections [425]:

$$\varepsilon_a = \left(\frac{\sigma_{f-}\sigma_m}{E}\right)\left(2N_f\right)^b + \left(2N_f\right)^c \quad (8)$$

The Smith-Watson Topper strain life model is mathematically expressed by **Eq 9.**

$$\sigma_{\max}\varepsilon_a = \frac{\sigma'_f}{E}\left(2N_f\right)^{2b} + \sigma'_f\,\varepsilon'_a\left(2N_f\right)^{b+c} \quad (9)$$

The three SL expressions involve various parameters. E represents the material modulus elasticity, σ_{max} denotes the true maximum stress, σ_m represents the mean stress, ε_a signifies the true strain amplitude, 2 N_f corresponds to the number of reversals to failure, σ_f' denotes the fatigue strength coefficient, *b* represents the fatigue strength exponent, ε_f' signifies the fatigue ductility coefficient, and *c* represents the fatigue ductility exponent.

6 DIGITAL TWINS METHOD

The DT method used includes five primary stages: (1) Current Real-Time (CRT) data collection, (2) IoT platform (ThingSpeak) for data aggregation, (3) Signal processing, (4) Finite Element Analysis (FEA) of the coil spring, and (5) Decision Making. ***Figure 4.4*** depicts the flow chart illustrating the methods used in this investigation.

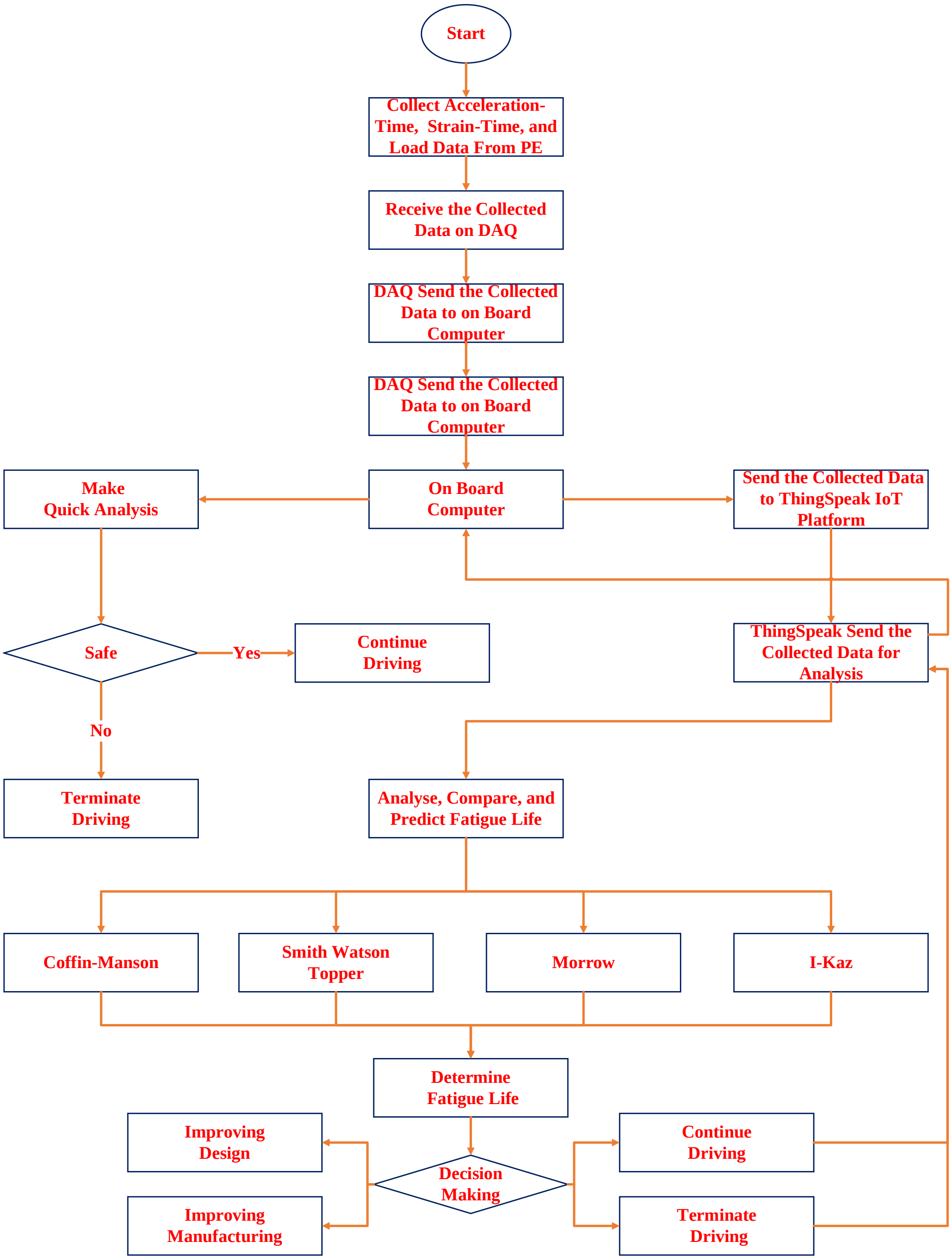


Figure 4.4 Flow process to create an actual and complete DT model

This research proposes four dimensions DT concept namely (Physical Entity (PE), Digital Entity (EE), Connection Entity (CE) between VE and PE, and Time) with high accuracy and efficiency, as shown in ***Figure 4.5***. The concept is validated through fatigue analysis and comparison with the latest literature methods of a coiled spring used in suspension systems in the automotive industry. Additionally, this concept is not limited to the automotive industry but is applicable to any industry, considering the different parameters for different applications with the same four dimensions mentioned. The proposed concept reports continuous CRT mechanical behaviours (force, displacement, stresses, and strains) acting on the system using intelligent sensors, as shown in ***Figure 4.5***. Sensors collect CRT data with any mechanical behaviour changes within the system; the Data is received by the ThingSpeak Internet of Things (IoT) platform, where the data are analysed and aggregated, then sent to software (MATLAB / ANSYS) to trigger a live simulation.

6.1 *Hardware and Data Collection*

For this research, a 2000 cc Peugeot 3008 car was selected for the case study. As shown in ***Figure 4.5,*** the car type under consideration is equipped with a front MacPherson strut suspension system, a widely used configuration across several vehicle models. A uniaxial accelerometer was affixed to the vehicle's lower control arm in proximity to the hub carrier, while a strain gauge was affixed to the coil spring. The location at which the strain gauge was affixed corresponds to the point of maximum stress, as estimated using FEA. ***Figure 4.5*** depicts the schematic design of the experimental configuration.

Table 4.3 Hardware components used in this study

Hardware and Equipment		
*Dell Laptop	*Peugeot 3008 car	*Microcontroller: ATMEGA 2560
*Load sensor	*2mm strain gauges	*Electric resistor using the Wheatstone bridge
*SoMat eDAQ	*2mm electric wires	*Voltage reader: HX711 amplifier for small voltage reading
*Wi-Fi module: DOIT ESP32 DEVKIT V1to transfer data to the server (ThingSpeak)		

A robust glue connected the accelerometer and strain gauge to the designated measurement locations to assure the stability of the sensors during data collection. The strain gauge used in the experiment had specified characteristics as shown in ***Table 4.3*** and as follows, including a gauge length of 2 mm, a gauge factor of 2.07 ± 1.0%, and a resistance of 120 X. The accelerometer was of the piezoelectric type, with a sensitivity of 1.02 mV/(m/s2), a measurement range of ±4900 m/s2, and a frequency range from 0.5 to 10 kHz. The data collection system was used to connect the accelerometer and strain gauge. This system captured the signals received by these sensors, which were then communicated to a laptop computer. Following this, the strain-time and acceleration-time histories were seen in real-time on the laptop computer and sent simultaneously to the ThingSpeak IoT platform, as shown in ***Figure 4.5.***

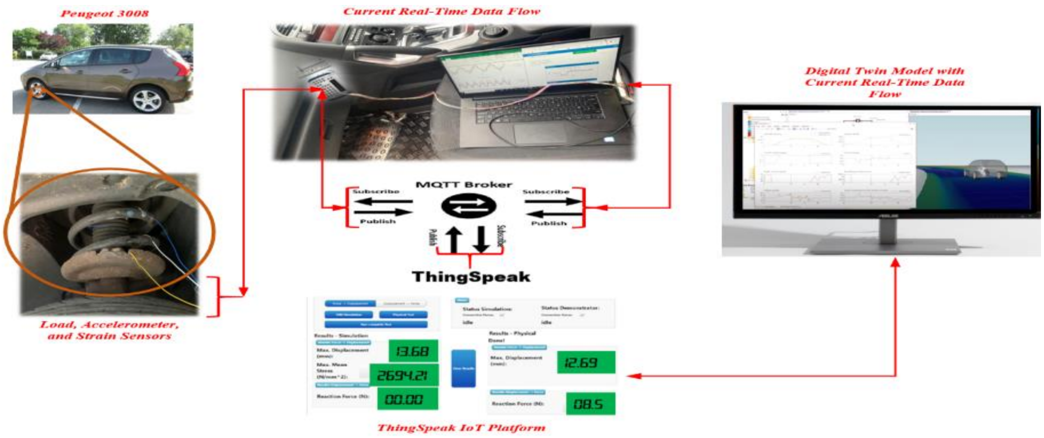


Figure 4.5 Process flow of the proposed Digital Twin Modelling concept

6.2 *ThingSpeak IoT platform for Data Aggregation*

The second stage is developing the IoT platform. This study selects the ThingSpeak IoT platform for its simplicity, cost-effectiveness, capabilities, and integration with MATLAB analysis. ThingSpeak is an IoT platform that facilitates collecting, visualising, analysing, and responding to current real-time data. The open-source programme was first released in 2010 by ioBridge[429]. It facilitates the development of IoT systems without establishing additional servers. Access to the ThingSpeak IoT is available from any browser. A dashboard was created to control, aggregate data, and connect the DTM and the PE. Public and private channels built under specific IDs write and read API keys. Each channel has up to 8 fields, representing input from one sensor, as shown in ***Figure 4.6***. The data collection process is facilitated using REST API or MQTT, as shown in ***Figure 4.5***.

The process of data analysis and visualisation is conducted via MATLAB analytics. Additionally, users can include numerous plugins that include Google Gauge and other customised visualisations and controls inside a private viewing setting. The primary component of ThingSpeak is its channel, which serves as a repository for data sent from diverse devices. Each channel can store a maximum of eight fields, including device location, URL, and other relevant information. The channel can be public, visible to other users, or private, requiring an API key for data access[429]. The private channel can be shared with a select group of users, as shown in ***Figure 4.6***. The communication mechanism used is based on the publish-subscribe paradigm. The entity responsible for generating and disseminating information is often called the publisher. The individual or entity expressing interest in obtaining the disseminated information is often called the subscriber.

Figure 4.6 IoT (Thingspeak) platform with a maximum of 8 fields (sensor)

6.3 *Signal Acquisition*

In this study, signal filtering was not conducted since the fatigue process relied on the peak and valley of the strain signals, with even minor amplitudes contributing to the fatigue calculations. The use of strain time history filtering has been shown to result in a reduction in computing time. However, it is important to note that this approach may provide major challenges in accurately predicting fatigue damage, as highlighted in previous research [430]. As stated by Ilic (2020), the sampling frequency for the load signals is recommended to exceed 400 Hz. However, as stated by [431], the typical frequency range for measuring vibration fatigue is between 10 and 1000 Hz.

Therefore, a sample frequency of 800 Hz was used to adequately capture the reactions generated by the road profiles across all frequencies. The fatigue study of automobile coil springs under time-varying loads becomes inherently difficult when a vehicle traverses a rough road since the stresses experienced are random and non-stationary. Most existing fatigue algorithms in the time domain rely on cycle-counting approaches and damage accumulation criteria [432]–[435]. In order to replicate a random process, it is necessary to use numerous time histories. Due to this rationale, it is necessary to use diverse road profiles to accurately anticipate the fatigue lifespan and assess the design of car coil springs. Subsequently, the Peugeot 3008 is operated on various road types, including highway, residential, rural, hill, and mixed, to gather random vibration data, as shown in ***Figure 4.7***.

Figure 4.7 Road profiles categorised according to the prevailing road conditions.

The highway road profile exhibited a more uniform road surface, leading to the anticipation of achieving a vehicle speed of 70 m/h. The rural road profile exhibited an irregular and coarse texture, with the anticipation of encountering some areas of pavement deterioration in the form of potholes. The residential road exhibited a notable presence of speed bumps, leading to anticipation of elevated vibration responses from vehicles traversing the road. Due to these constraints, the average speed of vehicles on rural and residential road profiles was around 25 m/h. The hill and mixed road profiles exhibit a notable presence of bends and curves, so introducing supplementary stresses on the automotive coil spring of the front MacPherson strut suspension system. The vehicle's velocity was around 50 m/h for the hill and mixed road profiles. Notwithstanding the fluctuations in vehicle velocity, the models included authentic vehicle vibrations generated by road stimuli using the corresponding data.

6.4 *Description of Signal Theory and Behaviour*

The investigation used a variable amplitude (VA) strain loading as the input signal, which was sampled at a frequency of 800 Hz for a record duration of 80 seconds. Consequently, a time series including 64,000 data points was generated. Including this suspension system component was deemed significant and viable for anticipating the onset of cracks to prevent fatigue failure by timely removal of the component from service, as opposed to subjecting it to fatigue life analysis using crack development methodologies [436]. Applying the crack inspection procedure to cheap components manufactured in large quantities is often deemed unsuitable due to the associated rise in cost [437]. The fundamental basis of the strain-life strategy is in the CM connection, which is mathematically expressed as **Eq 6.**

The practical implementation of fatigue service loading in real-world data shows that the mean stress significantly influences the fatigue characteristics of metallic materials. The strain-life technique generally employs two mean-stress effect models, namely the Morrow (Mo) and the Smith-Watson-Topper (SWT) SL models. The mathematical representation of Mo's strain-life model is given by **Eq 8**, and the mathematical expression for the SWT SL model is given by **Eq 9**, as stated in reference [438]. The Mo SL model exhibits significance when applied to smaller plastic strain magnitudes, whereas its impact diminishes as plastic strains increase. The

SWT technique is advised for estimating the FL of loading sequences that are mostly subjected to tensile stresses. When the pressure is mostly compressive, the Morrow technique may be used for more precise lifespan estimations [439]. The fatigue damage from each cycle is determined by referencing material life curves, namely stress-life (S-N) or SL(ε-N) curves. The N_f value for each cycle may be derived from **Eqs 6 to 9** for all three models. Additionally, the fatigue damage value, D, for a single cycle can be computed by **Eq 10.**

$$D = \left(\frac{1}{N_f} \right) \tag{10}$$

The cumulative damage inflicted by N cycles is often known as the Palmgren-Miner rule, where the accumulated damage, ΣD, is mathematically represented by **Eq 11.**

$$\sum D = \sum \frac{N_i}{N_f} \tag{11}$$

In this context, N_i represents the number of cycles occurring within a certain stress range and mean, whereas N_f denotes the number of cycles leading to failure within the same stress range and mean. A fatigue cycle may be described as a closed loop on a cyclic stress-strain curve. Fatigue Damage (FD) mostly correlates with cyclic amplitudes, or ranges, rather than peak values. The measured signal typically includes amplitude, frequency, phase, and energy variations. The primary goal of time series analysis is to ascertain the statistical properties of the underlying function by altering a sequence of discrete numerical values [440]. In scenarios involving fatigue analysis, it is typical to encounter nonstationary signals, whereby the statistical parameter values of a signal are contingent upon the measurement time. The statistical values of global signals in the context of nonstationary signals are contingent upon the specific moment the measurements are taken [441].

The use of global signal statistics is a typical practise in the classification of random signals. The statistical characteristics usually employed for this purpose are the Mean Value, Standard Deviation value, Root Mean Square (RMS) value, Skewness, and Kurtosis. The statistical analysis findings may vary depending on the kind of road since the fatigue signal patterns exhibit variations across various road types. This study uses the I-kaz technique as a novel statistical approach with the DT Models to comprehensively analyse the data for fatigue prediction compared with the traditional methods (Coffin Manson (CoM), M, and SWT). Based on its kurtosis, the I-kaz approach offers a three-dimensional graphical depiction of the frequency distribution of a recorded signal. The time domain signal has been partitioned into three distinct frequency bands: The X-axis represents the Low Frequency (LF) range of 10-20 kHz, the Y-axis represents the High Frequency (HF) range of 20-50 kHz, and the Z-axis represents the Very High Frequency (VHF) region of 50-100 kHz. The I-kaz coefficient is used to quantify the dispersion of data distribution by determining the distance between each data point and the signal centroid[442].

The I-kaz coefficient is formally defined in **Eq 12**

$$Z^{\infty} = \frac{1}{N}\sqrt{K_L S^4 L + K_H S^4 H + K_V S^4 V} \tag{12}$$

In this context, N represents the quantity of data points. The K_L, K_H, and K_V denote the kurtosis values of the signal within the LF, HF, and VHF ranges, respectively. Similarly, SL, SH, and SV represent the standard deviation of the signal within the LF, HF, and VF ranges, respectively. The mathematical definition of the RMS and Standard Deviation (*StD*) for a set of n data points is expressed in units of seconds for a roadway in **Eq 13.**

$$RMS = \sqrt{\frac{1}{n\sum_{j=1}^{n} X_j^2}} \tag{13}$$

$$SD = \left\{ \frac{1}{n} \sum_{j=1}^{n} \left(X_j - \bar{X} \right) \right\}^{\frac{1}{2}} \tag{14}$$

Kurtosis, as the fourth statistical moment of a signal, is a global statistical measure that exhibits high sensitivity to the presence of sharp peaks or spikes in the data. Higher kurtosis values suggest outliers that are more severe than what would be expected in a normal distribution. Kurtosis is used in engineering applications to identify fault symptoms because of its heightened responsiveness to large amplitude events. The Kurtosis value is defined mathematically in **Eq 14**

$$K = \frac{1}{n\left(RMS\right)^4} \sum_{j=1}^{n} \left(X_j - \bar{X} \right)^4 \tag{15}$$

$$K = \frac{1}{n\left(SD\right)^4} \sum_{j=1}^{n} \left(X_j - \bar{X} \right)^4 \tag{16}$$

7 EXPERIMENTAL METHOD RESULTS

7.1 *Relaxation Test*

The relaxation test results are shown in ***Figure 4.8.*** The diagram illustrates the relationship between the spring constant, denoted as (*k*), and the number of load cycles. It should be noted that the parameter k remains constant under cyclic loading conditions, except for the 200°C for 5 minutes group, where a gradual reduction in *k* is noticed. However, after 700,000 cycles, a stable value of *k* is achieved. In order to enhance the performance of a spring during the spring season, it is crucial to understand the impact of heat treatment on the coefficient of spring stiffness (*k* value). The behaviour shown by the group subjected to a temperature of 200°C for 10 minutes may be elucidated by considering the occurrence of a relaxation phenomenon inside the material due to cyclic loading. The observed phenomenon may be likened to cyclic softening when the stress decreases as the number of cycles increases. This behaviour has been shown in some materials during cyclic plasticity testing, such as SAE steel, as documented in reference [437].

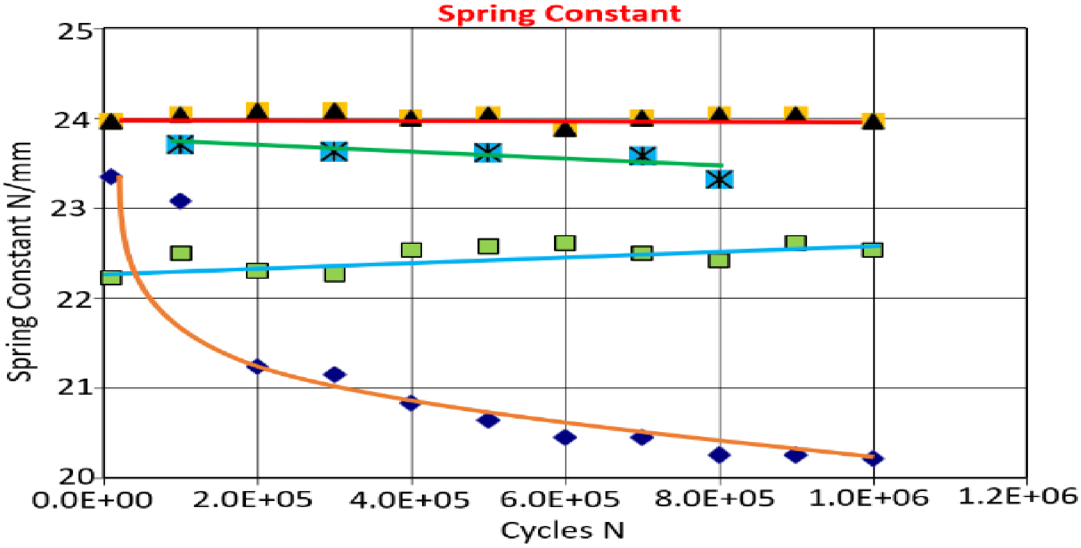


Figure 4.8 Spring constant variation for the number of load cycles

7.2 *Fatigue test*

The fatigue curves are established for each spring or for each group of springs. The findings are shown in ***Figure 4.9***, whereby the arrows inside the plot indicate instances when the test was terminated prior to the occurrence of spring failure. As shown in the provided figure, it can be seen that the group exhibiting the highest fatigue limit τ_e was subjected to a temperature of 500°C for 25 minutes, resulting in an estimated value of τ_e = 160 MPa. The experimental condition, characterised by a temperature of 200°C and a duration of 10 minutes, had the lowest fatigue limit, measured at 120 MPa. Furthermore, this condition demonstrated the most variability in the spring constant, as seen during the relaxation tests. The experimental condition with a temperature of 400°C and a duration of 20 minutes exhibited an intermediate fatigue limit, denoted as τ_e, with a value of 148 MPa. Similarly, the experimental group subjected to a temperature of 300°C for 15 minutes exhibited a fatigue limit of 140 MPa.

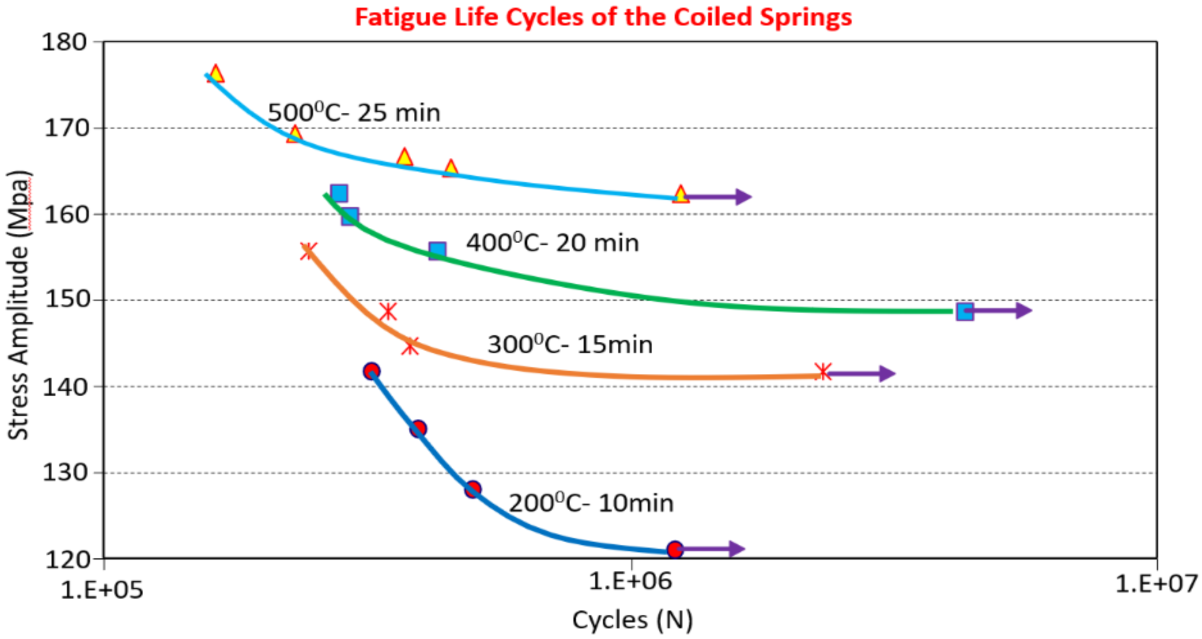


Figure 4.9 Fatigue curves of the springs under variable stress amplitude load

Since no cracks were noticeable on the spring and the resultant spring stiffness was nearly the same, the spring sustained 8.9*10^6 cycles during the accelerated block load cycle test without any failure, as shown in ***Table 4.4.***

Table 4.4 Load, deformation, and lifecycles resulting from the experimental method

EXPERIMENTAL RESULTS			
Load (KN)	0.66 (Resembles Highway AVG)	0.8 (Resembles Residential AVG)	0.98 (Resembles Rural AVG)
Deformation(mm)	36	43	49
Stress (Mpa)	155.7	168	214.3
Lifecycles	5.4*10^7	9.1*10^6	4.6*10^6
AVG-load (KN)	0.8		
AVG-lifecycles	8.9*10^6		

8 **COMPUTATIONAL METHOD RESULTS**

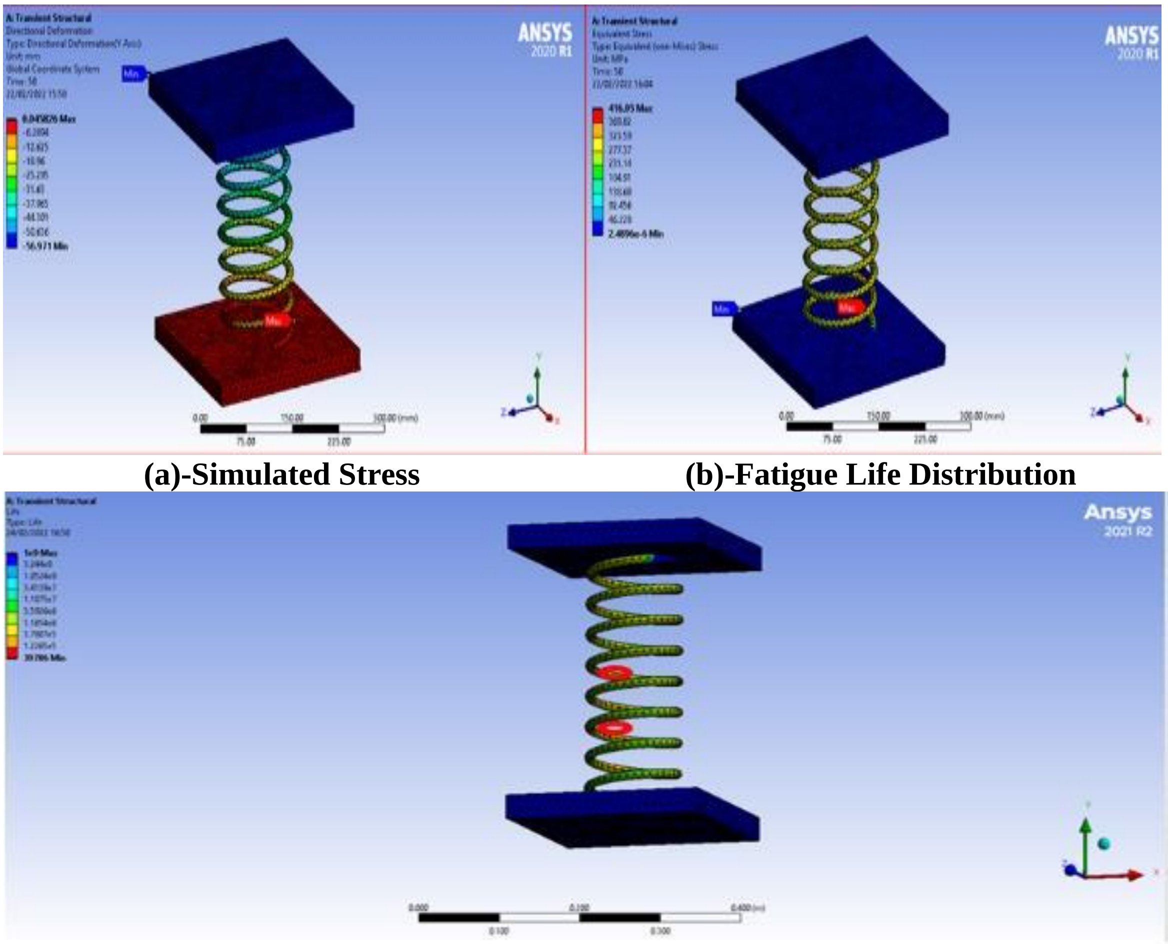
The comparison in ***Table 4.5*** demonstrates a minimal discrepancy between the von Mises, Tresca, and maximum primary stress values obtained from hexahedral and tetrahedral mesh configurations. A comparative analysis was conducted on the structural flaws. The findings obtained from HEX20 elements had a higher accuracy level than TET10 elements, indicating that elements of approximately equal size were more effective in predicting the outcomes. The structural defect exhibits a significant disparity due to the increased size of the HEX20 element. The structural error caused is significantly affected by the bigger size of the HEX20 element.

The convergence of stress mostly determines the selection of mesh type and size. The findings in ***Table 4.5***, which correspond to the crucial region depicted in ***Figure 4.11***, indicate that the HEX20 element with a sweep mesh size of 0.02 m and a face mesh size of 0.008 m exhibits the most favourable combination of structural error and CPU time. The decision not to implement a smaller HEX20 mesh size is primarily driven by the significant increase in CPU time, storage capacity, and memory demand despite its potential to reduce structural error. Therefore, the fatigue life study employs a HEX20 mesh with an element size of 0.02 m and a face mesh size of 0.008 m.

Table 4.5 Variation of mesh size and stress results for Hex20 and Tet10 mesh

Size (mm)	Total Nodes	Total Elements	Stress (MPa			Structural Error ($\times 10^{-6}$)
			Von Mises	Tresca	Max Principal	
HEX20 Mesh						
0.008	160,200	40,900	1578	2087	1154.24	259.137
0.02	83,400	18,396	1579.3	2087.9	1152.47	261.972
0.03	25,990	9,600	1621.9	2137	1174.3	444.2
0.011	15,200	8,589	1616.1	2130.3	1170.59	524.9
0.020	14,740	9,376	1619.8	2134.6	1170.11	640.8
TET10 Mesh						
0.007	94,783	68,986	3731.8	4900.4	200.27	400
0.008	78,876	7,863	3875.7	4100.8	2100.6	300

The linear stress analysis was conducted using finite element analysis ANSYS software to ascertain the outcomes of stress and strain states. The maximal primary stress outcome is used in the study of tiredness. The distribution of maximum primary stress resulting from the linear static analysis is shown in ***Figure 4.10 (a).*** The simulation findings revealed that a maximum primary stress of 1864 MPa was observed at the crucial point. The Von Mises and Tresca criteria were used to calculate the equivalent stress at the critical location, resulting in 1621.9 MPa and 2137 MPa, respectively, as shown in ***Table 4.5***. These stress values indicate that the spring does not experience structural failure, as they are significantly lower than the yield strength of SAE 9254, which is 2270 MPa, as shown in ***Table 4.1***. The determination of FL becomes significance in this context. Hence, the operational lifespan of the spring may be determined. Furthermore, it is evident from the stress analysis findings that a significant change occurs in the orientation of the highest primary stress at the extremities of the spring after a full revolution of the coil. This phenomenon may be attributed to the contact definition, which posits that the first turn of the coil consistently contacts the surface geometry used to apply load on the spring.



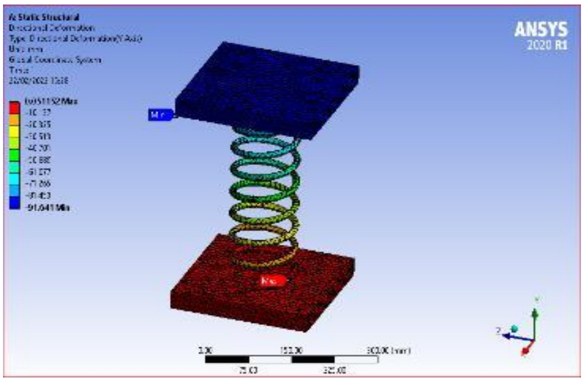
(a)-Simulated Stress **(b)-Fatigue Life Distribution**

(c)-Fatigue Damage Distribution

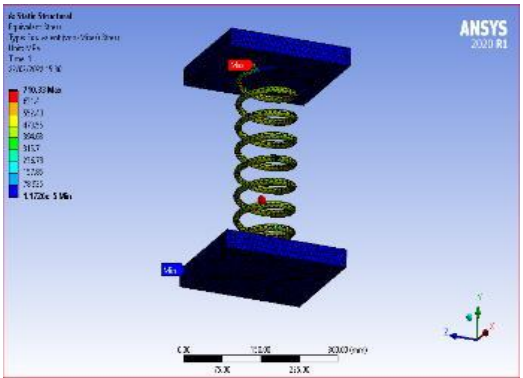
Figure 4.10 Abs max principal stress with FL and FD for a triangular wave at 4 Hz

The examination of fatigue is mostly centred on the outcomes obtained at the key area and its surrounding vicinity, as seen in ***Figure 4.10***. The selection of this location is based on the experimental findings presented by [42], [436], which demonstrate that FF in coil springs occurs mostly in the active coils located distant from the inactive coil that serves as the spring's seat. Contours in ***Figure 4.10 b and c*** depict the representation of life and reported damage. The spring will not experience FF throughout its designated lifespan of 4×10^{5} cycles at the key site, as shown by both time histories [46]. The figures denoted as ***Figures 4.10, 4.11, and 4.12*** show the highest recorded levels of damage, as indicated by circular markers. The observed phenomenon may be attributed to a geometric modelling discontinuity resulting from the variable pitch of the coil. Abrupt changes in the orientation of the coil result in an elevated area of mechanical strain. Due to the considerable distance between these sites and the crucial area, their impact on the findings provided at the key site is deemed insignificant, hence warranting their exclusion from the fatigue study.

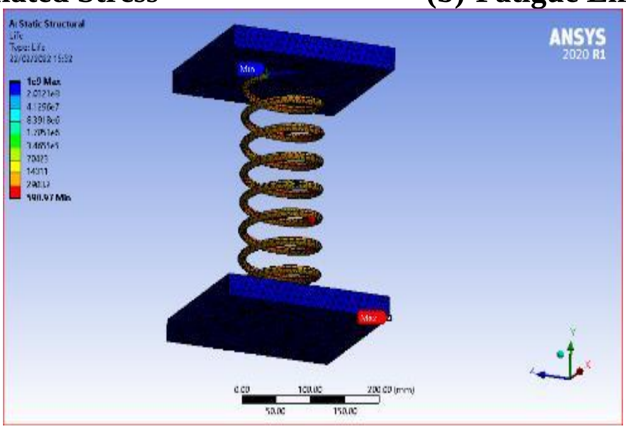
Figure 4.11 shows sudden changes in the stresses throughout the spring from top to middle; however, the top result is likely obtained from the surface contact definition with the spring. In order to take into consideration the effects of mean stress during the process of estimating FL, researchers have turned to not one but two separate models: Mo and SWT models. The life estimate plot derived using the SWT model can be found shown in Figure 5. In environments with the highest levels of stress, the average number of life cycles of the coil spring is around 4.24*10^6. Using the Mo model, we calculated that the predicted FL SWT is 5*10^5.



(a)-Simulated Stress

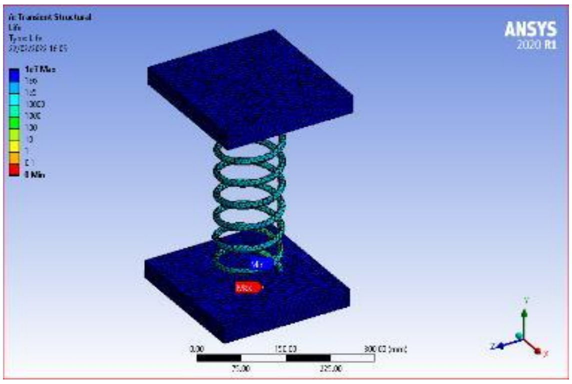


(b)-Fatigue Life Distribution

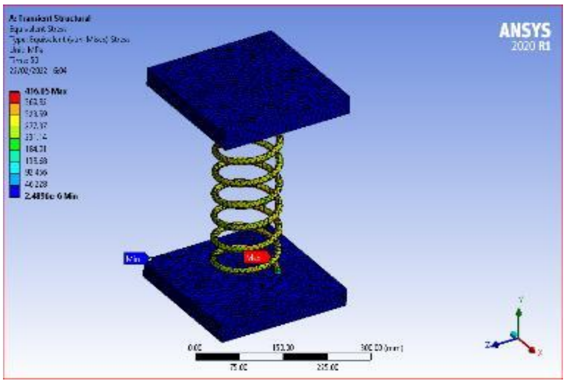


(c)-Fatigue Damage Distribution

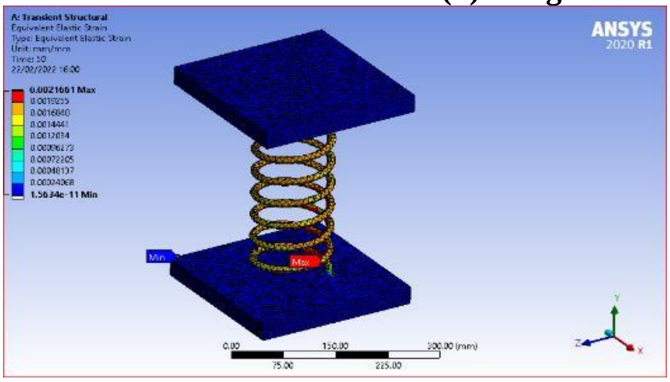
*Figure 4.11 Fatigue Life Distribution of 4.24*10^6 using Morrow's model.*



(a)-Simulated Stress



(b)-Fatigue Life Distribution



(c)-Fatigue Damage Distribution

*Figure 4.12 Fatigue Life Distribution of 5*10^5 SWT's model.*

It is essential to show the critical location for the fatigue analysis because it will focus on the critical places and their area. In the experimental work, selected critical locations that impacted the failure of the spring in the active coils, which were far from the inactive coils; ***Figures 4.11 and 4.12*** show that might be the exact scenario; therefore, in this case, the system withstands its design life cycles of 3.6*10^6. ***Figures 4.10***, ***4.11 and 4.12*** show that the maximum damage at the critical locations marked with red circles is likely because of the change of directions of the coil, and these are the areas where the modelling discontinuity occurs; therefore, the critical locations marked with red circles experience the highest stress across the spring. The observed locations are marked with red circles far from the critical regions used for fatigue analysis.

Table 4.6 Load, deformation, and lifecycles resulting from the computational method

COMPUTATIONAL				
Characteristics	**Absolute**	**CM**	**Morrow**	**SWT**
Load (KN)	0.66	0.74	0.8	0.98
Deformation(mm)	46.9	49.63	57	70.2
Stress (Mpa)	220	374	243.7	320
Lifecycles	4.24*10^6	3.33*10^6	5*10^5	2*10^5
AVG-load (KN)	0.8			
AVG-lifecycles	***8.6 *10^6***			

9 DIGITAL TWINS METHOD RESULTS

9.1 *Time Domain Signal Analysis*

Figures 4.13 **and *4.14* from A to E** The acceleration-time histories and microstrain time histories for five road profiles were obtained. A comprehensive set of 64,000 data points was collected over 80 seconds for each road profile. Crest Factor (CF) is a waveform parameter; CF is the waveform's peak amplitude divided by the waveform's RMS value, such as alternating current or sound, showing the ratio of peak values to the effective value. In other words, CF indicates how extreme the peaks are in a waveform. CF of 1 indicates no peaks, such as a direct current or a square wave. Higher CF indicate peaks; for example, sound waves tend to have high cf. The CF, RMS, and kurtosis values were computed to extract relevant information on the acceleration-time and microstrain-time histories' characteristics. The statistical parameters obtained from the acceleration-time histories are shown in ***Table 4.7***.

The CF measures the maximum peak in a stochastic time-varying signal. It is observed that the campus road profile exhibits the greatest CF because of the numerous occurrences of bends and curves, which impose significant consequences on the vehicle's suspension system. The impact of the crest factor on the vertical vibrations of the vehicle and the FL of the automobile coil spring is noteworthy. A higher CF may increase FD, substantially diminishing the automotive component's fatigue life[443]. Nevertheless, it should be noted that the CF does not substantially influence the vehicle ride quality. This is because the high peak value is often linked to a specific occurrence, while the vehicle ride quality encompasses the general comfort experienced by the passengers over a certain time frame [443].

The data in ***Table 4.6*** shows that the acceleration-time history of the mixed road profile exhibits the greatest CF, measuring 84.32. This result aligns with expectations since the vehicle in question was traversing a speed bump at a notably high velocity at the 63-second mark. Therefore, it can be inferred that the characteristics of random time-varying signals are modified not only by the roughness of the road surface but also by the conduct of the driver [443]. The acceleration-time history of the mixed road profile exhibits an exceptionally high CF value; however, it is noteworthy that the RMS value is the lowest, measuring at 0.122. A system with a high RMS value signifies a greater energy content, whereas a high kurtosis value suggests that the signal's random pattern plays a more significant role in contributing to FD.

Consequently, the evaluation of the FL of the automobile coil spring mostly relied on the assessment of the RMS value of the microstrain-time histories. ***Figure 4.14*** displays the microstrain-time histories acquired for several road profiles, including highway, rural, residential, hill, and university roads. The statistical parameters derived from these microstrain-time histories are reported in ***Tables 4.6 and 4.7***. The microstrain-time history of the rural road profile exhibits the greatest RMS value, as seen in ***Table 4.7.*** The microstrain-time history in question exhibits the highest kurtosis value of 5.642 among the other analysed microstrain-time histories. However, it is worth noting that the difference in kurtosis values between this particular history and the others is not statistically significant. Typically, a high kurtosis value suggests the presence of non-stationary behaviour in the strain-time histories [444].

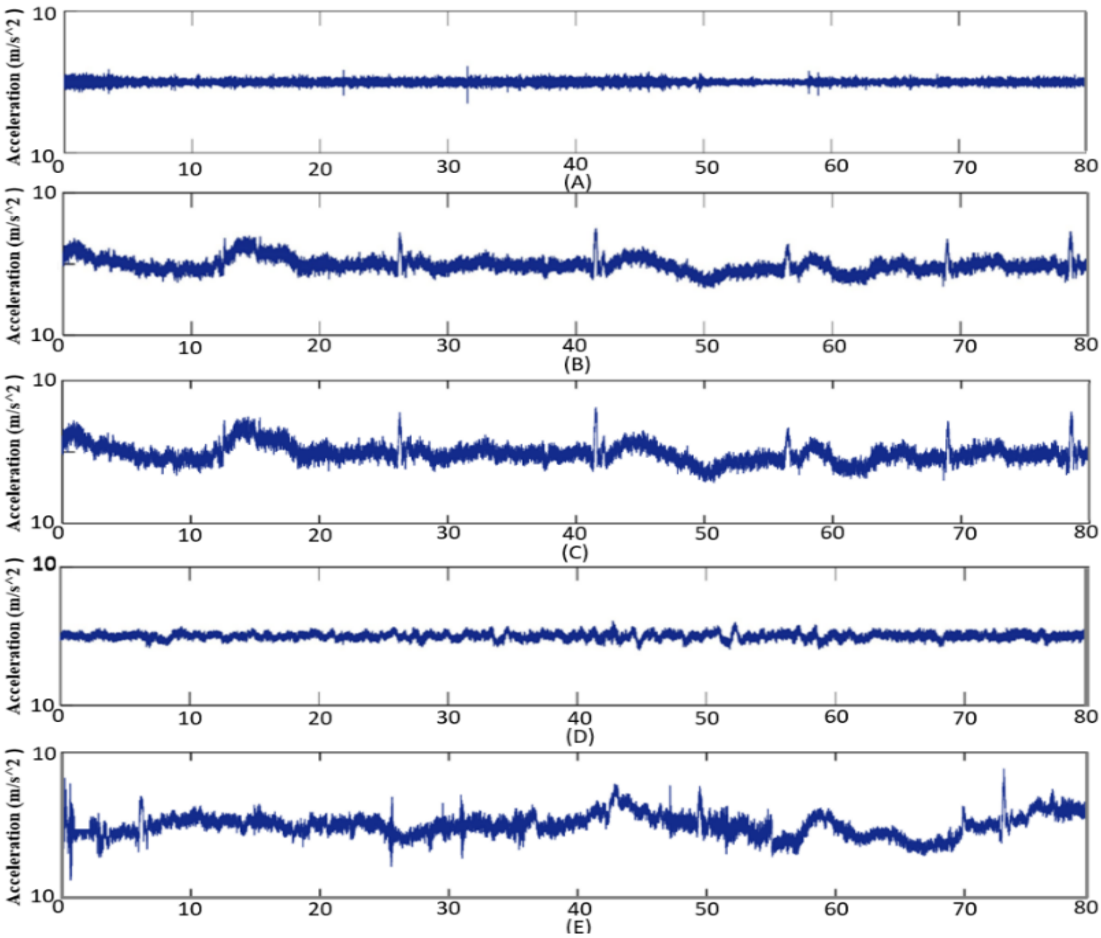


Figure 4.13 Measured acceleration-time history (a)highway, (b) residential, and (c) rural.

The time domain signal plots were used to analyse the data gathered about strain loading. After obtaining the original time domain signal for each kind of road, the time history can be examined, as shown in ***Figures 4.13 and 4.14***. According to the findings, the total strain amplitude or strain range for the highway, residential, rural, hill and mixed road are shown in ***Tables 4.6 and 4.7***. The spikiness of the fatigue statistics may be attributable, in part, to the various road hazards, such as potholes and bumps. This can be noticed at every light; for instance, the spikiness was noted at the 48-second mark on the highway. At the same time, the phenomena of spikiness also occur at a high amplitude compared to the other signal amplitudes.

The analysis of ***Figures 4.13 and 4.14*** reveals that the damage-surface road exhibits a considerable increase in spikiness between the 24th and 71st seconds. This phenomenon may be attributed to transmitting a significant amount of amplitude loading to the coil spring as the vehicle traverses the road surface. The data was examined to assess fatigue damage and determine the coefficient based on kurtosis.

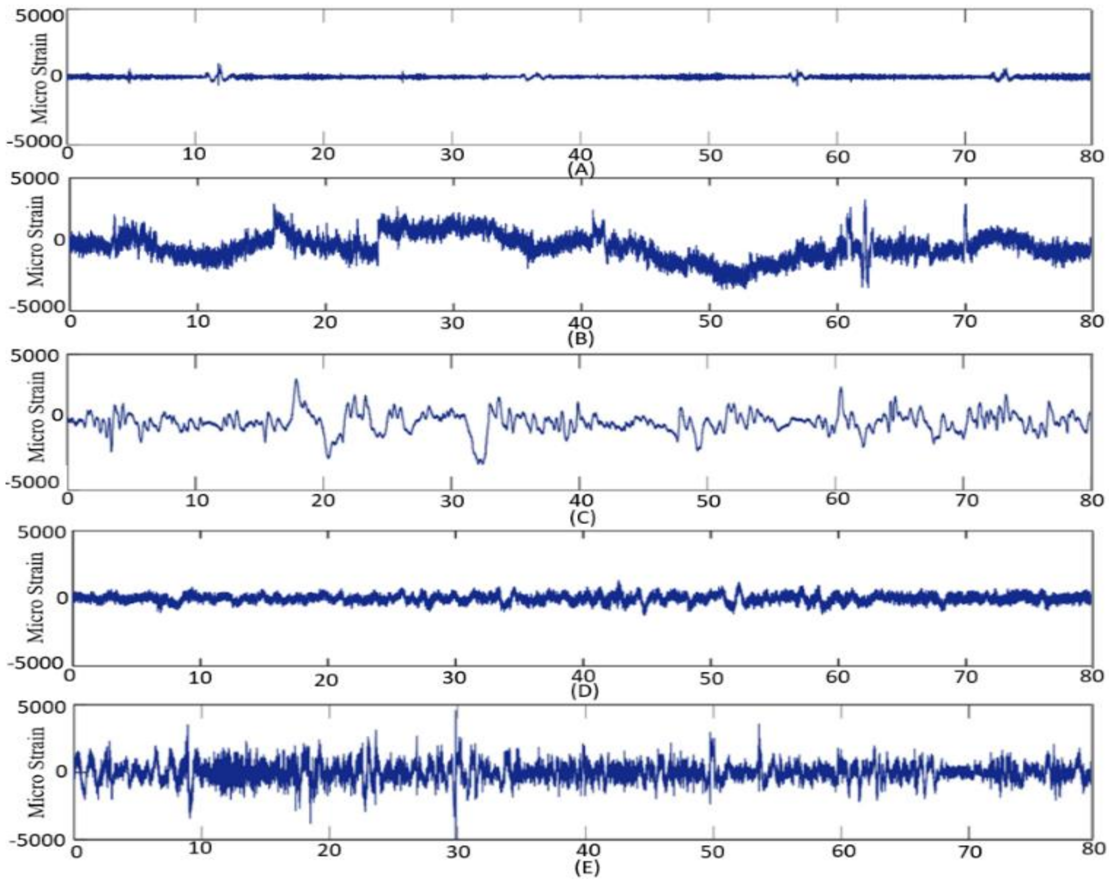


Figure 4.14 Measured strain-time history ((a)highway, (b) residential, and (c) rural.)

9.2 *Fatigue Damage (FD) analysis*

The FD data obtained from the analysis conducted are shown in ***Table 4.6*****.** This study was conducted using the CoM, Mo, and SWT methodologies. In terms of FD incurred by different road types, it is seen that damage-surface roads exhibit the greatest levels of FD, followed by rural roads. The CoM, Mo, and SWT approaches indicate that the roadway incurs the least amount of FD. The FD values may be found in ***Table 4.6.*** The road with the shortest FL incurred the most damage despite the automobile travelling at a low speed compared to other roads. This may be attributed to the road surface's poor physical state, characterised by potholes and an uneven surface.

The distances between each pothole are quite short, and the depth of the potholes varies inconsistently. The high strain is seen when the vehicle traverses the damaged surface road despite its 50 m/h velocity. The results were consistent with the time domain signal shown in ***Figures 4.13 and 4.14***, indicating that the road with a damaged surface exhibited the largest range of strain amplitude compared to the other roads. A mixed road travelled at a 70 m/h speed is associated with decreased FD compared to a motorway driven at the same speed. Driving on a country residential road at a speed of 30 m/h results in less tiredness damage than driving on a motorway at the same speed. Several irregularities, such as bumps and potholes, are present throughout the rural route. The variables above substantially burden the coil spring as the vehicle traverses over it. In terms of highways, smooth surfaces result in minimal displacement of the coil spring compared to rough and rural roads. This phenomenon is directly linked to FD, as indicated in ***Table 4.6.*** Specifically, highways exhibit the lowest fatigue values for CM, Mo, and SWT approaches, measuring at 0.00059x 10^{-3}, 0.00063x 10^{-3}, 0.0004, and 0.0163x $10^{-3,}$ respectively.

9.3 *I-Kaz Coefficient*

The I-Kaz coefficient, denoted as Z^{∞} in **Eq 12**, is calculated to quantify the extent of scattering in the I-Kaz display. Upon doing the study using MATLAB®, the I-Kaz Coefficient, denoted as Z^{∞}, was acquired for each route. The results were afterwards shown in **Figure 4.15.** According to the data shown in **Figure 4.15**, it can be seen that the damage-surface road has the largest Z^{∞} value, measuring 0.547 for the mixed road. The rural road with a $Z\infty$ value of 0.496 follows this.

Conversely, the highway displays the lowest Z^{∞} value, amounting to 0.163. Furthermore, it is evident from the I-Kaz display that the scattering space of the frequency distribution increases proportionally as the value of Z^{∞} becomes larger. This implies that when the frequency of the fatigue signal increases, the value of Z^{∞} also increases. This is the primary cause of the most significant dispersion of damage on the road surface. To conduct a comparison analysis, it is evident from the presented data in ***Table 4.6*** that larger Z values$^{\infty}$ correspond to higher levels of FD.

Table 4.6 presents the kurtosis and standard deviation values for highway, residential, rural, hill, and mixed roads. The statistical data were produced using the Glyphworks programme [445]. According to the data in ***Table 4.6,*** the kurtosis value for mixed roads was greater than the kurtosis value for damaged roads. This phenomenon may be attributed to the observations made in ***Figure 4.15***, where it is evident that the rural and mixed road exhibited a higher degree of spikiness or transience compared to the damaged road, although having a smaller strain amplitude. This phenomenon may be attributed to the fact that kurtosis exhibits a high degree of sensitivity towards the presence of extreme values in the dataset. The fatigue damage of the coil spring was calculated using the GlyphWorks® programme, while the analysis to derive the I-Kaz coefficient and three-dimensional graphical representations of the collected fatigue signal from the road test was conducted using MATLAB® software, as shown in ***Figure 4.15***.

Table 4.7 FD for each road based on CM, Mo, SWT, and I-Kaz

Road Type	Fatigue Damage			
	CM	Morrow	SWT	I-Kaz
Highway (70 m/h)	0.0059	0.0063	0.004	0.163
Residential (30 m/h)	0.006	0.0083	0.006	0.289
Rural (25 m/h)	0.285	0.465	0.316	0.946
Hill (50 m/h)	0.693	0.069	0.471	0.342
Mixed (5 -70 m/h)	0.932	0.570	0.864	0.547

Table 4.8 Statistical parameters from acceleration and strain time history

Parameters	Highway	Residential	Rural	Hill	Mixed
Statistical Parameters from Acceleration-Time History for Different Road Profiles					
Mean (m/s^2)	0.006	0.005	0.044	0.082	0.142
RMS (m/s^2)	0.866	0.584	0.448	0.332	0.122
Kurtosis (m/s^2)	3.232	4.842	4.462	3.432	5.231
Standard Deviation	60.462	82.446	94.222	89.653	99.623
Crest Factor	05.45	08.22	11.84	07.37	84.32
Statistical Parameters from Strain-Time History for Different Road Profiles					
Mean (m/s^2)	0.019	0.015	0.044	0.132	0.252
RMS (m/s^2)	210.95	509.26	748.91	310.23	832.58
Kurtosis (m/s^2)	3.316	4.332	5.732	3.946	5.642
Standard Deviation	48.645	63.247	71.723	61.278	82.662
Crest Factor	7.34	11.35	23.34	9.23	6.45

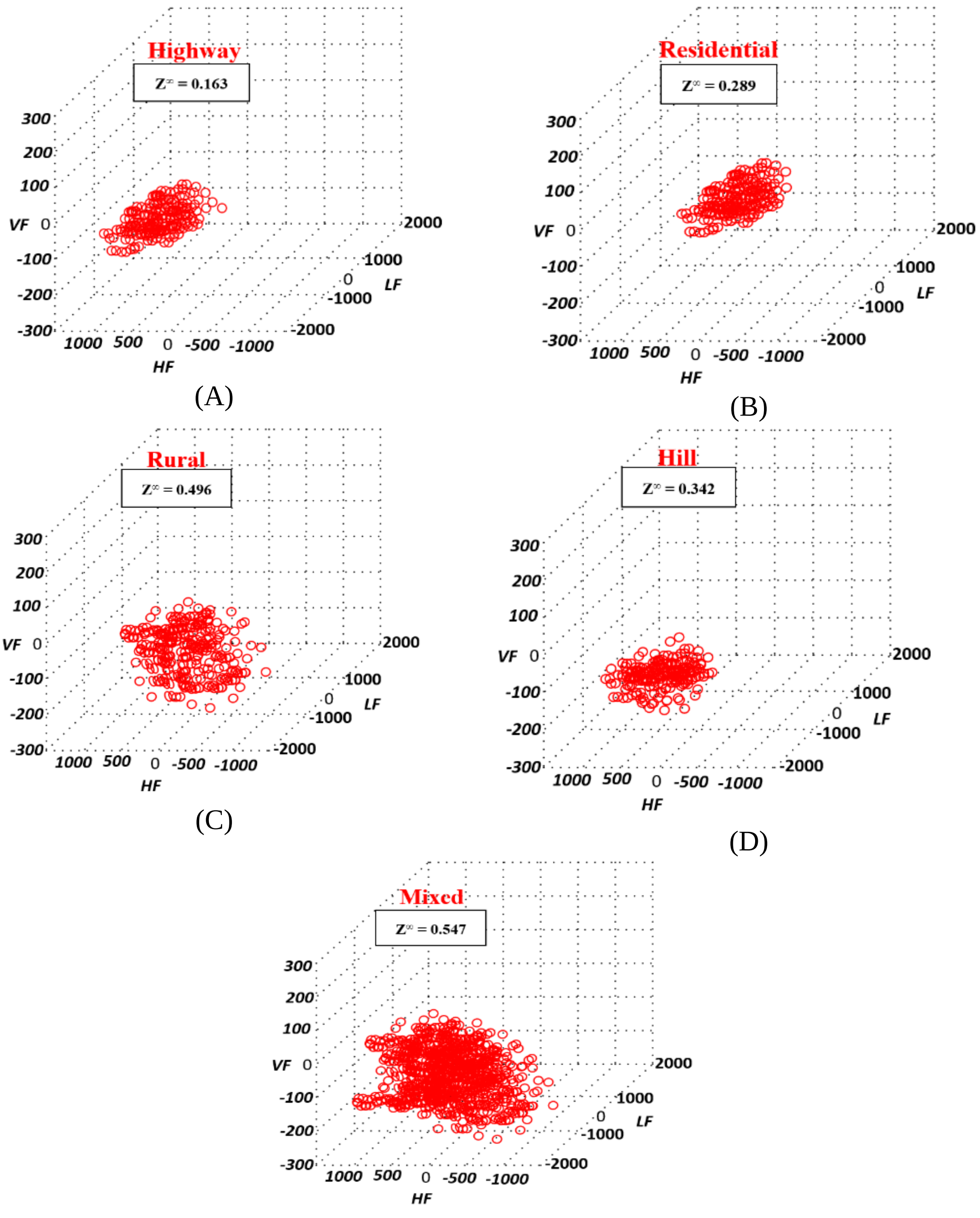
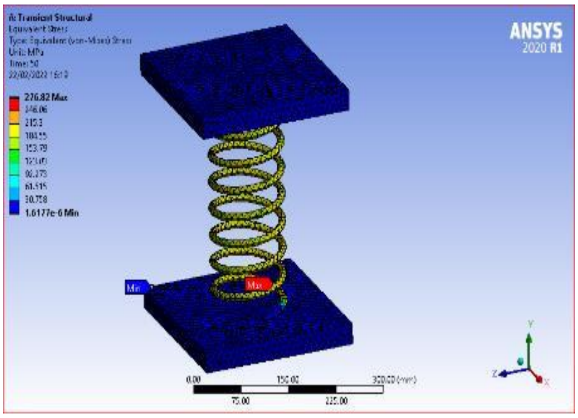


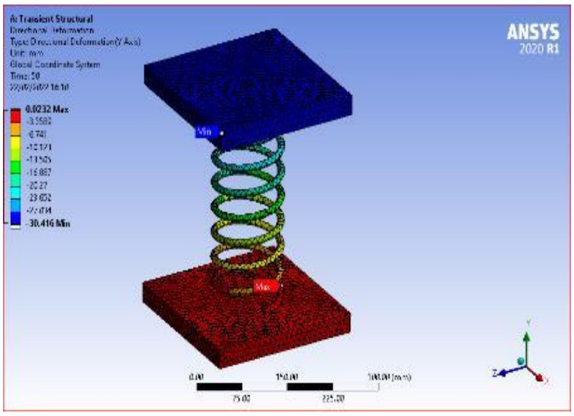
Figure 4.15 I-Kaz results and the I-Kaz coefficients Z^{∞} for five road types

9.4 *FEA-Based Digital Twin*

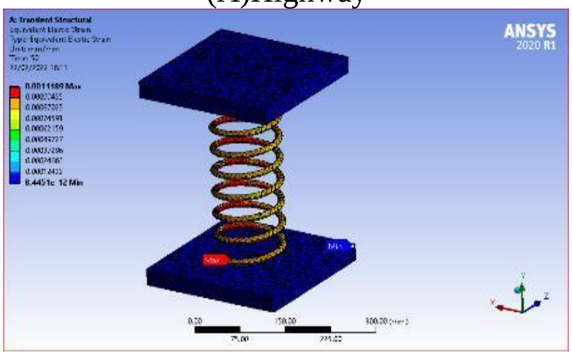
At this point, we are in a position where we can obtain the capacity to capture a wide variety of data variables and features, including load and deformation. Consequently, we can determine the exact stresses placed on the springs at the current time. As a consequence, the transmission of RT data to different stakeholders such as manufacturers and designers, is made possible by the sensors attached to the spring. Because of this, it is possible to carry out FEA using the most recent and unique real-time data stream specific to the individual user and the current instant. ***Figure 4.16*** presents the current DT modelling that is based on FEA. In addition, a summary of the real-time data acquired from the sensors while operating the vehicle on various road surfaces may be found in ***Table 4.8*****.** In addition, the fatigue life cycles that were calculated using the currently available real-time data may be seen in ***Table 4.8.*** The experiment was repeated, but this time, wireless sensors rather than cable sensors were used to transfer data to a laptop inside the car. One may see a few anomalies in the results, which can be attributed to the accuracy and time delay of the connected sensors. These inconsistencies can be detected.



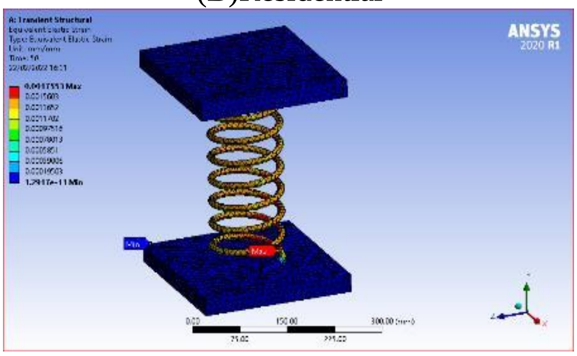
(A)Highway



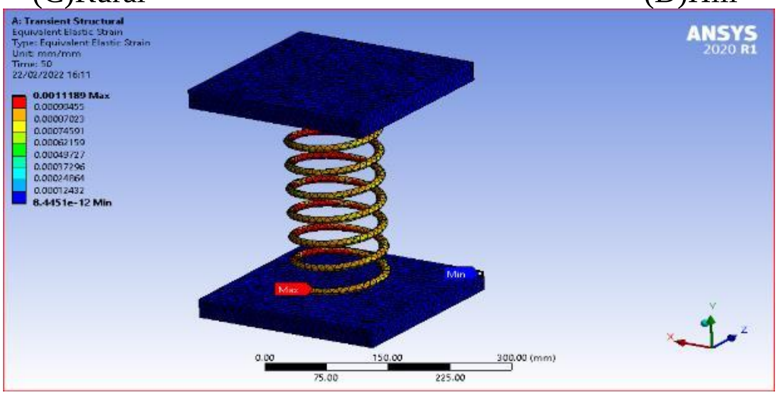
(B)Residential



(C)Rural



(D)Hill



(E)Mixed

Figure 4.16 FD results from FEA based DT modelling

Table 4.9 Fatigue lifecycles from the wired and wireless DTM

Model	Parameters	Load (KN)	Deflection (mm)	Stress (Mpa)	Life Cycles	AVG -load (KN)	AVG-lifecycles
Wired Digital Twin Model (DTM)	**FEA Based DT Simulation (Figure 4.18)**						
	Highway	0.43	30	130	$8.1*10^{7}$	0.52	$2.3*10^{7}$
	Residential	0.54	38	153.8	$1.2*10^{7}$		
	Rural	0.6	42.5	185.6	$6.9*10^{6}$		
	Hill	0.52	29	162.5	$1.1*10^{7}$		
	Mixed	0.7	45	184.3	$4.3*10^{6}$		
	Strain Life Approach						
	Parameters	**Abs**	**CM**	**Morrow**	**SWT**	0.52	$3.7*10^{5}$
	Load (KN)	0.43	0.54	0.6	0.52		
	Def (mm)	30	38	42.5	29		
	Stress (Mpa)	130	153.8	185.6	162.5		
	Lifecycles	$5.3*10^{6}$	$4.6*10^{6}$	$4.6*10^{6}$	$6*10^{5}$		
Wireless Digital Twin Model (DTM)	**Parameters**	**Load (kN)**	**Deflection (mm)**	**Stress (Mpa)**	**Life Cycles**	**AVG -load (kN)**	**AVG-lifecycles**
	FEA Based DT Simulation (Figure 4.18)						
	Highway	0.33	27	118	$1.48*10^{8}$	0.46	$4.6*10^{6}$
	Residential	0.44	35	141.8	$4.2*10^{7}$		
	Rural	0.5	39.5	173.6	$2.1*10^{6}$		
	Hill	0.42	26	150.5	$3.6*10^{7}$		
	Mixed	0.6	42	172.3	$1.9*10^{6}$		
	Strain Life Approach						
	Parameters	**Abs**	**CM**	**Morrow**	**SWT**	0.46	$8.6*10^{5}$
	Load (KN)	0.33	0.44	0.5	0.42		
	Def (mm)	0.69	52	230	0.69		
	Stress (Mpa)	0.84	57	243	0.84		
	Lifecycles	$3.2*10^{7}$	$1.8*10^{6}$	$5*10^{5}$	$2*10^{5}$		

It is clear from ***Tables 4.4***, ***4.6***, **and** ***4.9*** that the proposed DTM has a more accurate load reading, improving the predetermined experimental and simulation presented in ***Tables 4.4*** **and** ***4.6*****,** respectively, by 35.7 %. Since the load is the actual load applied in real-time, the DT model has better results than the empirical predetermined average lifecycles of the system by 12 times compared to the simulated results and nine times more than the experimental results. The proposed wired DTM still improves the average lifecycles of the system by 19.7% (1.2 times more) compared to the results of the second experiment (wireless DTM), which is based on the same load as the digital loads, as shown in ***Table 4.9***. The wireless DTM is still more accurate than the wireless because the experiment does not consider the deterioration factors impacting the system over time. The absence of historical data makes it impossible to determine the exact mechanical conditions of suspension systems worldwide for different users while carrying out experiments or simulations. However, the DTM uses current real-time data.

9.5 *Results Comparison with Existing Literature for DTM Validation*

Table 4.10 Comparison of strain signal between this research and literature

Ro	**Ref**	[446] **2018**	[447] **2019**	[448] **2020**	[449] **2020**	[450] **2022**	[230] **2023**	**This Research**
Statistical Analysis for Strain Signal (με)								
Highway	Mean	0.009	22	13.4		−0.079	−26.87	0.019
	RMS	211	X	25	X	12.28	17.90	210.95
	Kurtosis	3.317	X	1.8	X	3.02	3.64	3.316
	Crest Factor	X	X	X	X	X	X	48.645
Resident	Mean	0.005	−0.47	122.6	X	0.078	−19.81	0.015
	RMS	509.3	X	124.1	X	13.90	24.08	509.26
	Kurtosis	4.35		2.3		2.78	24.34	4.332
	Crest Factor	X	X	X	X	X	X	63.247
Rural	Mean	0.044	39	39.2	X	−0.925	48.96	0.044
	RMS	748.91	X	54.1	X	27.05	52.55	748.91
	Kurtosis	5.732	X	3.3	X	1.11	6.41	5.732
	Crest Factor	X	X	X	X	X	X	71.723
Hill	Mean	X	X	X	X	X	X	0.132
	RMS	X	X	X	X	X	X	310.23
	Kurtosis	X	X	X	X	X	X	3.946
	Crest Factor	X	X	X	X	X	X	61.278
Mixed	Mean	X	X	X	X	X	2.77	0.252
	RMS	X	X	X	X	X	19.87	832.58
	Kurtosis	X	X	X	X	X	12.49	5.642
	Crest Factor	X	X	X	X	X	X	82.662

Table 4.11 Comparison of acceleration signal between this research and literature

Road	Ref	[446] **2018**	[447] **2019**	[448] **2020**	[449] **2020**	[450] **2022**	[230] **2023**	**This Research**
Statistical Analysis for Acceleration Signal (m/s^2)								
Highwa	Mean	0.0064	X	X	X	X	X	0.006
	RMS	0.2664	X	X	X	X	X	0.866
	Kurtosis	4.0169	X	X	X	X	X	3.232
	Crest Factor	X	X	X	X	X	X	60.46
Resident	Mean	0.0045	X	X	X	X	X	0.005
	RMS	0.1584	X	X	X	X	X	0.584
	Kurtosis	4.8416	X	X	X	X	X	4.842
	Crest Factor	X	X	X	X	X	X	82.44
Rural	Mean	0.0442	X	X	X	X	X	0.044
	RMS	1.2479	X	X	X	X	X	0.448
	Kurtosis	4.4625	X	X	X	X	X	4.462
	Crest Factor	X	X	X	X	X	X	94.22
Hill	Mean	X	X	X	X	X	X	0.082
	RMS	X	X	X	X	X	X	0.332
	Kurtosis	X	X	X	X	X	X	3.432
	Crest Factor	X	X	X	X	X	X	89.65
Mixed	Mean	X	X	X	X	X	X	0.142
	RMS	X	X	X	X	X	X	0.122
	Kurtosis	X	X	X	X	X	X	5.231
	Crest Factor	X	X	X	X	X	X	99.62

Table 4.12 Comparison of FD between this research and literature

Ref	Method	Fatigue Damage				
		High	Res	Rur	Hill	Mix
2023 [230]	X	X	X	X	X	X
2022 [450]	X	X	X	X	X	X
2020 [449]	X	X	X	X	X	X
2020 [448]	**CM**	3×10^{-3}	42×10^{-3}	5.2×10^{-3}	X	X
	Mo	6×10^{-3}	83×10^{-3}	6.4×10^{-3}	X	X
	SWT	8×10^{-3}	12×10^{-3}	7.1×10^{-3}	X	X
	I-Kaz	X	X	X	X	X
2019 [447]	**CM**	3×10^{-6}	5×10^{-6}	5×10^{-6}	X	X
	Mo	3×10^{-5}	1×10^{-5}	5×10^{-6}	X	X
	SWT	5×10^{-5}	3×10^{-5}	1×10^{-5}	X	X
	I-Kaz	X	X	X	X	X
2018 [446]	**LL**	3.7×10^{-18}	4.5×10^{-12}	5.4×10^{-8}	X	X
	Di	1.9×10^{-18}	1.6×10^{-12}	2.3×10^{-8}	X	X
	NB	1.4×10^{-17}	2.3×10^{-11}	1.8×10^{-7}	X	X
	I-Kaz	X	X	X	X	X
This Research	**CM**	5.9×10^{-3}	6×10^{-3}	28.5×10^{-2}	69.3×10^{-2}	93×10^{-2}
	Mo	6.3×10^{-3}	8.3×10^{-3}	46.5×10^{-2}	6.9×10^{-2}	57×10^{-2}
	SWT	4×10^{-3}	6×10^{-3}	31.6×10^{-2}	47.1×10^{-2}	86×10^{-2}
	I-Kaz	0.16	0.29	0.95	0.34	0.547

Table 4.13 Comparison of FL cycles between this research and literature

Ref	Method	Fatigue Life Cycles				
		High	**Res**	**Rur**	**Hill**	**Mix**
2023 [230]	**CM**	X	X	X	X	X
	Mo	10^9	10^5	10^5	10^6	X
	SWT	10^{10}	10^5	10^5	10^6	X
	I-Kaz	X	X	X	X	X
2022 [450]	**LL**	9.8×10^6	1.51×10^8	4.09×10^6	X	X
	Di	2.6×10^8	1.51×10^8	6.02×10^6	X	X
	NB	1.4×10^6	1.32×10^6	1.00×10^6	X	X
	I-Kaz	X	X	X	X	X
2020 [449]	**CM**	8.073	5.600	4.835	X	6.732
	Mo	8.393	5.728	4.684	X	6.536
	SWT	8.839	5.808	4.608	X	6.434
	I-Kaz	X	X	X	X	X
2020 [448]	**CM**	X	X	X	X	X
	Mo	X	X	X	X	X
	SWT	X	X	X	X	X
	I-Kaz	X	X	X	X	X
2019 [447]	**CM**	3×10^5	2×10^5	2×10^5	X	X
	Mo	2×10^5	7×10^4	3×10^4	X	X
	SWT	1×10^5	3×10^4	2×10^4	X	X
	I-Kaz	X	X	X	X	X
2018 [446]	**LL**	2.7×10^{17}	2.2×10^{11}	1.8×10^7	X	X
	Di	5.2×10^{17}	6.5×10^{11}	4.4×10^7	X	X
	NB	7.1×10^{16}	2.2×10^{11}	5.6×10^6	X	X
	I-Kaz	X	X	X	X	X
This Research	**CM**	5.9×10^{-3}	6×10^{-3}	28.5×10^{-2}	69.3×10^{-2}	93×10^{-2}
	Mo	6.3×10^{-3}	8.3×10^{-3}	46.5×10^{-2}	6.9×10^{-2}	57×10^{-2}
	SWT	4×10^{-3}	6×10^{-3}	31.6×10^{-2}	47.1×10^{-2}	86×10^{-2}
	I-Kaz	0.16	0.29	0.95	0.34	0.547

Table 4.14 Comparison between methods used in literature and this research

Comparison Between This Research's Method and Existing Literature's Methods with Features and Limitations	
Ref	**Features**
This Research	1-Consider acceleration signal analysis. 2- Considers fatigue lifecycles. 3- Consider fatigue damage. 4- Considers crest factor. 5- Considers I-kaz factor. 5- Considers various types of roads such as hill and or mixed roads. 6- Considers the sample size of strain and acceleration signals.
	Limitations
2023 [230]	1-Does not consider acceleration signal analysis. 2-Does not consider fatigue damage. 3-Does not consider crest factor. 4-Does not consider the I-kaz factor. 5-Does not consider hill and or mixed roads. 6-The paper does not consider the limitation of the ESD model with other probabilistic models for fatigue life assessment, making it difficult to determine the superiority or effectiveness of the proposed approach to assess the accuracy and reliability of the results based on this lack of consideration
2022 [450]	1-Does not consider acceleration signal analysis. 2-Does not consider fatigue damage. 3-Does not consider crest factor. 4-Does not consider the I-kaz factor. 5-Does not consider various types of roads such as hill or mixed roads.6- Lack of sample size or statistical analysis to determine the reliability of the predictors.7- The paper does not consider the limitations of the used methods; all of this made it difficult to assess the accuracy and reliability of the results based on this lack of consideration
2020 [449]	1-Does not consider acceleration signal analysis. 2-Does not consider fatigue damage. 3-Does not consider crest factor. 4-Does not consider the I-kaz factor. 5-Does not consider various types of roads such as hill and or mixed roads.6- sample size or the specific vehicle used in the study, which may affect the reliability and applicability of the results.7-multifractality-based durability predictive models with other existing models or methods, which may limit the assessment of their effectiveness. All of this made it difficult to assess the accuracy and reliability of the results based on this lack of consideration
2020 [448]	1-Does not consider acceleration signal analysis. 2-Does not consider fatigue lifecycles. 3-Does not consider crest factor. 4-Does not consider the I-kaz factor. 5-Does not consider various types of roads, such as hill and or mixed roads.6-

	The study relied on the Palmgren-Miner linear cumulative fatigue damage rule and the strain-life procedure, which have their limitations and assumptions. 7-The paper does not consider the limitation of converting strain signals into stress using the Ramberg-Osgood equation; all of this made it difficult to assess the accuracy and reliability of the results based on this lack of consideration
2019 [447]	1-Does not consider acceleration signal analysis. 2-Does not consider crest factor. 3-Does not consider the I-kaz factor. 4- Does not consider various types of roads such as hill or mixed roads. 5- limitations of using the Gumbel distribution or the Akaike information criterion (AIC) method in the context of strain-life probabilistic modelling; all of this made it difficult to assess the accuracy and reliability of the results based on this lack of consideration
2018 [446]	1-Does not consider crest factor. 2-Does not consider I-kaz factor. 3- Does not consider various types of roads such as hill and or mixed roads. 4- The paper does not consider the limitations of the used methods; all of this made it difficult to assess the accuracy and reliability of the results based on this lack of consideration

10 CHAPTER SUMMARY

This chapter proposed a new, cost-effective, straightforward DT model for LCM and PdM using a real-life case study. This paper investigated three methods used for fatigue analysis: computational, experimental and digital. The method resulted in higher accuracy and allowed in-depth analysis of the entire mechanical behaviour of the suspension system in RT.

In this chapter, the dimensions of the DT modelling improved from five to Four dimensions, keeping an up-to-date report about the conditions of the suspension system. The three dimensions to create the DT model are PE, DE, CE, and CRT; the DT model still has high accuracy and more efficiency. In this chapter, the predetermined average load of simulation and experimental results improved by 35.7 %, and the average lifecycles of the system improved by 12 and 9 times more than the simulated and experimental results, respectively. Additionally, the proposed wired DTM Improved the average lifecycles of the system by 19.7% compared to the wireless DTM results.

This chapter proposes DTM, which continuously visualises and evaluates systems' mechanical conditions in CRT. Fatigue analysis is based on CRT data that considers the impact of specific factors that cause systems' deterioration throughout a given period, compared to the existing methods to analyse FL where factors of systems' deterioration are based on predetermined empirical calculations, estimation or not considered. DT method is used to improve systems' empirical predetermined loads and lifecycles. The entire mechanical behaviours of systems are visualised continuously in CRT. The DTM increased the accuracy of the data obtained from the dynamical system (coil spring) because the model represented the mode shapes and frequencies where the peaks of the loadings on each mode shape were identified. Regardless of the sampling rate, the obtained frequency still consists of a reasonable range. Direction for future research; currently, the way the data is collected is not sufficient to fulfil the requirement of the DT models; therefore, all the traditional methods of collecting data need to redevelop.

CHAPTER 5

Advanced Digital Twin Modelling for Predictive Fatigue Lifecycles of Coil Springs-Based Machine Learning

1 CHAPTER OVERVIEW

Research on Artificial Intelligence (AI) based equipment failure diagnoses is significant; However, integrating AI with the data-driven approach uses numerical models to anticipate fault propagation and find flaws remains challenging. Due to the system's complexity, it still needs to be easier to build, develop, improve, and regulate mechatronic systems. It is still impossible to routinely communicate machine health in real-time with users through the Live-Connection between Physical systems and their Digital Twins Models (DTM) by integrating intelligent information systems equipped with Machine Learning (ML).

HMLPANN topologies used with the I-kaz, Coffin Manson (CoM), Morrow (Mo), and Smith Watson Topper (SWT) Strain Life (SL) models to improve vehicle coil spring Fatigue Life (FL) prediction. To find the best Hybrid Multilayers Perceptron Artificial Neural Network (HMPANN) models with the lowest Mean Square Error (MSE) values, the number of neurons in the hidden layer/s and hidden layers was rigorously varied. The best CoM HMPANN model has two hidden layers. Three and seven neurons comprise the first and second buried layers, respectively. The MSE for this model is 0.0237. Mo and SWT's optimum HMPANN models have three hidden layers with MSE scores of 0.2353 and 0.2462. To verify the ideal HMLPANN models' accuracy, conservative correlation was used to compare their predicted fatigue life values to the required ones. Validation results suggest that most ideal HMPANN model data points coincide with the 1:1 and 1:2 or 2:1 correlation demonstrated in the I-kaz technique.

Integration between DTs and ML for monitoring the system's current and futuristic conditions is fully presented with a prediction error of less than 0.0001 %. The ANN model was improved, classifying the system's faults with regression accuracy throughout training, validation, and testing were 0.99997, 0.99954, and 0.99931, respectively, for a total accuracy of 0.99986. With the development of the ANN model and the proposed Advanced Digital Twin Model (ADTM) framework, the machine's health conditions and faults are predicted and managed in the current and futuristic times. Confusion matrices show the promising revolution in industry 5.0 for Self-Learning Digital Twins (SLDT).

2 INTRODUCTION

Due to the crucial function of coil springs in transportation systems in attaching the wheels to the car's body and absorbing road shocks, helical springs' Fatigue Failure (FF) is a serious worry for the automotive industry [229]. The springs are compressed to lessen the consequences of these dynamic shocks due to the stochastic dynamic forces that the wheels of the vehicle produce. The dynamic excitations brought on by various road conditions cause Fatigue Damage (FD) to a vehicle as it travels through various terrain types. FF arises as a result of this [451]. Since the suspension system's residual vibrations are transmitted to the car's body, they might cause discomfort for the passengers. As a result, engineers and designers must consider how suspension system parameters affect ride quality and the structural integrity of suspension system parts when constructing vehicle suspension systems. Dynamic road excitations are widely known to significantly affect a vehicle's ride characteristics, especially regarding spring design and fatigue.

After the fatigue limit has been achieved, coil springs are vulnerable to failure due to fatigue brought on by repeated cyclic road loadings. Many efforts have been made to analyse the fatigue design of springs using numerical approaches to avoid the early FF of these springs. Improving numerical techniques is the current area of research attention for coil spring FL prediction accuracy. The most efficient approach for forecasting the FL of a vehicle coil spring was found by [39] using a multi-axial fatigue algorithm in conjunction with Finite Element Analysis (FEA). The development of lightweight structures has received substantial attention in the automobile industry, mostly due to computing power and technology advancements. In this context, careful optimisation of automobile coil springs' basic geometry and form has been carried out [452]. The vehicle's vibration and fatigue characteristics will change when the spring settings are changed. Implementing a suitable spring design is essential for minimising vehicle vibrations and improving ride comfort while preserving the structural integrity of the springs [453].

Both factual and subjective elements are considered when evaluating a car's ride quality. Due to its consistency and capacity to promote product placement in the market, objective assessment methodologies are often utilised to evaluate ride comfort. Models for automotive simulation are often used to evaluate vehicles objectively. Based on the recommendations in ISO 2631-1:1997. Simulation of a passive quarter vehicle model was used to assess ride comfort. By optimising the suspension system settings using metaheuristic algorithms as the Grey Wolf optimizer and Firefly algorithm, the simulations of car ride comfort were improved

[454]. A quarter-car model was used by [455] to evaluate the lower control arm of a vehicle's FL. The notion of durability transfer was utilised by [455]to forecast the FL of automobile components. This theory assumes that acceleration data acquired from the vehicle suspension system may be used to assess FD in various vehicle components exposed to operational loading conditions. The recorded acceleration values of the suspension system are used to calculate the ride comfort and FL of the vehicle. The durability transfer idea [455] suggests that the acceleration at certain points on the vehicle suspension system may be used to estimate the vehicle vibrations.

Regression and ANN models were compared for tool-chip modelling by [456]. According to the authors, the ANN model produces findings that are more accurate than the regression model. ANN have been extensively used in a variety of automotive applications, including the modelling of suspension systems for handling and passenger comfort [457] and categorization of road surfaces [458], [459]. ANN have also been utilised to forecast the wear and tear brought on by arbitrary fatigue loadings [460], [461]. In order to improve passenger comfort, [462] developed an ANN-based method for vibration control in an active vehicle suspension system exposed to road disturbances. The main driving force behind this study is the lack of studies on spring fatigue modelling and its effects on ride comfort in connection to automobile coil spring designs.

By employing the fault conceptual framework of ADTM, this research investigates the possibility of integrating AI with DTMs to collect data about various metrics, including speed, current, input fluid flow, fluid pressure, output fluid flow, and fluid pressure signals. The live simulation model will use the parameter to model the entire mechanical behaviour of a suspension system. The individual parts of the suspension system are modelled in three dimensions to serve as a biophysical representation of the part itself. In this live DTM, the system will appear and function like in real life. Current Real Time (CRT) data access necessitates utilising data analytics techniques such as big data analytics and cloud computing, which will link together DTs of linked cases analogous to one another [463].

Different Machine Learning (ML) approaches, such as Decision Trees (DeT), Support Vector Machine (SVM), and ANN, may be utilised to classify systems’ conditions according to the level of precision possessed by the target variable. Guidance for CRT intervention is constructed according to the ideal conditions that have been decided. During the live monitoring, a digital copy of the part is created that instantly incorporates every activity and unanticipated event. After that, the plan that would work best for the real thing will be implemented using its DT as a reference point. CPS, as shown in ***Figure 5.1,*** and DTs are two elements that are essential for the deployment of smart manufacturing systems [464]. Cyber-Physical Systems (CPS) enhance communication between smart manufacturing entities (sensors, actuators, control, and many more) and cyber-computing resources to simplify monitoring, data collection, perception, analysis, and real-time control of production resources.

In the fifth generation (5G) of communications and beyond, there will be a proliferation of devices connected to the IoT. Managing the network is becoming increasingly complicated because of the ever-increasing demands placed on Internet of Things (IoT) networks concerning their performance, dependability, and safety. These complications are because modern methods for managing networks mainly rely on mathematical network models, which take the current state of the network as input and incorporate actions and performance feedback at the level of individual devices and protocols [3]. However, in the current IoT networks, the enormous number of IoT devices and the massive amounts of data they produce present a significant barrier to implementing model-driven approaches, which gives the impression that such a management mechanism could be more effective. Consequently, a completely new architecture is needed to meet the urgent requirement for monitoring and control in the imminent IoT networks that will be helped by 5G and beyond. The DTMs may have such a capability [3], [465], [466]. Hybrid Digital Twins (HDTs) or ADTs are the same and are autonomous networks that can respond to their environment in a predictable and adaptable manner at an advanced level. The term DT is now being used to advance the development of intelligent systems.

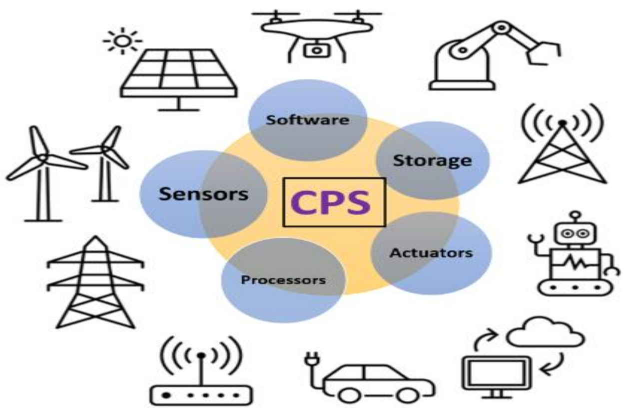


Figure 5.1 Industry 4.0 integrates digital technologies that make up the CPS.

It stimulates and maps the whole product life cycle by using simulation models that are both incredibly accurate and dynamically modified [467]. As a result, it reduces design and maintenance costs while increasing production efficiency and quality. The features of DTs are hyperrealism, computability, controllability, and predictability. Now, DTs could be viewed as a live simulation of any physical asset (A component, A subsystem, or A system of systems) that simultaneously visualises and evaluates the asset's external and internal dynamic behaviour and conditions in CRT as shown in ***Figure 5.2***. DTs materialised as isolated models that are either empirical or first principals-based.

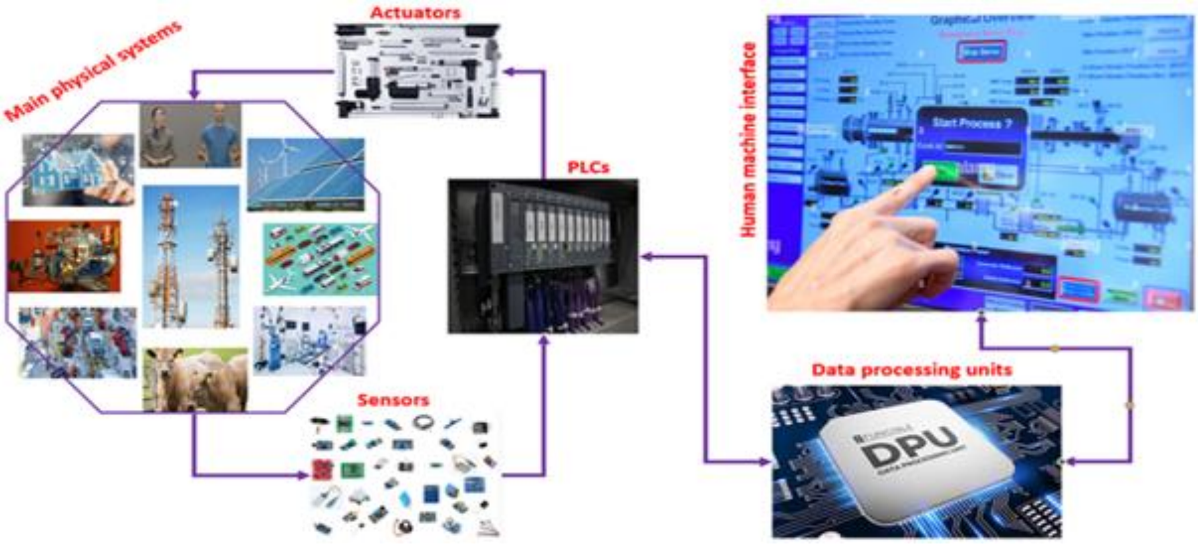


Figure 5.2 Architecture of the DTs modelling in industry 4.0 with no integration of ML

Industry 5.0 integrates many digital technologies, including but not limited to cloud fog computing, AI, autonomous robots, autonomous vehicles, visualisations, new data transmission protocols for the IoT, and many more. Together, these technologies comprise the CPS that integrates these digital resources with real physical objects into a consistent environment; this environment is the foundation for DTs.

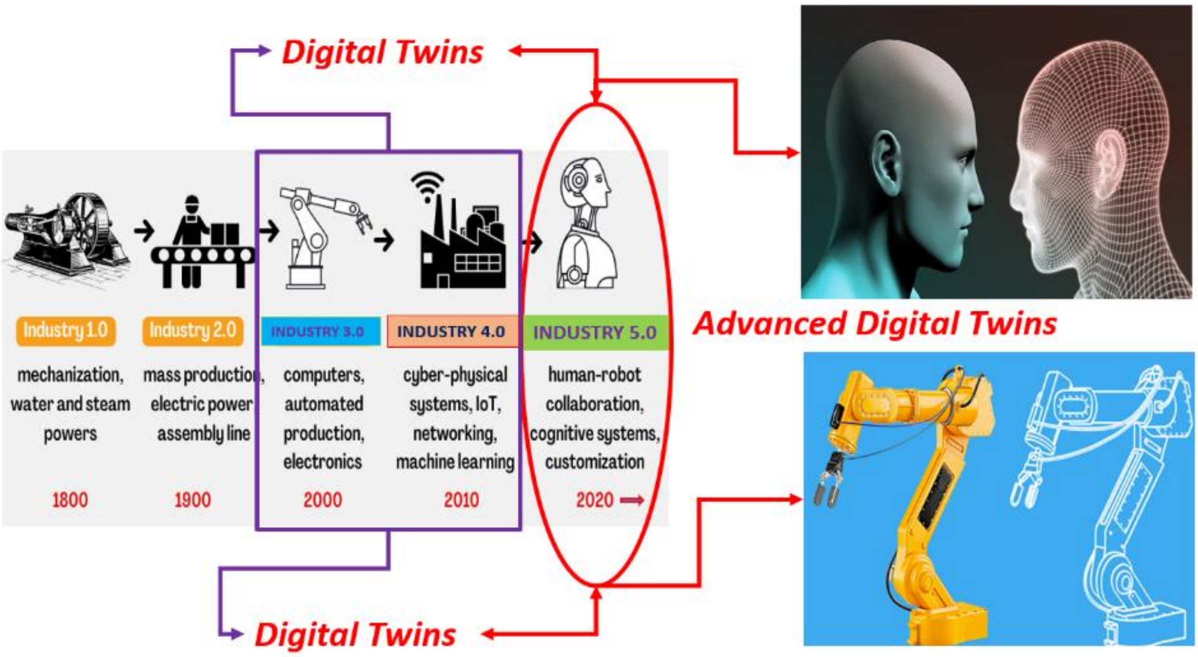


Figure 5.3 ADT architecture with the integration of ML in Industry 5.0

2.1 ***Advanced Digital Twins (ADTs)***

complicated mechatronic systems integrated with AI contain numerous objects with many attributes. A multi-domain unified model must be strongly linked with all life stages of ADTs to meet the criteria of ADTs, as shown in ***Figure 5.3***. This model will consider overall performance and the coupling between each component, a necessary foundation for realising self-adjustment, self-prediction, and self-assessment, which may all be summed up as SLDTs. DTMs are currently created using various packages; one of the most suitable packages is the unified modelling language (MATLAB), HLA, and multi-domain system modelling and simulating approaches.

2.2 ***Advanced Digital Twin Characteristics:***

To emphasise the crucial characteristics of ADTs, they should combine CRT Condition Monitoring (CRTCM), Complete mechanical behaviour visualisation, risk-free, minimum downtime to no downtime, minimum maintenance, maximum productivity levels, maximum efficiency, maximum effectiveness, high reliability, and high profitability. The quality of DT models depends on the reliability of physical objects and the reliability of the CPS used on the physical objects. The reliability of the physical objects is well-developed because it is based on ideal theoretical calculations. However, the issues with the reliability of the CPS still need to be solved because the calculations are still based on estimated calculations rather than actual calculations. Traditional maintenance methods can be used for either preventative or corrective purposes.

In corrective maintenance, the components are maintained only when necessary, generally after a substantial breakdown. This method contrasts with preventive maintenance, in which the components are maintained per a conservative timetable to prevent frequent failures. However, preventative maintenance techniques are more expensive since components must be changed regularly. Corrective maintenance strategies render the system inaccessible for longer than preventative maintenance [468]. As a result, a new Predictive Maintenance (PdM) method is required to discover any potential problems with components in advance. Predicting future problems with various vehicle components is called "vehicle fault prediction analysis". We investigate the potential failure modes of several different vehicle components and put into practice an appropriate architectural model so that we can assess the condition of a vehicle part or the amount of residual useful life it has.

DT develops digital counterparts with high integrity, awareness, and adaptability to provide digital predictive services for manufacturing organisations. It integrates real-time and historical data from physical systems, physics-based models, and advanced analytics. It enhances the openness and viability of CPS operations and allows for RT monitoring, modelling, optimisation, and control of cyber-physical aspects [469]. A based CPS (DT-CPS) should continually capture, integrate, analyse, simulate, and synchronise data across different product life cycle phases to give on-demand predictive services to customers in real and virtual locations. Alternately, the capabilities of production equipment in terms of sensors and connectivity are rapidly expanding [470]. In the digital realm, computational intelligence can be realised by analysing large amounts of data. Recent developments in sensor and communication technology have laid the framework for integrating the cyber domain of computing with the physical world of machines [471], [472].

A renewed emphasis has been placed on digital twins as a direct result of integrating CPS into industrial environments and the convergence of these two realms, where it offers a comprehensive digital portrayal of the lifecycle of a Physical System (PS), beginning with its conception and ending with the use of the finished product [473]. Optimisation and decision-making can use the same type of data that is updated in real-time on the PS thanks to synchronisation facilitated by sensors. The definition of the notion and its function within the

CPS have been evaluated [474]. The applicability of DTs to several aspects of the manufacturing life cycle is investigated via the simulation lens.

2.3 *Constructing ANN*

In this case study, the HMPANN is used for fatigue prediction issues; the network has one input neuron for each predictor variable and one output neuron for each response class. The NN uses the input values (X1, X2, …) in the input layer and passes them or feeds forward from the values from one layer to the next. Each neuron in NN is connected to all forward neurons; these connections allow a numeric weight (W) value to be given as a connection strength [475], as shown in ***Figure 5.4***. The values passed to a neuron are calculated by taking all the values of the neurons in the previous layer and multiplying them by the corresponding weight. Furthermore, the sum of the results plus an extra offset, known as the bias (b), is passed as the input to a function known as the transfer function for that layer. The output of this function is the value passed to the neuron.

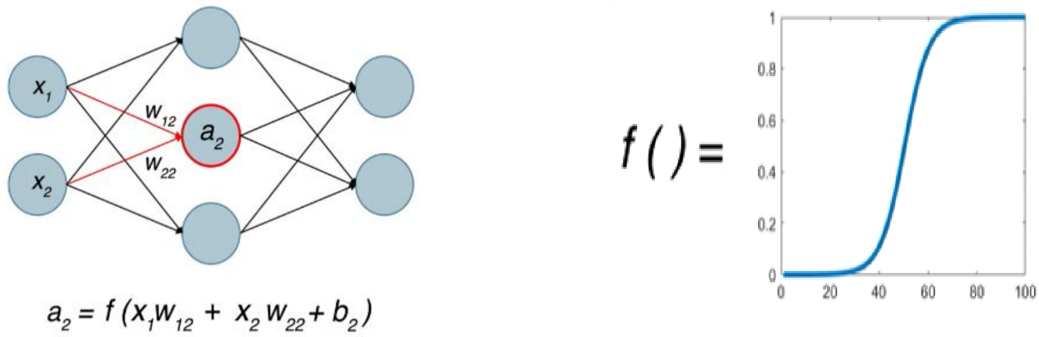


Figure 5.4 General concept of how the FFANN works and how the functions behave

The process is repeated for every neuron in the layers. The transfer function for the last layer maps values to the range 0 to 1, and the value of each output neuron is the degree to which the network predicts that the observation comes from that corresponding response. Therefore, the weight biases and transfer functions determine how inputs are transformed into outputs[476]. The Feed Forward Networks (FFN) are defined by the weight and biases of each layer, but how do we determine or define these parameters? Training an FFN involves adjusting the Ws and Bs to match the training data to achieve the desired outcome; this happens over many iterations each time the data goes through the network; the Ws and the Bs are updated to minimise the prediction error [477].

However, with so many parameters that can be adjusted, it is easy to drive the prediction error to the minimum, overfitting the data in the process. One way to avoid overfitting is to stop training before reaching the local minimum, but how do we know when to stop? One option is to partition the data into training and validation sets for the training phase; the training data is used to update the parameters by applying the minimisation routine[478]. However, the current network performance is evaluated on the validation data after each iteration. one the validation error starts to increase, the network is no longer generalising well, which is a sign that the network starts to overfit, and we can use this as a trigger to stop training. For this reason, we often split the data into three groups when training an FFN: a training set, a validation set to use during the training phase, and a final test set to use after training is complete to evaluate the trained network.

The rest of this chapter is organised as follows:

The rest of this chapter is organised as follows: ***Section 3*** is the methodology; ***Section 4*** presents results analysis and discussion; ***Section 5*** shows the Conclusion

3 METHODOLOGY

The approach used in this work has four main stages: (1) the gathering of data from road experimental driving, (2) Conducting FEA simulations, (3) Acceleration and Strain time histories data processing, and (4) the modelling an ADT model based on HMLPANN. ***Figure 5.5*** illustrates the flow chart depicting the methods used for HMLP modelling.

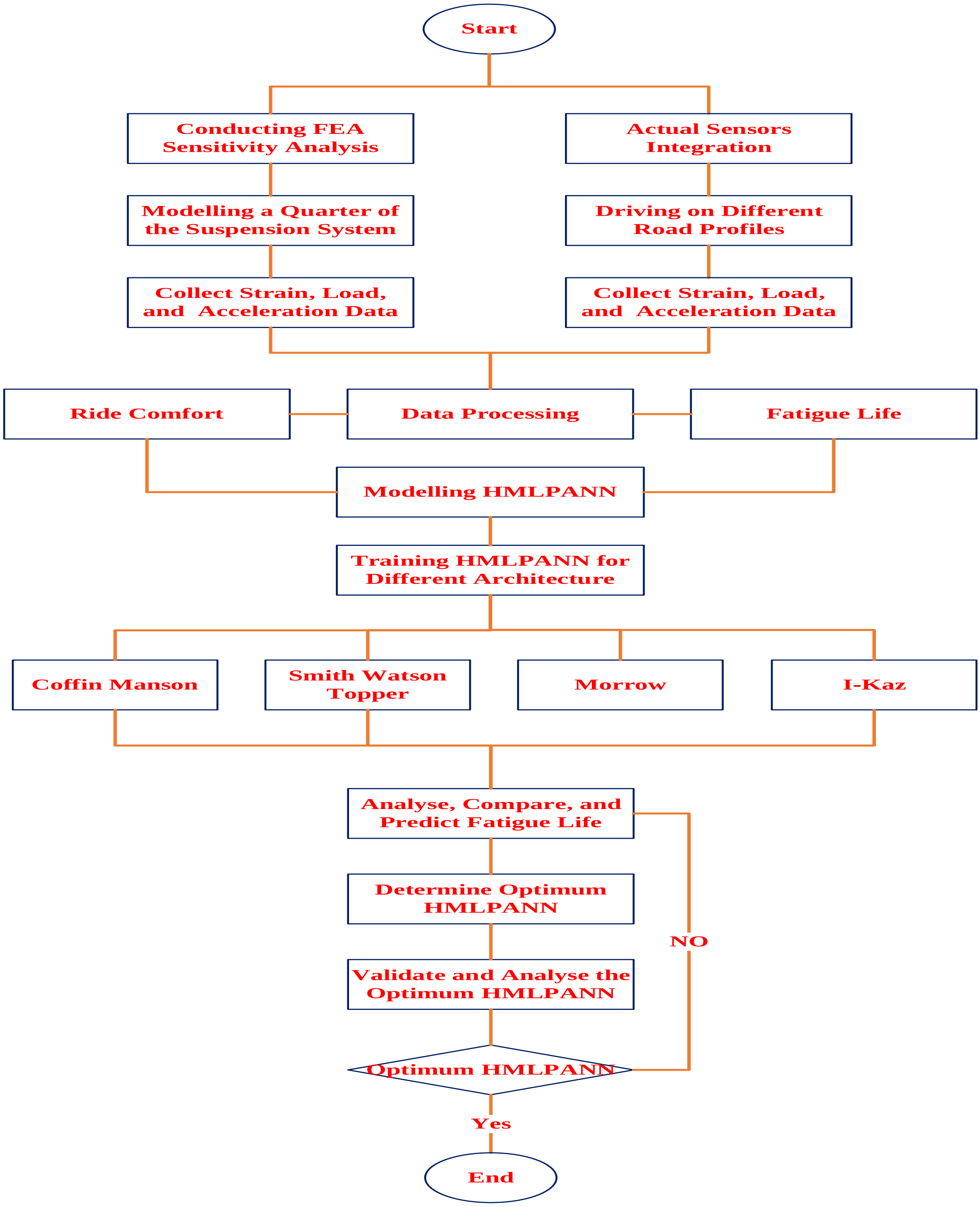


Figure 5.5 Flow chart of the methodology used for HMPANN modelling

3.1 *Data Collection Procedure*

Initially, the car specified in the previous chapter **(*Section 6.1*)** was driven on various roads **(*Section 6.3*), and** acceleration and strain signals were collected **(*Figures 4.13* and *4.14*).** To enhance the results, as there might be some doubts about the variety of data or the data is not enough simultaneously, a Computer-Aided Design (CAD) model of the car coil spring was created on Ansys software, followed by the meshing of the model using three-dimensional solid parts. The meshed model had a total of 8348 elements and 6520 nodes. The upper end of the automobile coil spring was affixed to a sturdy structure, and a concentrated load of 4000 N was applied at the midpoint of the coil spring from below. The selection of the applied load was predicated on the premise that the vehicle's total weight, when fully loaded, was 1600 kg and was uniformly distributed over all four wheels [479]. The model was provided with the cyclic material characteristics of SAE 9254 carbon steel [480]. A linear static analysis was conducted to get stress-strain data before making predictions about the fatigue life of the automotive coil spring [481]. ***Figure 5.6*** displays the stress contours derived from FEA for the vehicle coil spring model.

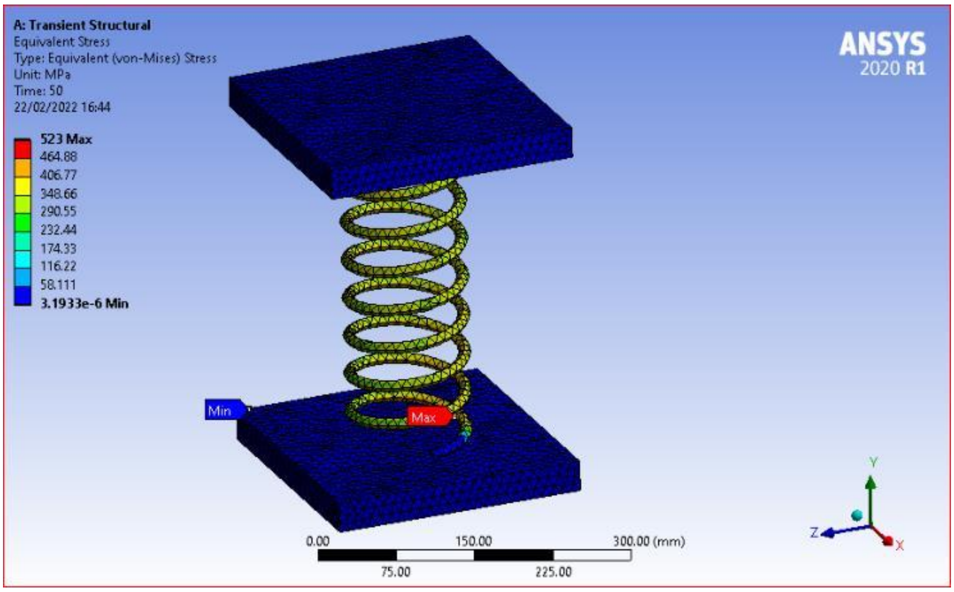


Figure 5.6 Stress contours of the automotive coiled spring obtained from FEA

The collecting of loading data is a crucial component of the process. The acceleration-time data was gathered for the lower control arm of a sedan across several driving situations, including highway, rural, residential, campus, and urban. In order to compensate for the restricted availability of measurement data of five road conditions, artificial road profiles were produced following the ISO 8608:2016 standard. The measured and artificially manufactured loading-time histories were used as inputs for the quarter-car simulations. This was done to generate the spring force and vehicle body acceleration-time histories for modelling. ***Table 5.1*** shows the Parameters or the data types collected for fatigue prediction. The parameters listed in ***Table 5.1*** are used as input for FEA to forecast the fatigue life of the automobile coil spring.

Table 5.1 Data type collected for fatigue prediction

Parameters Used for Prediction of Fatigue Life	
1. Vertical displacement	2. Acceleration
3. Horizontal displacement	4. Spring's Force
5. Fatigue Strength Exponent (b)	6. Springs Stiffness
7. Fatigue Ductility Coefficient (ε_t)	8. Cyclic Yield Strength (σ_y)
9. Fatigue Ductility Exponent (c)	10. Cyclic Strength Coefficient (K)
11. Fatigue Strength Coefficient (σ_t)	12. Cyclic Strain Hardening Exponent (n)

The FF of the coil spring was predicted using simulated spring force-time histories, while the vertical vibration index was obtained using vertical acceleration-time histories under the ISO 2631-1:1997 standard. The inputs for the strain-based fatigue models consisted of the cyclic characteristics of the material, the finite element model of the automobile coil spring, and the loading-time histories obtained from the quarter-car simulations.

3.2 *Hybrid Multilayer Artificial Neural Network Modelling (HMANN)*

The SL models were chosen over the stress-life models in this research due to the assumption that automotive components experience failure with the onset of fractures. The strain-based fatigue models used in this work included the CoM, Mo, SWT and I-kaz SL models; the theory of these models are presented in **Eqs 5.1, 5.2, 5.3, and 5.4,** respectively.

The mathematical expression of the link between the total strain amplitude (Δε/2) and the number of reversals to failure (2N$_f$) is given by the CoM Model [425], as shown in **Eq 5.1** below. The meaning of each term is shown in ***Table 4.1*****.**

$$\varepsilon_a = \frac{\sigma_f}{E}\left(2N_f\right)^b + \varepsilon_f\left(2N_f\right)^c \tag{5.1}$$

The Mo model used for mean stress (σ_m) corrections is mathematically expressed by **Eq 5.2** [425].

$$\varepsilon_a = \left(\frac{\sigma_{f-}\sigma_m}{E}\right)\left(2N_f\right)^b + \left(2N_f\right)^c \tag{5.2}$$

The SWT SL model is mathematically expressed by **Eq 5.3.**

$$\sigma_{\max}\varepsilon_a = \frac{\sigma'_f}{E}\left(2N_f\right)^{2b} + \sigma'_f\,\varepsilon'_a\left(2N_f\right)^{b+c} \tag{5.3}$$

The three SL expressions involve various parameters. E represents the material modulus elasticity, σ_{max} denotes the true maximum stress, σ_m represents the mean stress, ε_a signifies the true strain amplitude, 2 N_f corresponds to the number of reversals to failure, σ_f' denotes the fatigue strength coefficient, *b* represents the fatigue strength exponent, ε_f' signifies the fatigue ductility coefficient, and *c* represents the fatigue ductility exponent.

Additionally, the HMANN for CoM, Mo, SWT and I-Kaz are presented in ***Figures 5.10*, *5.11*, *5.12*, and *5.13*** respectively. The acceleration-time profiles are obtained from various spring stiffness configurations and then transformed into vertical vibrations following the guidelines outlined in the ISO 2631-1:1997 standard. It is important to note that the weighted vertical acceleration requires the consideration of the one-third octave band of the acceleration signal. Based on the ISO 2631-1:1997 standard. The weighted vertical acceleration is presented in **Eq 5.4.**

$$a_w = \sqrt{\sum_i \left(W_i a_i\right)^2} \tag{5.4}$$

Where the a_w is the frequency weighted root mean square acceleration, W_i is the weighted factor for the ith octave band given by the ISO 2631-1:1997. Vertical vibrations are indicative of the ride quality of a vehicle. Typically, increased vertical accelerations are associated with elevated levels of passenger discomfort [482].

3.3 *Importing Data Into MATLAB*

CRT data was obtained and recorded into an Excel sheet. The data sets contain information about coil springs used in a suspension system and their data. For the models to generate these predictions, they were given two distinct inputs: the Natural Frequency (NF) of the suspension system, as well as the ISO 2631-1:1997 vertical vibrations of the vehicle. Sensor's data are stored and organized into .xlsx files. Using the following code to import the signals data into MATLAB and assign it to a data name = **readmatrix('Fatigue.xlsx');.** The initial two columns are assigned to be the predictors or the input for the FFANN; these two columns were allocated to the variable X as the input data. The variable Y was assigned to the output data, the fatigue prediction. Finally, the letter M was given to the number of observations. Assigning the three variables was done as follows: X = data (:, 1:2); Y = data (:,2); M = length (Y);

3.4 *Initial Visualization of the Output Data (Fatigue Life)*

Output data: At first, the output FL predicted data is displayed, which consists of displaying and confirming the categories or the classes of the outcome output. The output is in the range where the prediction falls between 0 and 100. ***Figure 5.7 (a)*** below shows missing output data between 6 to 8. Normalizing the output data will solve the issue of missing data and ensure that the model integrates all the output possibilities, as shown in ***Figure 5.7 (b).***

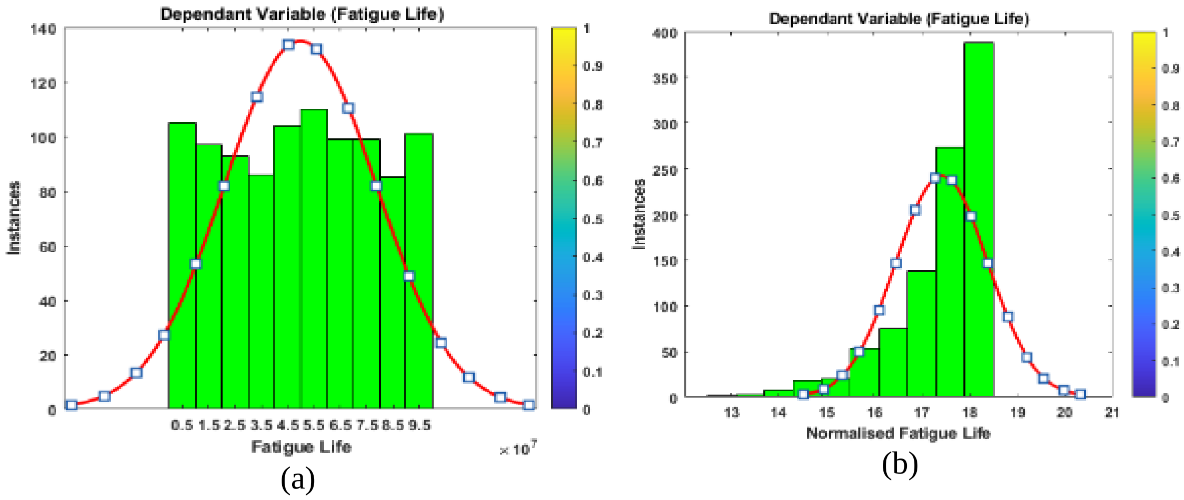


Figure 5.7 Initial visualisation of the output (a) and normalised output (b)

The issues with the output data are accomplished by normalising the features. Because the output could be zero, it is required to prevent the log of zero by adding one to the output to establish a new output variable by taking the log of one plus the output value. This is done so that the log of the new output variable is the same as the original output variable. Y2 = log (1+Y); histfit (Y2, 10). The updated output adjusts the output value and normalises the features to prevent one output variable centred around zero and only a few output variables centred around the higher parameters.

3.5 *Impact and Validation of Input Data Concerning the Output*

Understanding the connection between the input and output data is essential to decide whether the categories used for the input variables still apply or require updating. It is not easy to detect the relationship between the input and output variables because the input variables have a significantly greater variety than the features of the output variables. ML model is constructed for the training; as a result, the input variables change simultaneously. The link between each input variable and the output is studied and evaluated. Because several variables serve as inputs, a machine learning model is developed to be trained. As can be seen in the resulting visualisations of ***Figure 5.8***, they all have a linear relationship with the output class regardless of the number of observations, which is a good sign for machine learning models.

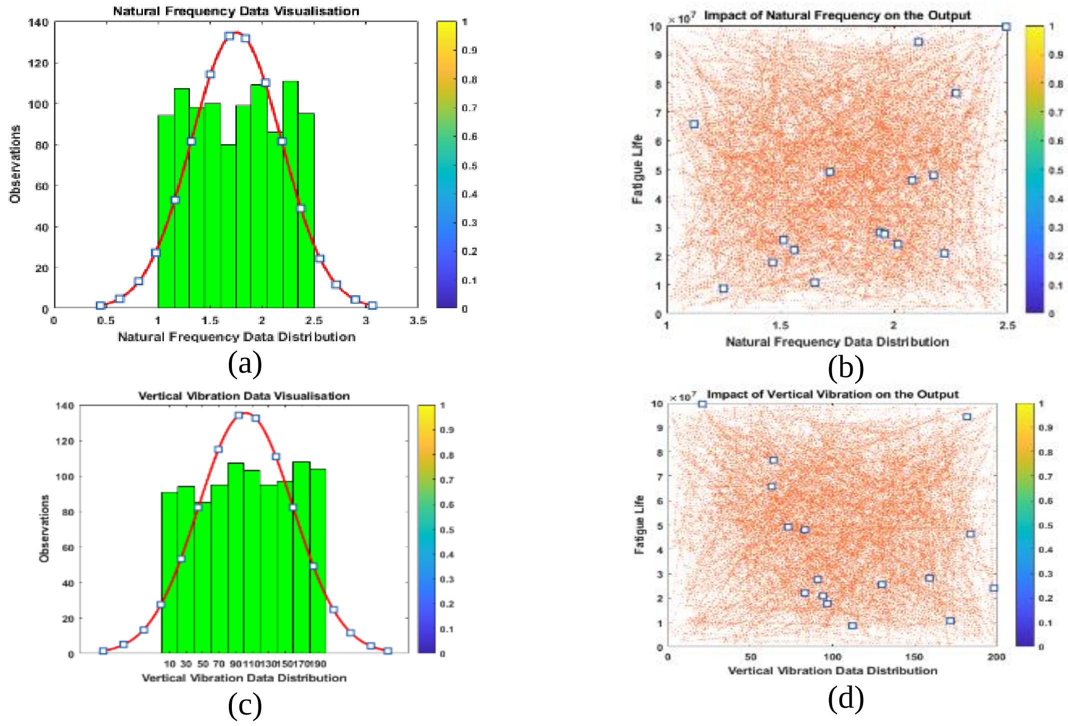


Figure 5.8 (a) & (b), visualisation of the input (c) & (d) is the impact

3.6 *Normalising the Input Data*

Since the impact of the input data on the output, even though it is linear, might be that some of the input data is missing or not yet. Therefore, a normalisation of the input data must be taken into account. As previously discussed, it is difficult to express the relationship between the factors considered and the results obtained. This issue was resolved by normalising the input from X to X2. However, since there is more than one input, looping them for normalisation is better than applying the results of the logarithmic function for better performance. ***Figure 5.9*** shows the normalised input data (a) NF and (b) vertical vibration in a manner that normalises all of the input variables and their respective features, guarantees that each input variable carries the same weight, and accelerates the training of the model.

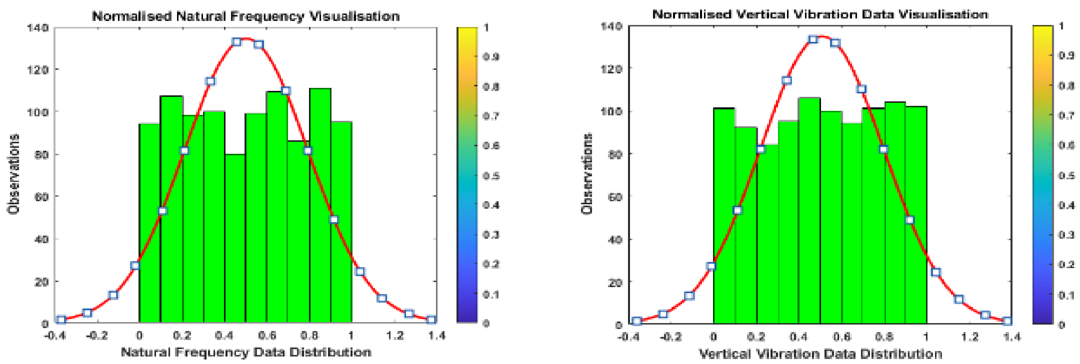


Figure 5.9 (a) normalised input natural frequency and (b) vertical vibration

3.7 *ANN Modelling*

After obtaining the spring fatigue and ISO 2631-1:1997 vertical vibration parameters, a series of HMPANN models are created by manipulating the number of neurons in the hidden layer(s) and the number of hidden layers. This aimed to establish a connection between the variables [476]. The HMPANN is a kind of NN architecture that linearly links the input and output layers. According to previous research [476], it is often believed that conventional MPANN Network models exhibit a significant degree of non-linearity, rendering them inappropriate for certain applications. Therefore, the introduction of HMPANN models was motivated by their ability to perform linear and non-linear analysis [483].

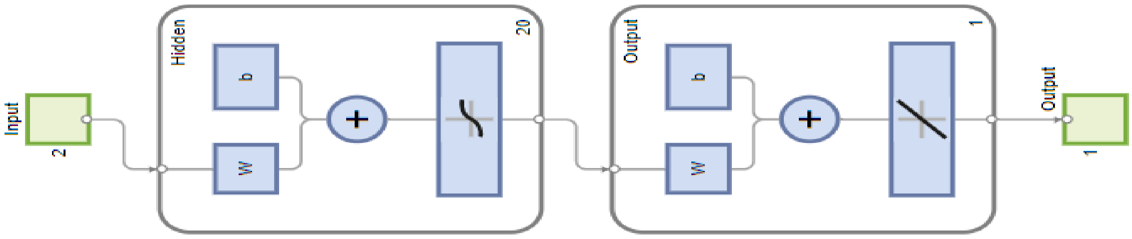


Figure 5.10 Improved ANN diagram

3.8 *Selecting the Optimal Number of Neurons*

The characteristics of the over-fitted and under-fitted layers are depicted in ***Figure 5.11,*** which can be found below. The model is under-fitted from zero to twenty due to the small number of hidden layers. The small number of hidden layers indicates that the model is excessively straightforward and will have a significant degree of bias. The complexity of the model increases from 1 to 20 neurons. This increase leads to a rise in its variance and makes it less responsive to data that has not been validated or tested. On the other hand, the model is quite good at generalising to the data it was trained on, and it keeps its consistency regardless of the number of neurons used.

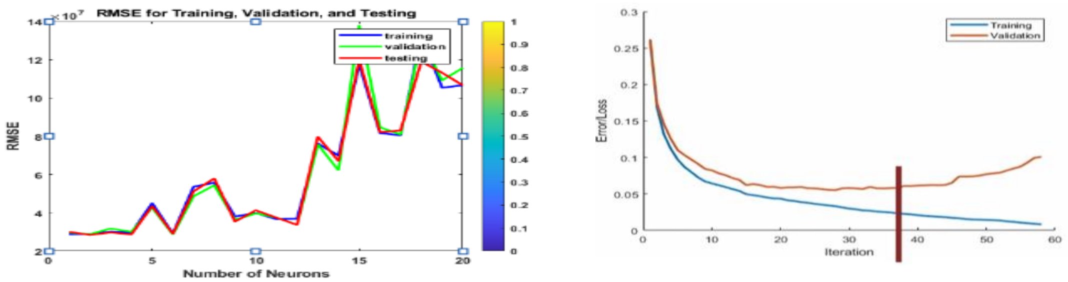


Figure 5.11 RMSE for the ANN and where and where the iteration should stop

As seen in ***Figure 5.10***, the new architecture indicates that the number of neurons in the hidden layer will gradually increase to 20 until it achieves that amount. This procedure is demonstrated in further detail below. The network and the identified fractions of the train, validate, and test sets have been determined (70, 15, and 15), and the network has also been defined. The Root Mean Square error (RMSE) is stored as multiple neurons.

3.9 *Optimizing The Number of Neurons in The Hidden Layer*

The RMS for the validation is investigated as a function of the recently decided number of neurons. This procedure ensures that the hidden layer receives the appropriate neuronal connections. These results in the lowest RMS value possible for the validation set, considering the number of selected neurons. Depending on the circumstances, one to sixty neurons will be selected. On the other hand, ANN is trained this time with substituted numbers of neurons, where (i) ranges from 1: 20. Both the network and the identified fractions of the train, validate, and test sets (70, 15, and 15) have been determined at this point. The network has also been defined. To facilitate further charting, the RMSE is stored as numerous neurons (RMSE train i). Many aspects influence the number of neurons, including the intricacy of the activation function used, the design of the neural network, the training procedure utilised, and, notably, the database of training samples [484].

Therefore, a limited number of 10 neurons were chosen to investigate the impact of the number of neurons in the hidden layer(s) on the predictive capacity of the HMPANN models. The upper limit for the number of concealed layers was defined as three. An ANN structure of three hidden layers is typically deemed enough to address intricate non-linear issues. Utilising intricate ANN designs is deemed unnecessary due to the substantial reduction in training time achieved by employing a minimal number of hidden layers [484]. ***Figure 5.12*** shows that the Levenberg-Marquardt training technique was subsequently used to train the ANN model due to its superior accuracy to other training algorithms [485]. **Eq 5.5** Shows the Levenberg algorithm is defined as in [486].

$$\left[J^T WJ + \lambda I\right] h_{lm} = J^T W\left(y - \hat{y}\right) \tag{5.5}$$

In this context, J represents the Jacobian matrix, h_{lm} denotes the perturbation matrix, W stands for the weighting matrix, i represents the identity matrix, λ symbolises the non-negative damping factor proposed by Levenberg as an enhancement to the Gauss-Newton technique, and y represents a vector with the ith component. Marquardt subsequently enhanced the technique, leading to the development of the Levenberg-Marquardt algorithm, as shown in **Eq 5.6.**

$$\left[J^T WJ + \lambda diag(J^T WJ)\right] h_{lm} = J^T W\left(y - \hat{y}\right) \tag{5.6}$$

Training Progress

Unit	Initial Value	Stopped Value	Target Value
Epoch	0	3	1000
Elapsed Time	-	00:00:01	-
Performance	1.82e+16	3.55e+15	0
Gradient	3.65e+16	7e+15	1e-07
Mu	0.001	1e+11	1e+10
Validation Checks	0	0	6

Training Algorithms

Data Division: Random dividerand
Training: Levenberg-Marquardt trainlm
Performance: Mean Squared Error mse
Calculations: MEX

Figure 5.12 Outcome of the Levenberg-Marquardt algorithm

The training inputs for the HMPANN models consisted of the natural frequencies of the vehicle suspension system and the ISO 2631-1:1997 vertical vibrations. The training output, on the other hand, was determined by the FL of the automobile coil spring. The evaluation of prediction accuracy by the HMPANN models included the use of the MSE, as specified by **Eq 5.7** [487].

$$MSE = \frac{\sum_{i=1}^{n} (Y_i' - Y_i)^2}{n} \qquad (5.7)$$

In this context, 'n' represents the total number of samples. 'Y'_i' denotes the actual output, whereas 'Y_i' represents the anticipated output. The hyperbolic tangent sigmoid transfer function was used to connect the input layer with the hidden layer(s), whereas the linear transfer function was utilised to connect the hidden layer(s) with the output layer. The effectiveness of this combination of transfer functions has been empirically shown to provide satisfactory outcomes in most training instances [488].

3.10 *ANN Optimization*

The optimal design of the model is based on the previous finding, in which the RMSE is minimum. Retrain the model by returning to the training ANN and changing the number of neurons in the hidden layer from seven to 10 this time. Even if the new performance can be calculated, the model must be trained multiple times to produce more accurate results. In the present investigation, the upper limit for the number of neurons was established at 10. Ensuring the appropriate allocation of neurons is crucial in mitigating the risk of overfitting the data [484]. It is necessary to determine the number of neurons in the hidden layer as the average of the neurons in the input and output layers [489] to get satisfactory performance for the HMPANN models. The minimum number of neurons in this scenario must be set to 2.

4 **RESULTS AND DISCUSSION**

The parameters listed in ***Table 5.1*** are used as input for FEA to forecast the FL of the automobile coil spring. A set of 980 data points was obtained from the quarter car simulations, conducted using ten spring FEA models built for the purpose. These simulations were performed, and the car was also driven under the influence of five different road excitations. The independent variables selected for analysis were the natural frequencies of the suspension system and the ISO 2631-1:1997 vertical vibrations, whereas the variable of interest was FL. The SL models used the FEA findings derived from the spring model implemented in a single quadrant of the vehicle. Additionally, force-time profiles acquired at different levels of spring stiffness were employed as input parameters. The automotive car coil spring's FL and the vehicle's mass acceleration were measured and studied for each degree of spring stiffness.

To accurately simulate the operational scope of the suspension system, the NF of the system mentioned above was ascertained by maintaining a consistent vehicle mass while manipulating the spring stiffness. This endeavour aimed to simulate the extent of movement within which the suspension system is capable of functioning. For the models to generate these predictions, they were given two distinct inputs: the natural frequencies of the suspension system and the ISO 2631-1:1997 vertical vibrations of the vehicle. In order to determine which HMPANN models provide the best results in terms of their MSE values, several different architectures are put through training. The first to be carried out was to analyse FFANN models with a single hidden layer.

The HMPANN designs that have been chosen are shown in ***Figures 5.13*, *5.14*, *5.15*, and *5.16***. Specifically, ***Figure 5.13*** illustrates the architecture of the CoM FL ANN that has undergone training. ***Figures 5.14*, *5.15* and *5.16*** depict the architecture of the HMPANN used to predict fatigue life in **CoM**, **Mo, SWT**, and **I-Kaz,** respectively. ANN architecture conducted the processing of input data by utilising the created weights and biases, afterwards producing an output related to FL. In this particular instance, the ANNs that were acquired had variations in their architectural characteristics, specifically in the number of neurons and hidden layers. The training process is concluded after six consecutive iterations in which there was no observed reduction in the validation performance, as stated in reference [490], to enhance the efficiency of the numerical procedure. Following this, experimental data was used to authenticate the developed HMLPANN models.

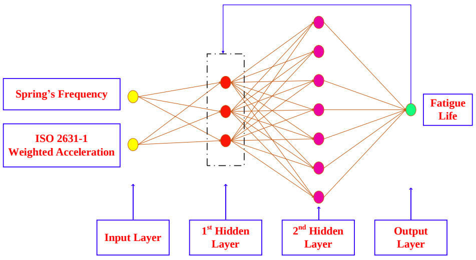


Figure 5.13 Selected HMANN for CoM

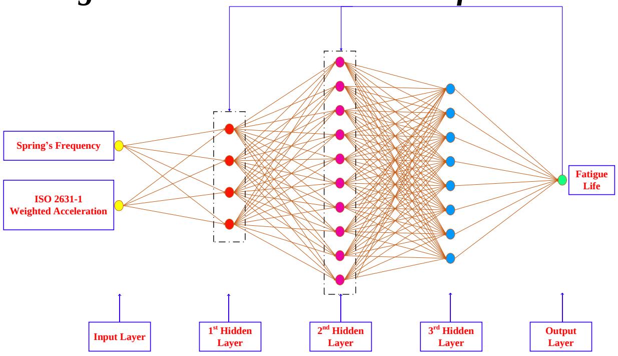


Figure 5.14 Selected HMANN for Morrow

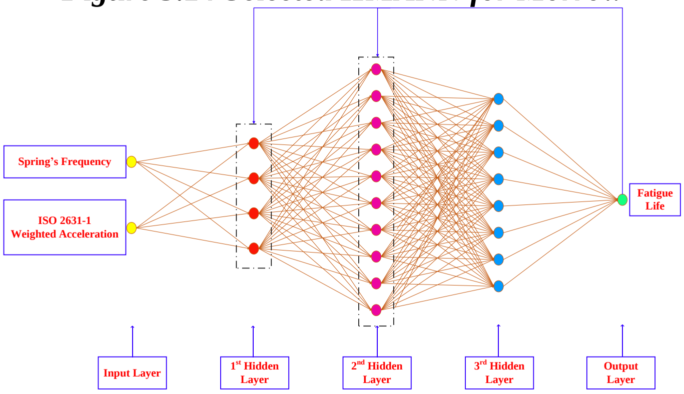


Figure 5.15 Selected HMANN for SWT

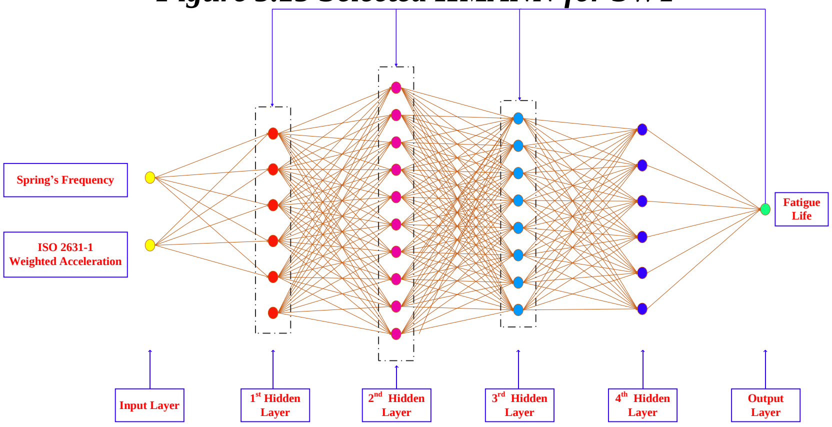


Figure 5.16 Selected HMANN for I-kaz

Figure 5.17 shows 2D line plots showing the MSE values for the **(a) CoM, (b) Mo, (c) SWT** and **I-kaz** FFANN models with one hidden layer and different number of neurons in the hidden layer. These values change depending on the neuronal activity in the hidden layer. After training, the **I-kaz** FFANN model shows the lowest MSE, 0.0543, as demonstrated in ***Figure 5.17 (d);*** when seven neurons are in the ANN's hidden layer, the system functions at its highest possible efficiency level. When seven neurons are in the hidden layer, the CoM FFANN model has MSE that is 0.0773, the lowest possible value ***Figure 5.17 (b)***. When nine neurons are in the hidden layer, the Mo FFANN model has MSE that is 0.0753, the lowest possible value ***Figure 5.17 (b)***. On the other hand, it is clear that the **SWT** FANN model has a value of MSE of 0.1546, and this is the case in particular when the hidden layer is made of a single neuron ***Figure 5.17 (c)***.

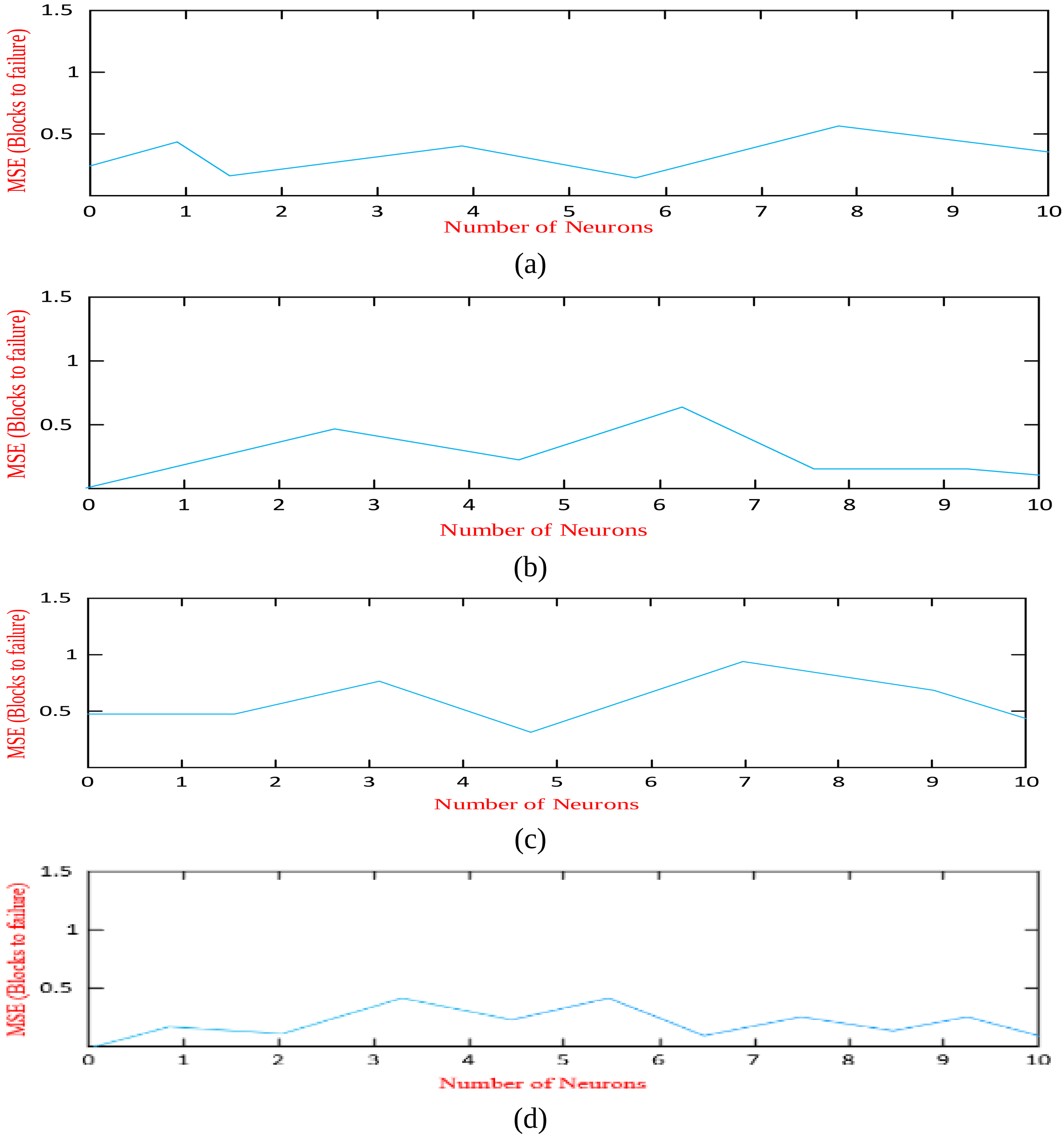


Figure 5.17 2D MSE: (a) CoM, (b) Mo, (c) SWT and (d) I-Kaz.

The evaluation of how well each trained FFANN suited the data was carried out for the networks with the MSE value with the smallest absolute value. The coefficient of correlation (R) and the coefficient of determination (R^2) were used to arrive at this conclusion. The training dataset was used to modify the weights and biases to train ANN models using the approach above. Using distinct training and testing datasets allowed for an evaluation of the effectiveness of the developed FFANN models. The performance of the models on the testing datasets was used to decide the final solutions to be implemented.

Regarding data segregation, the suggested allocation ratio is 70 % for one group and 15 % for the other two categories [491]. The primary dataset was divided using the division ratio determined over the course of this investigation. To be more specific, 70 % of the data was set aside for use in the training process, while validating and testing were each given 15 % of the total data set and the final 15% assigned to the testing set. The fitted training datasets for the CoM, Mo, SWT and I-kaz FANN models are shown in ***Figure 5.18***, along with their respective names.

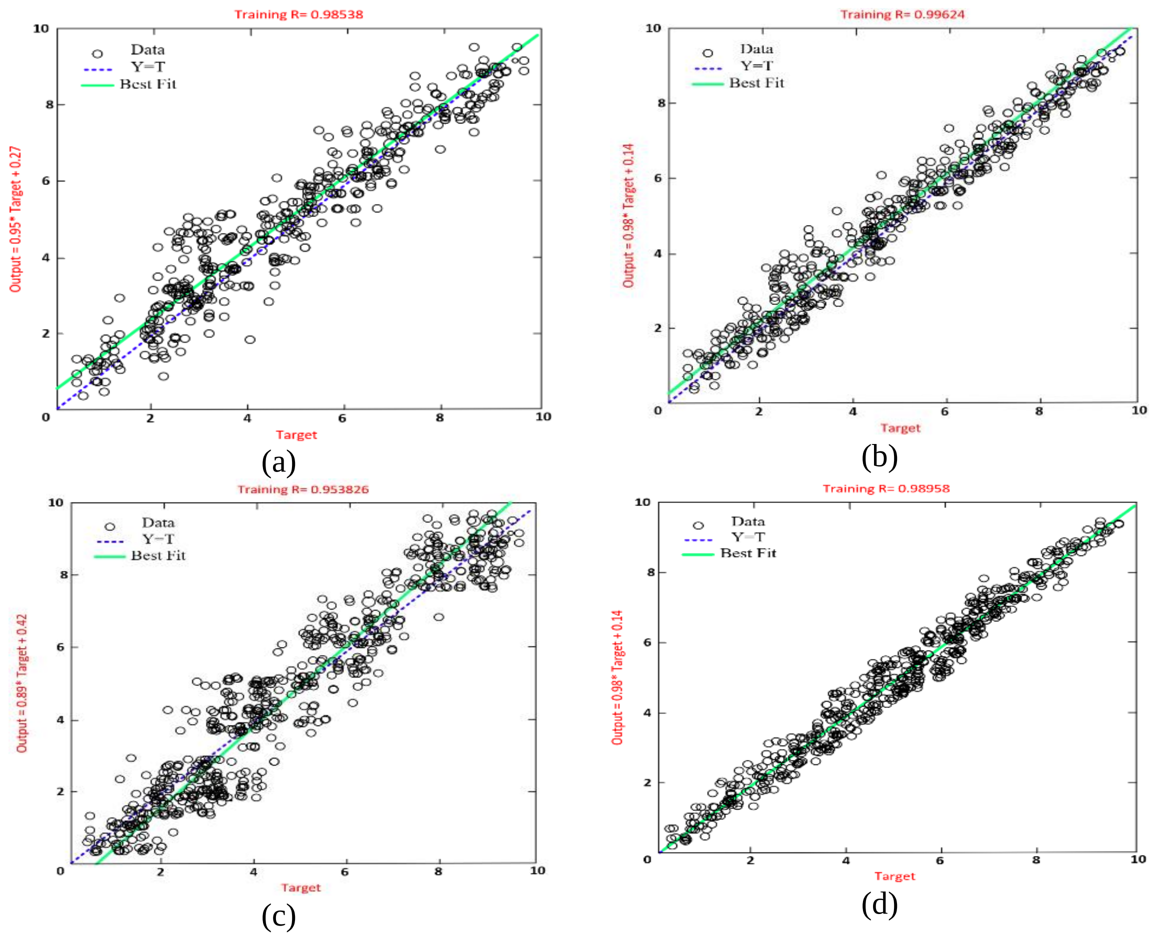


Figure 5.18 Trained curve fitting (a) CoM, (b) Mo, (c) SWT, and (d) I-Kaz with one HL.

In order to arrive at a set of definitive answers for this study, the testing datasets were used. ***Figure 5.19*** presents the results of the fitted testing datasets for the FFANN models developed by CoM, Mo, SWT, and I-kaz. The fitted testing dataset for the **I-kaz** FFANN model has an R-value of 0.9987 and an R^2 value of 0.9977. Both of these values indicate that the model is very accurate. The R and R^2 values for the fitted testing dataset are lower when using the **CoM** FFANN model; these values are, respectively, 0.9782 and 0.9568. The R and R^2 values for the fitted testing dataset are lower when using the **Mo** FFANN model; these values are, respectively, 0.9624 and 0.9530. The testing dataset has an R-value of 0.9928 and an R^2 value of 0.9857; these values are interpreted within the framework of the **SWT** model. As a general rule, the training datasets demonstrate a high degree of compatibility with the models, which is to be expected given that the ANN models have learned from the input data. According to the findings of [492], a model is considered "very good" if it has an R^2 value that is greater than 0.90, and it is considered "good" if it has an R^2 value that is greater than 0.80. Based on this assertion, the FFANN models that have undergone training exhibit a high level of concordance with both the training and testing datasets.

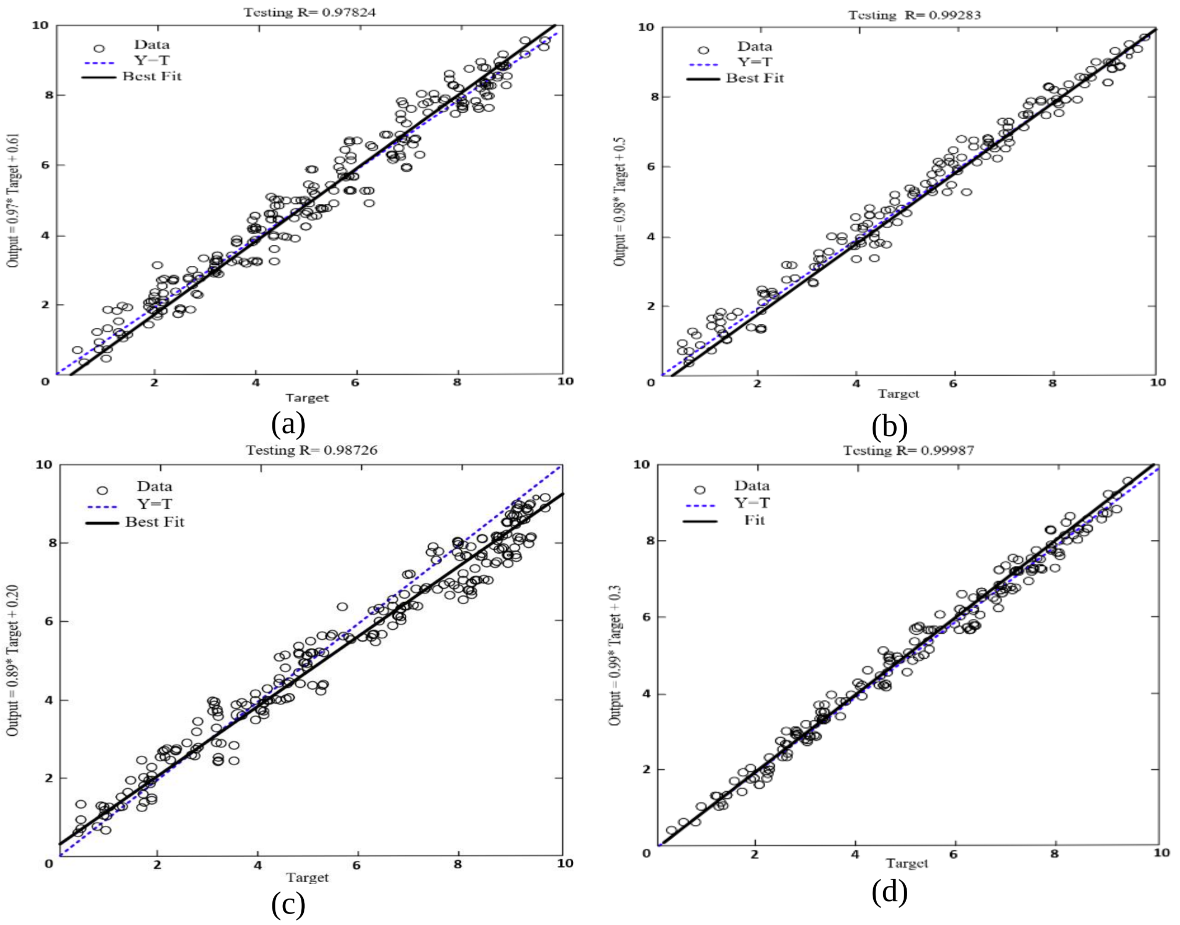


Figure 5.19 Test curve fitting (a) CoM, (b) Mo, (c) SWT, and (d) I-Kaz with one HL.

Figure 5.20 displays the MSE values with two hidden layers that the ANN models achieved after being trained using a hidden layer architecture consisting of two layers. After being trained, the **I-kaz** HMPANN model has the lowest MSE of 0.0146; this model shows the best result. When trained with one neuron in the first hidden layer and six neurons in the second hidden layer, **CoM** shows a higher MSE of 0.237. When the model is designed with three neurons in the first hidden layer and seven neurons in the second hidden layer, the best performance may be attained with a setup of eight neurons in the first hidden layer and six neurons in the second hidden layer, the trained **Mo** HMPANN model can achieve a minimal MSE of 0.0273. This is a measure of how accurate the model is. When trained with one neuron in the first hidden layer and six neurons in the second hidden layer, the **SWT** HMLPANN model has the lowest MSE of 0.0742. Indicating that the HMPANN models, which are comprised of two hidden layers, have completed their training is the fact that the 3D scatter plots do not include any aberrant spots.

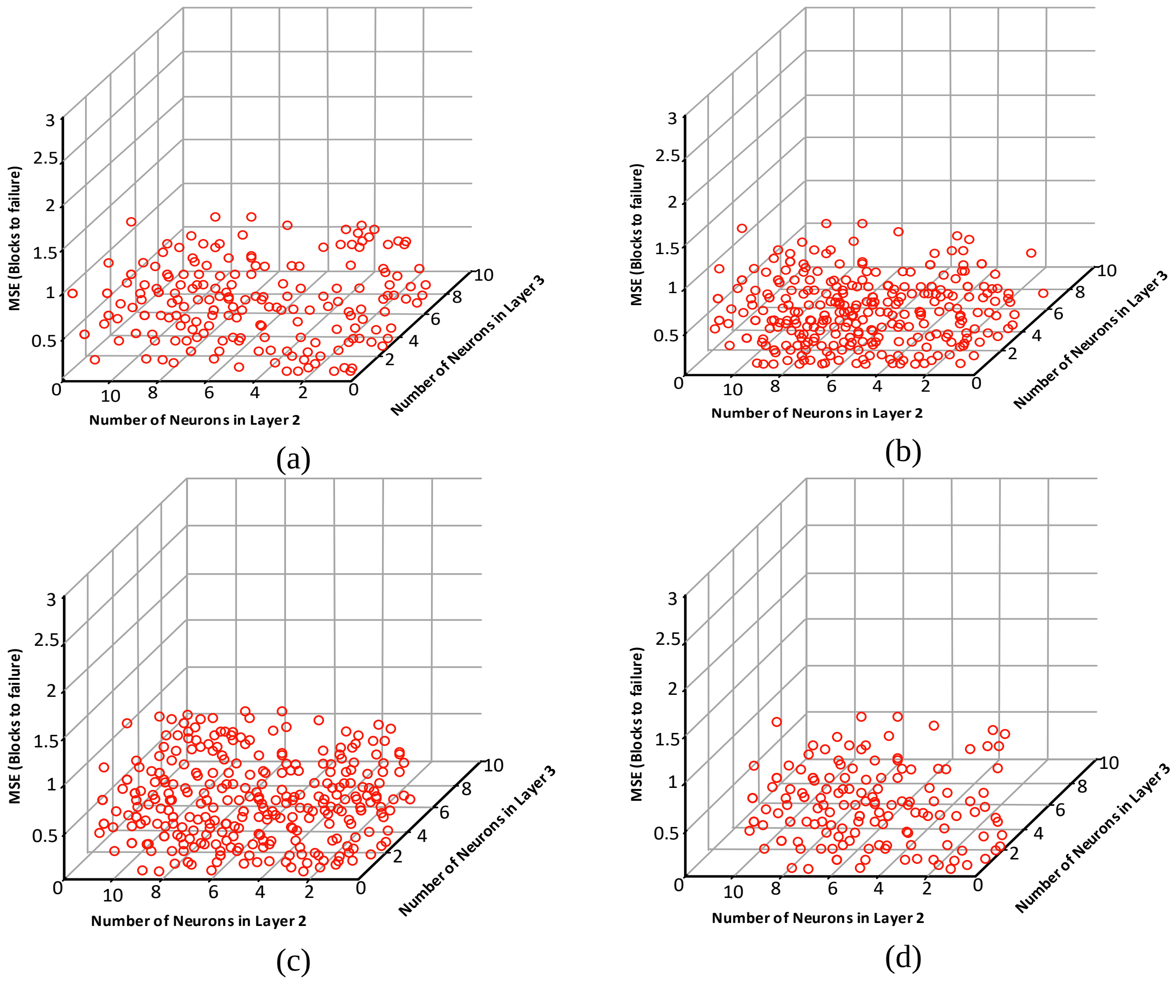


Figure 5.20 3D scatter plots of MSE for (a) CoM, (b) Mo, SWT and (d) i-kaz with 2 HLs

After determining which HMPANN models had the lowest values for MSE, an analysis was conducted to investigate how these models matched the curves of their respective training and testing datasets. ***Figure 2.21*** presents the fitted training datasets for the **CoM, Mo, SWT**, and **I-kaz** HMPANN models. These models, each with two hidden layers, were fitted using the same datasets. It is possible to conclude that the datasets used for training have a high level of congruence with the HMPANN models.

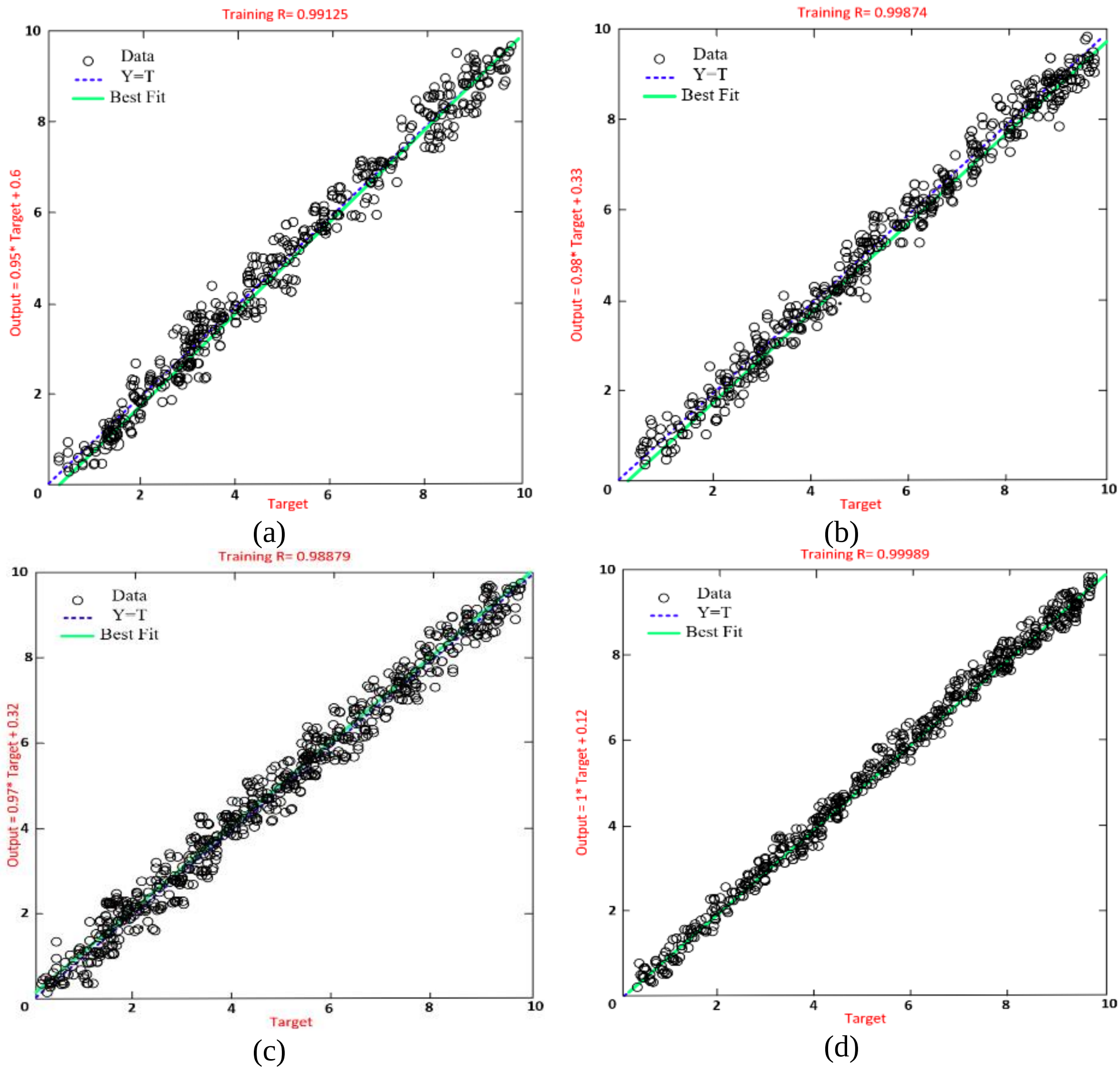


Figure 5.21 Trained curve fitting (a) CoM, (b) Mo, (c) SWT, and (d) I-Kaz with HLs.

The fitted testing datasets for the **CoM**, **Mo**, SWT and **I-kaz** HMPANN models, each equipped with two hidden layers, are shown in ***Figure 5.22.*** The same division ratio used in the FANN models with a single hidden layer was utilised when partitioning the original dataset. The acquired findings indicate that the HMPANN models with two hidden layers have been trained efficiently, as evidenced by the high R values in both the fitted training and testing datasets.

This is shown by the fact that the models have performed well in the tests that have been run on them. As shown in ***Figure 5.22 (a),*** the R and R2 values of the fitted testing data for the **CoM** HMPANN model are reported to be 0.9985 and 0.9970, respectively. The R and R2 values of the fitted testing data for the **Mo** HMLPANN model are reported to be 0.9957 and 0.9914, respectively. The R and R^2 values for the fitted testing data in the **SWT** HMPANN model are somewhat lower than average, coming in at 0.9986 and 0.9972, respectively ***Figure 5.22 (c).*** As shown in ***Figure 5.22 (b),*** the R and R2 values of the fitted testing data for the **I-Kaz** HMLPANN model are reported to be 0.9998 and 0.9996, respectively. In general, the R^2 values show bigger magnitudes in HMPANN models with two hidden layers compared to FANN models with only one hidden layer. This is mostly attributed to the improved learning capacity that is inherently present in the ANN.

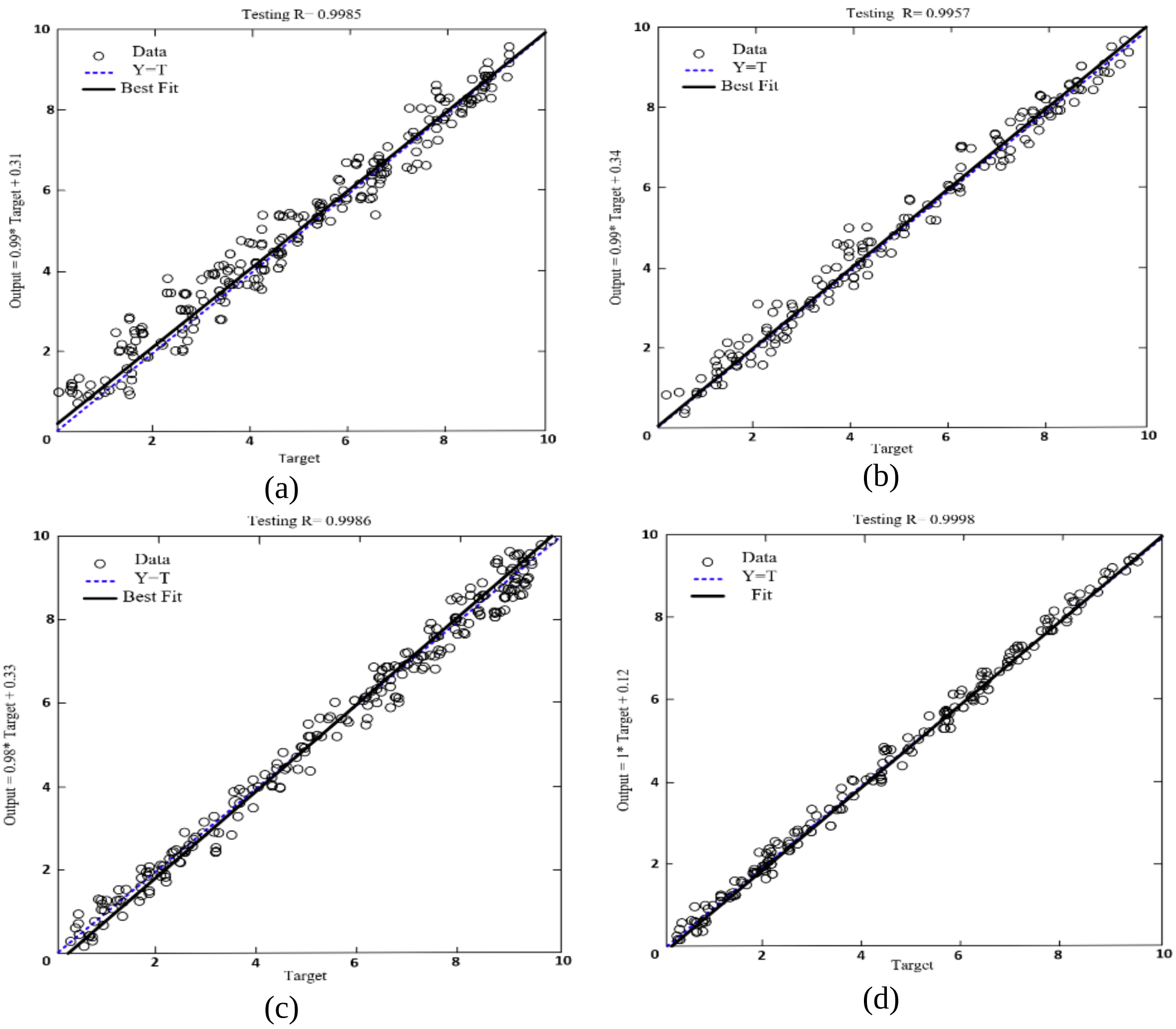
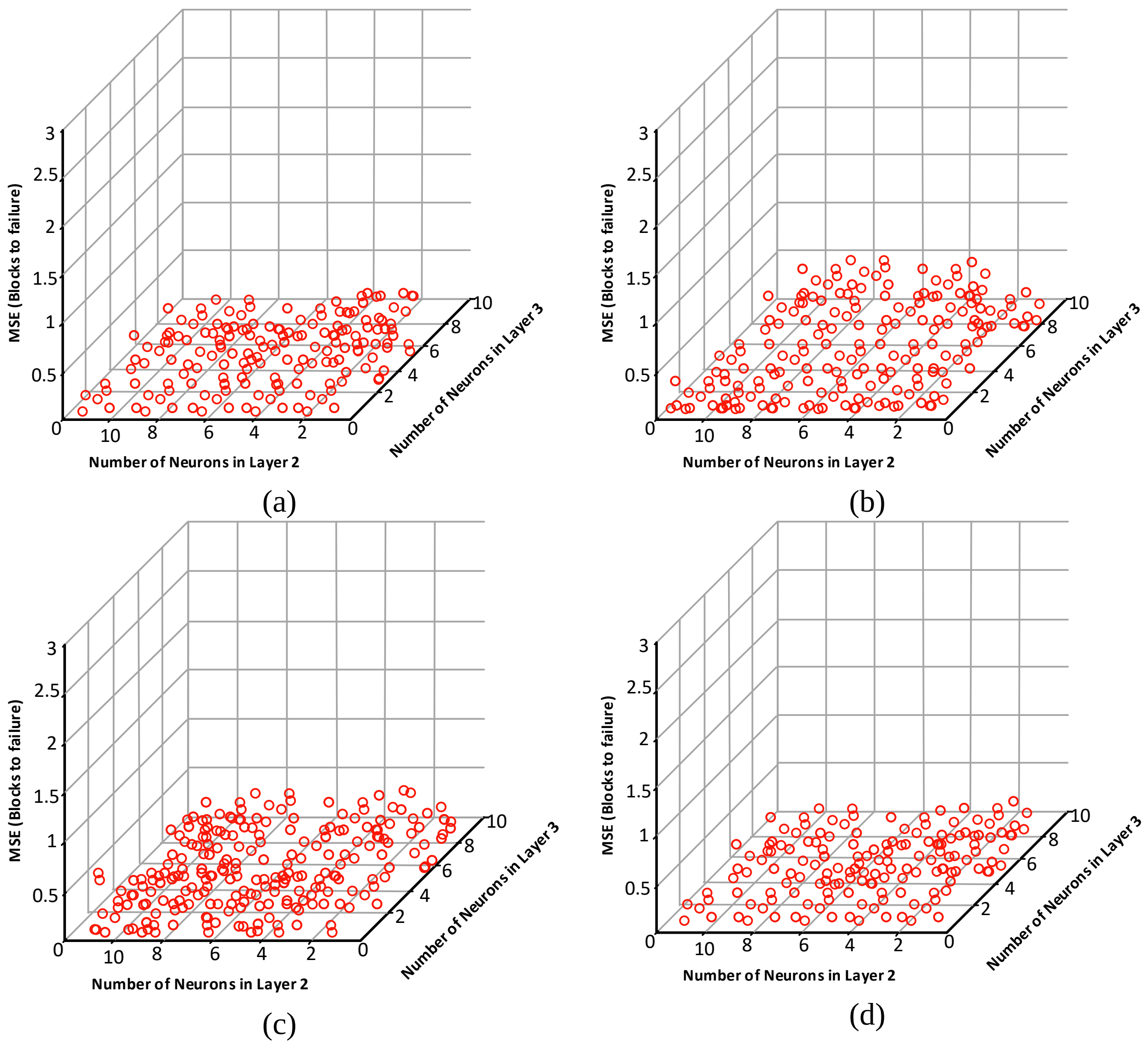


Figure 5.22 Test curve fitting (a) CM, (b) Mo, (c) SWT, and (d) I-Kaz with 2 HLs.

However, obtaining the optimum number of hidden layers remains difficult since there is a possibility of overfitting the data if the number of hidden layers is increased [484]. This makes the process of establishing the ideal number of hidden layers hard. This study also studied how the number of hidden layers affects the prediction performance of HMPANN models. The investigation primarily examined the MSE values of the HMPANN models. The models were developed using three hidden layers, and the number of neurons in each layer was modified. The study aimed to determine the most effective designs for HMPANNs that resulted in the lowest MSE values. The manipulation included altering the range of neurons in the first hidden layer, which varied from 1 to 20.

Figure 2.23 displays the 3D scatter plots illustrating the MSE values acquired from the trained **CoM** HMLPANN model. The **CoM** HMPANN model achieves an MSE value of 0.2645 when the first, second, and third hidden layers are composed of six, three, and three neurons, respectively.



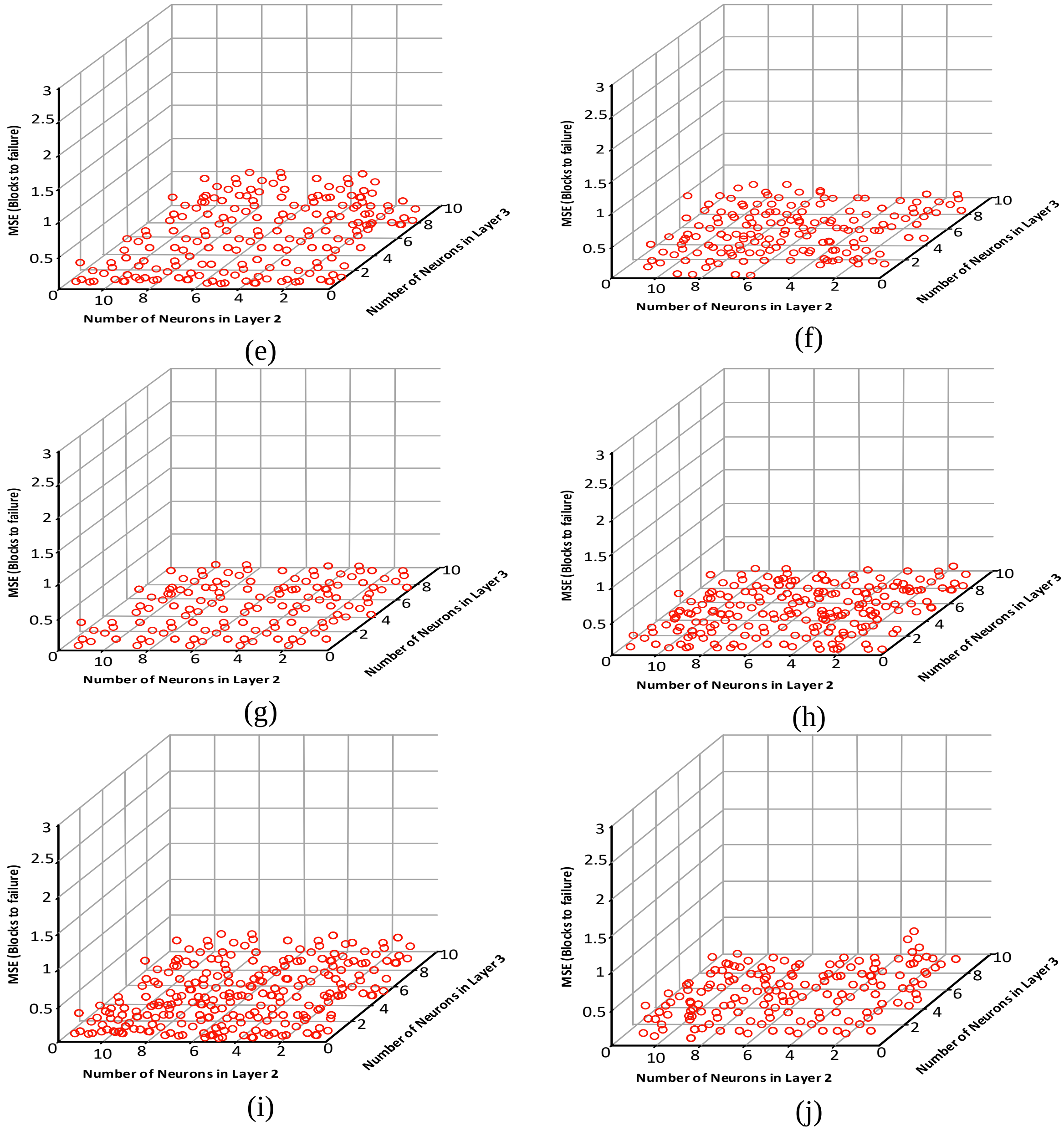
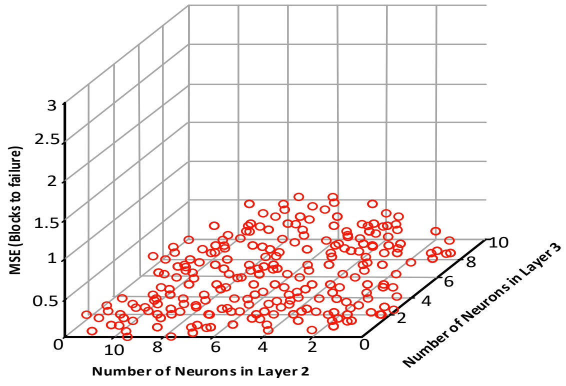
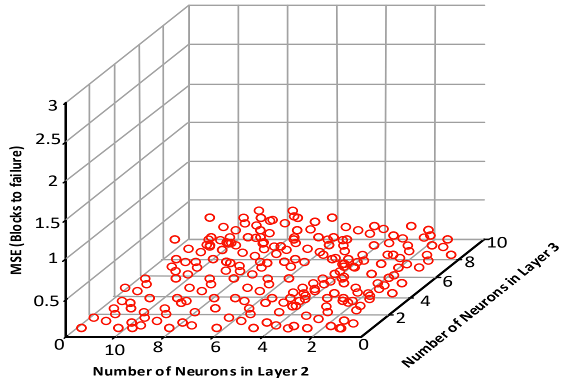


Figure 5.23 Trained 3D scatter plots of MSE for CoM with (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9, and (j) 10 neurons in the first HL

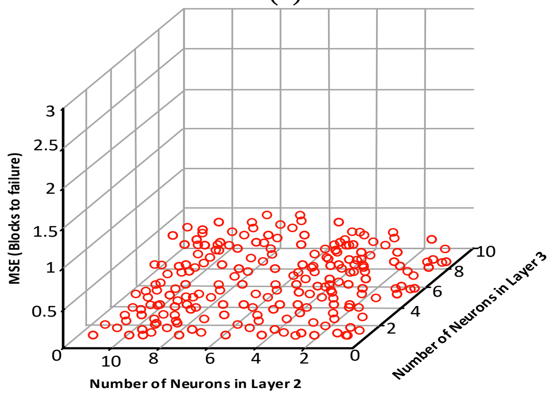
Figure 5.24 displays the MSE data of the trained **Mo** HMPANN model. The model demonstrates a minimal MSE value of 0.2353. The findings of the MSE findings for the trained SWT model equal to 0.2462 are shown in ***Figure 5.25***. ***Figure 5.26*** shows that I-Kaz with the lowest MSE of 0.01463. Generally, HMPANN models with three hidden layers provide higher predictive accuracy than ANN models with one and two hidden layers, as shown by the MSE values. Based on [493] findings, it is advised that the use of an ANN model should be limited to a maximum of three layers to prevent an increase in complexity and processing time. As a result of this reasoning, the study restricted its examination to a maximum of three concealed layers.


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

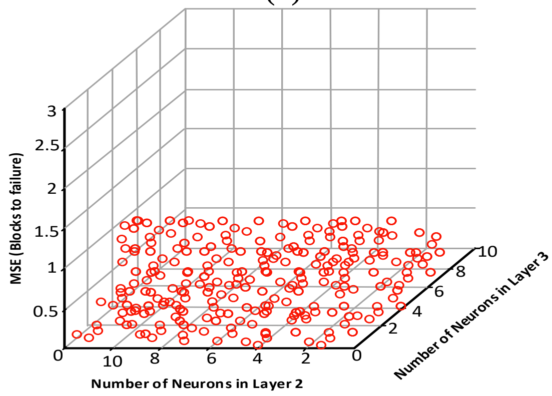
(a)


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

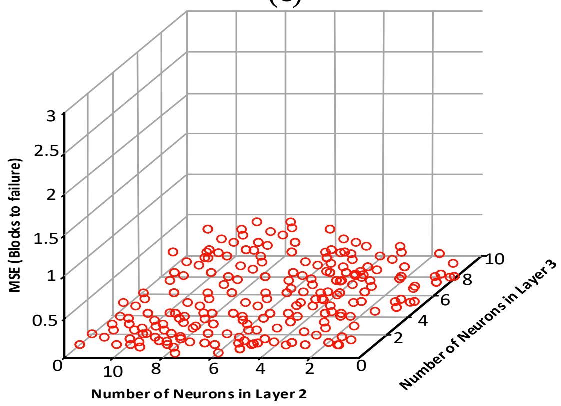
(b)


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

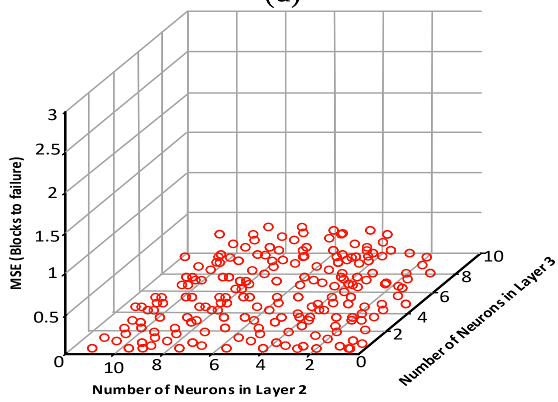
(c)


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

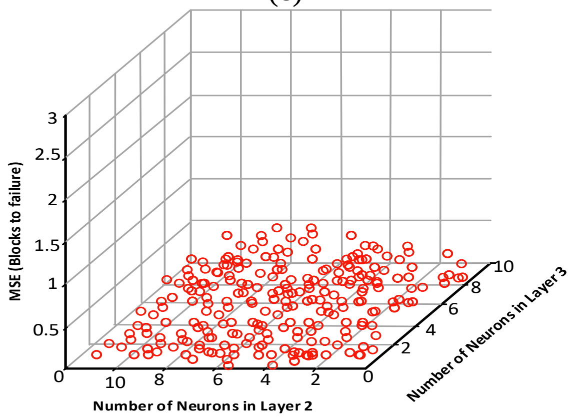
(d)


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

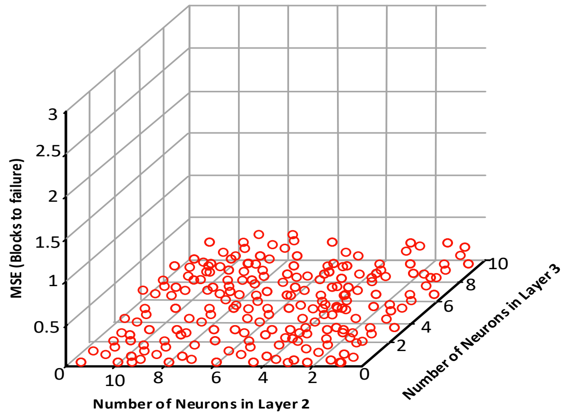
(e)


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

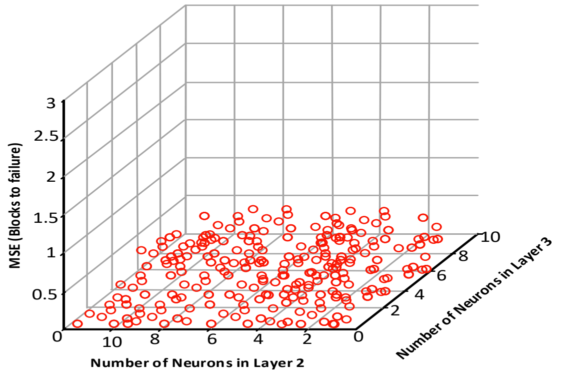
(f)


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

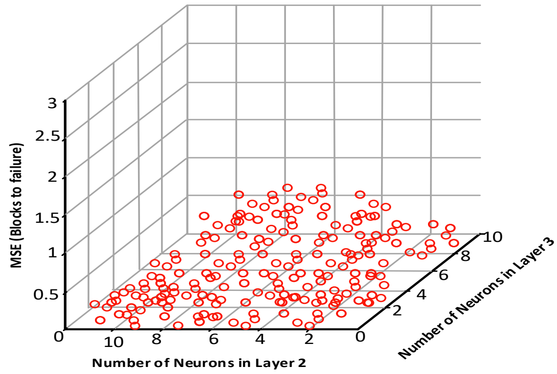
(g)


MSE (Blocks to failure)
Number of Neurons in Layer 2
Number of Neurons in Layer 3

(h)

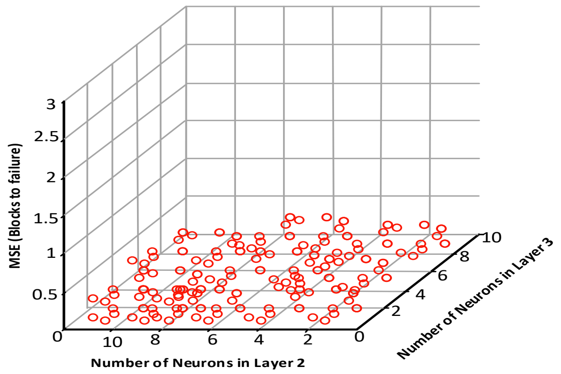


(i)

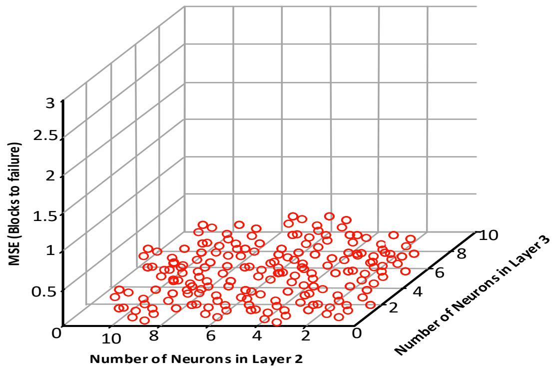


(j)

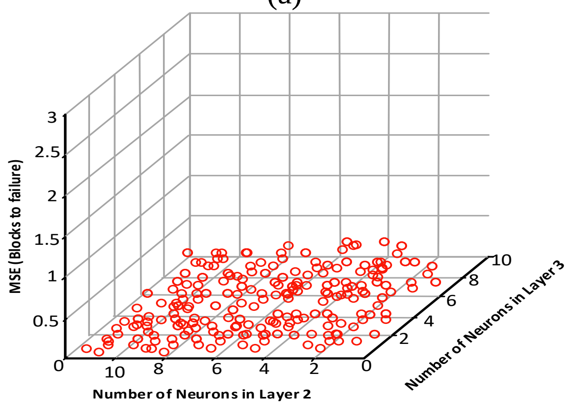
Figure 5.24 Trained 3D scatter plots of MSE for Mo with (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9, and (j) 10 neurons in the first HL



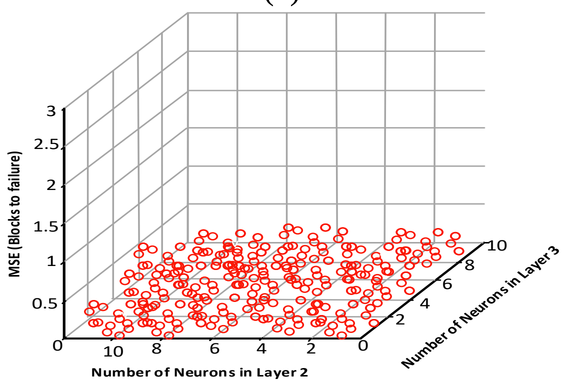
(a)



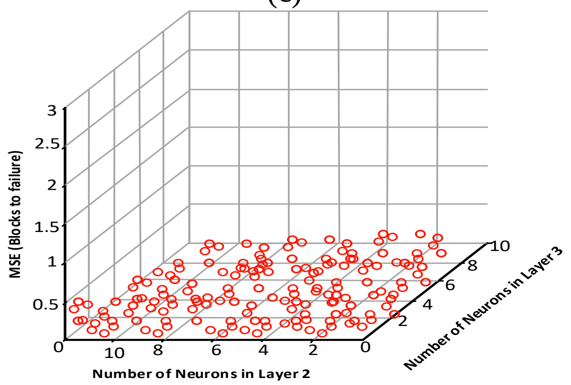
(b)



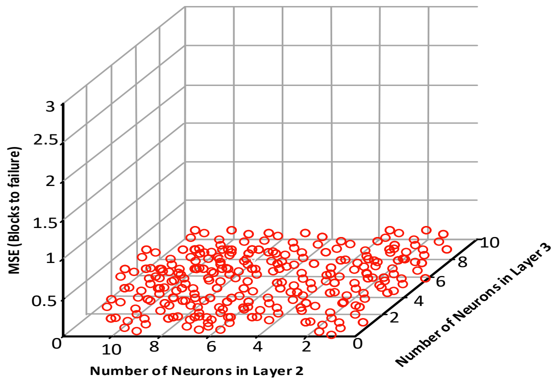
(c)



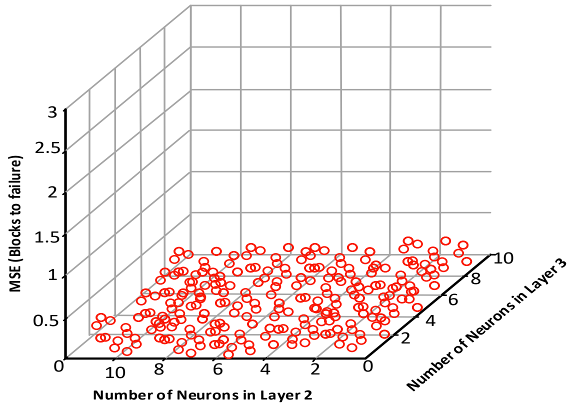
(d)



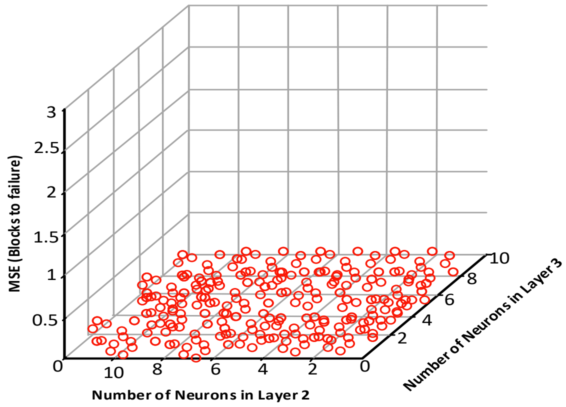
(e)



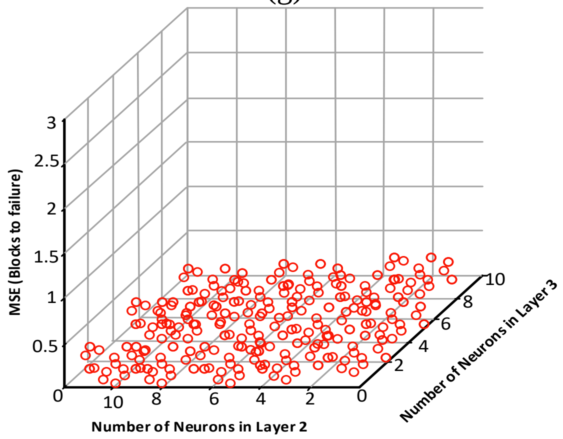
(f)



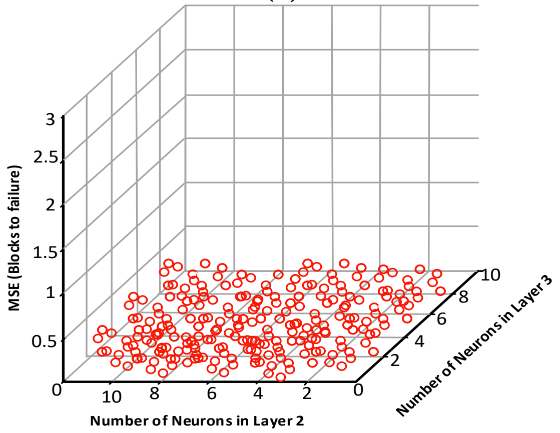
(g)



(h)

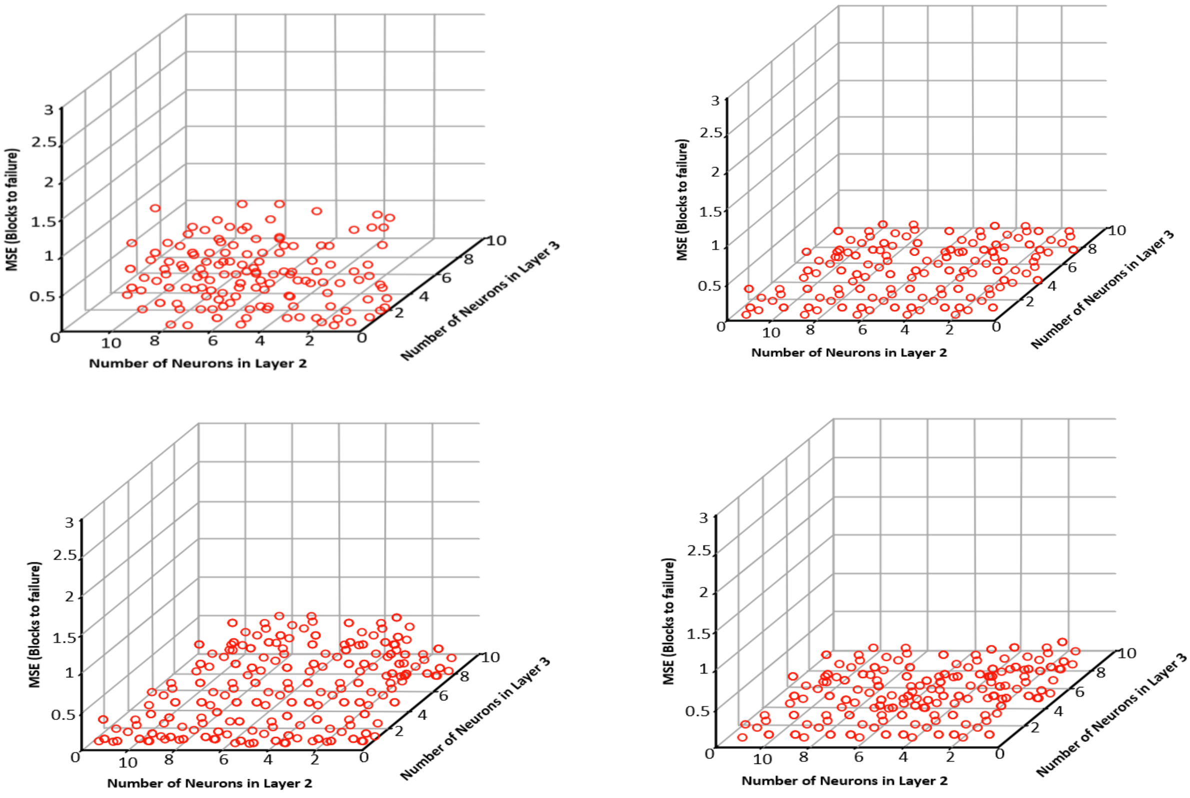


(i)



(j)

Figure 5.25 Trained 3D scatter plots of MSE SWT with (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9, and (j) 10 neurons in the first HL



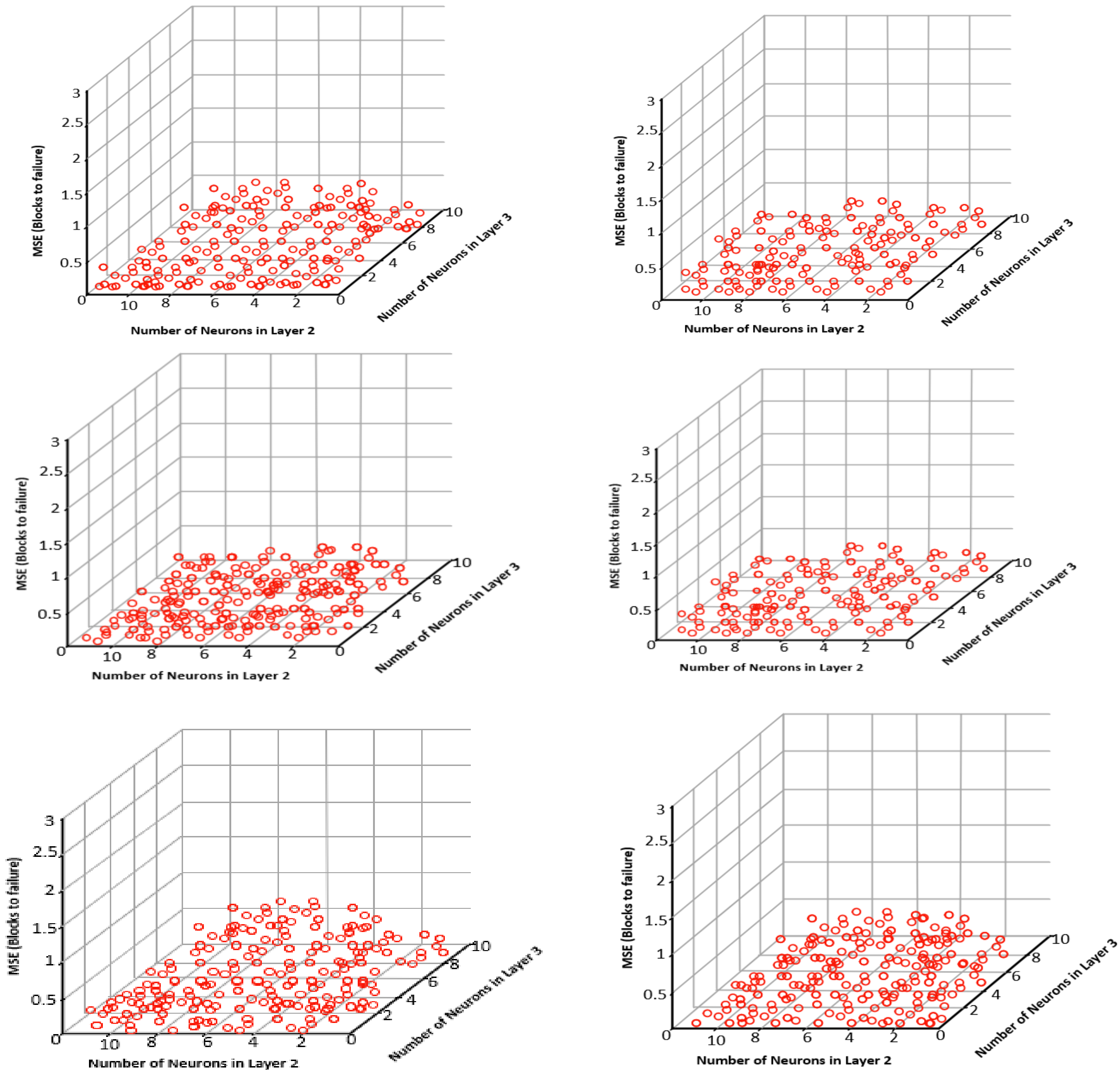


Figure 5.26 Trained 3D scatter plots of MSE for I-Kaz with (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9, and (j) 10 neurons in the first HL

The training datasets were examined after the identification of HMLPANN models, including three hidden layers that demonstrated the lowest MSE values. The plotted fitted training datasets for the **CoM**, **Mo**, **SWT** and **I-kaz** HMPANN models, each including three hidden layers, are shown in ***Figure 5.27***. Based on the obtained R^2 values, it can be deduced that a significant correlation exists between the training datasets and the HMLPANN models, suggesting a good degree of alignment.

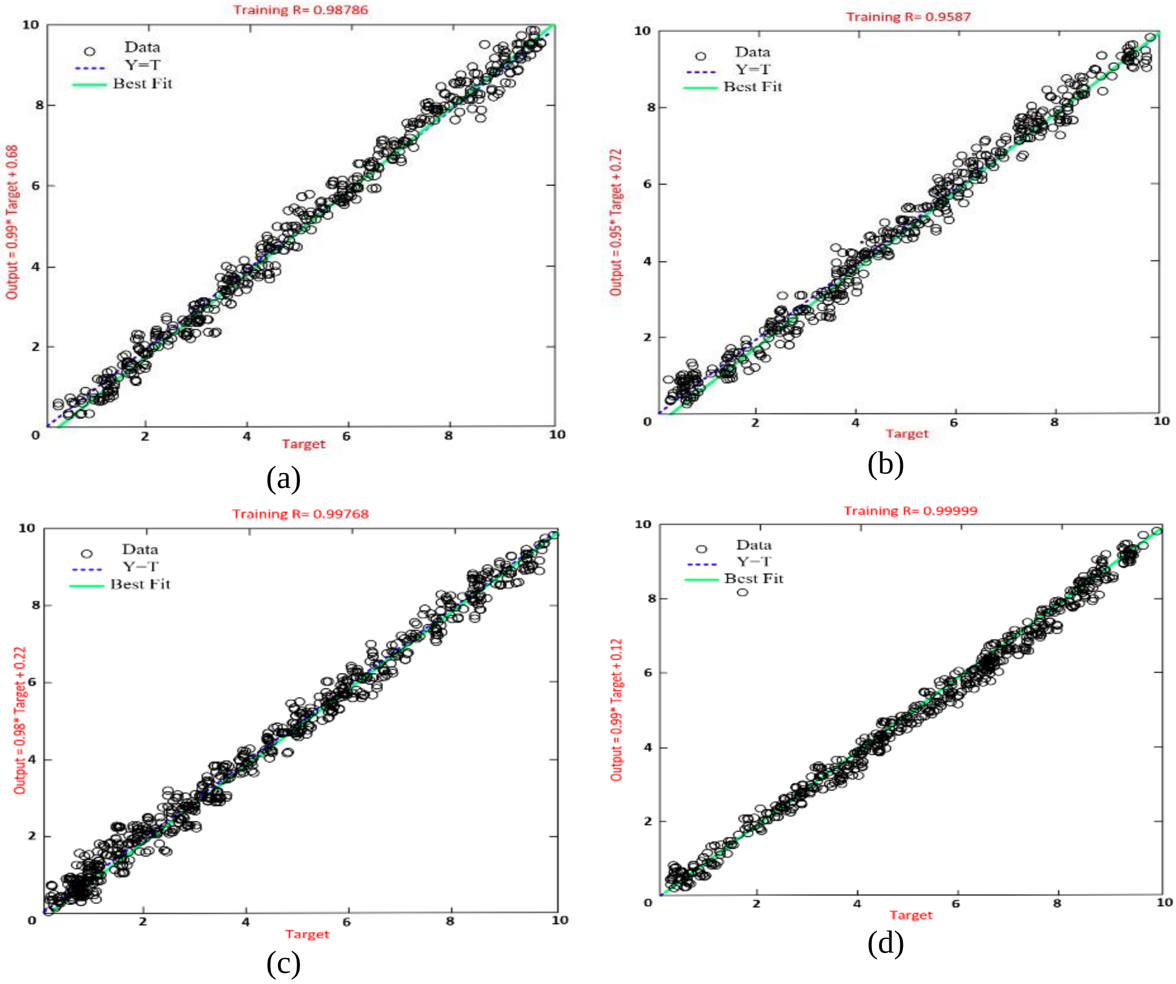


Figure 5.27 Trained curve fitting (a) CoM, (b) Mo, (c) SWT, and (d) I-Kaz with 3 HLs.

The diagram identified as ***Figure 5.28*** illustrates the testing dataset fitted for the **CoM** HMPANN model, which has undergone training. The estimated values for the R coefficient and R^2 coefficient are 0.9977 and 0.9940, respectively; the fitted testing dataset for the **CoM** HMPANN model is seen in ***Figure 5.28 (a)***. The R-value and R^2 value are shown as 0.9968 and 0.9936, respectively; the findings indicate a significant correlation between the testing data and the **Mo** HMPANN model, as seen in ***Figure 5.28 (b).*** The testing dataset fitted for the **SWT** HMANN model is shown in ***Figure 5.28 (c);*** the figure demonstrates that the fitted curve displays a correlation coefficient, R-value of 0.9668 and a coefficient of determination, R^2 value of 0.9347. The values for the R and R^2 coefficients are 0.9998 and 0.9996, respectively, for the fitted testing dataset for the **I-kaz** HMPANN model, is seen in ***Figure 5.28 (d)***. The trained HMPANN models with three hidden layers generally have continuous upward trends in the fitted curves, indicating a favourable data distribution.

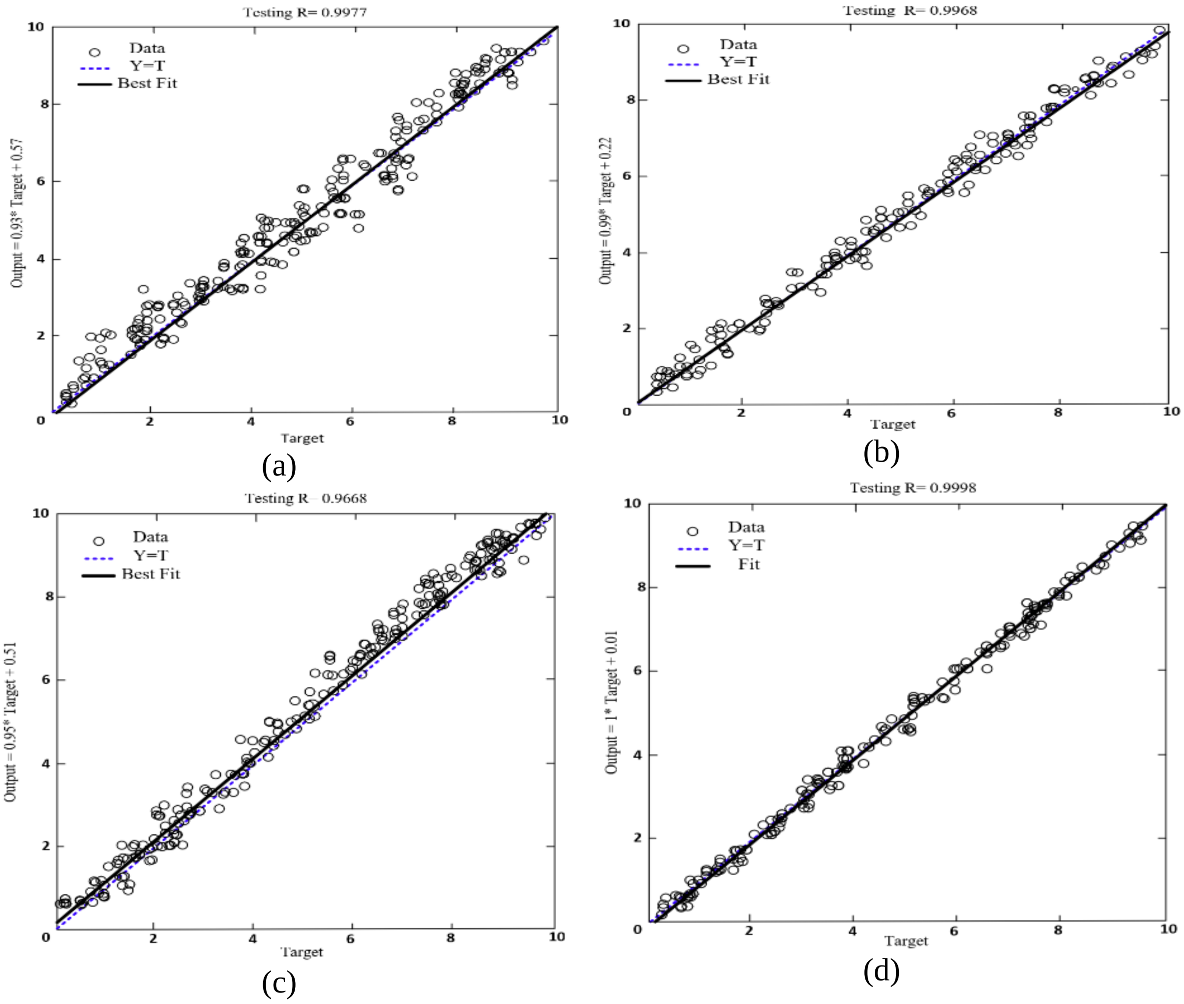


Figure 5.28 Test curve fitting for (a) CoM, (b) Mo, (c) SWT, and (d) I-Kaz with 3 HLs.

Table 5.2 shows the MSE values attained by the ANN models, which were trained using one, two, and three hidden layers. The methods shown in ***Figures 5.17*** to ***5.28*** resulted in the acquisition of the HLMPANN that exhibited the lowest MSE. The analysis yielded a significant finding: the successful discovery of a suitable HMPANN structure to maximise fatigue life, as seen in ***Figures 5.13*** **to** ***5.16***. The ANN designs that demonstrated the MSE values were chosen for further validation. The selected architectural design, namely a HMPANN, showed a high level of efficacy in accurately forecasting fatigue life via empirical data.

Table 5.2 Comparison between MSE for different hidden layers

Model	Coffin-Manson	Morrow	SWT	I-kaz
One hidden layer	0.0773	0.0753	0.1546	0.0543
Two hidden layers	0.0237	0.0273	0.0742	0.0146
Three hidden layers	0.2645	0.2353	0.2462	0.1487

The analysis of the MSE values shown in ***Table 5.2*** indicates that the HMPANN models proposed by **Mo** and **SWT** exhibit enhanced predictive performance when using three hidden layers, as compared to models with one or two hidden layers. The **I-kaz** has the lowest MSE of 0.0543, 0.0146, and 0.1487 regardless of the number of hidden layers and then **CoM, Mo,** and **SWT** HMPANN models have the low MSE values of 0.0249, 0.0117, and 0.0824, respectively but still higher than the **I-kaz**. These optimal MSE values are achieved when the **I-kaz** model consists of two hidden layers, while the **CoM, Mo** and **SWT** models consist of three hidden layers each. The experimental data obtained from a real vehicle consisted of strain and acceleration time records; these data were afterwards analysed to determine fatigue life according to ISO 2631 vertical vibration. The ISO 2631 vertical vibration data received from the experiment and the computed suspension frequency were used as input for the HMPANN model, as seen in ***Figures 5.13*** **to** *5.16***.**

The output of the model was the anticipated FL determined by the ANN. Therefore, additional analysis was conducted on these models to assess the degree of deviation between the projected and intended data. The accuracy of the fatigue life predictions was estimated by validating the projected fatigue life of the ANN with the experimental FL, using a correlation ratio of 1:2 or 2:1. ***Figure 5.29 (a)*** illustrates the correlation analysis and comparison between the anticipated FL of the car coil spring using the trained **CoM** HMPANN model with two hidden layers and the desired FL. The correlation analysis was conducted using a sample size of 14 data points from the testing data. The observed data points align strongly with the 1:1 and 1:2 or 2:1 correlation, as seen by their proximity to the corresponding correlation lines. Therefore, it can be inferred that the **CoM** HMPANN model, which has been trained with two hidden layers, can predict the fatigue life of an automobile coil spring with satisfactory accuracy.

Figure 5.29 (b) illustrates the correlation between the intended FL and the projected FL, as determined by the **Mo** HMPANN model using three hidden layers. Most of the data points projected by the **Mo** HMPANN model exhibit a strong alignment with the 1:1 and 1:2 or 2:1 correlation. Nevertheless, a tiny deviation exists in one of the data points from the expected 1:2 or 2:1 correlation, as shown by its position above the top 1:2 or 2:1 correlation line. Nonetheless, the 13 remaining data points are within the confines outlined by the 1:2 or 2:1 correlation line. This suggests that the **Mo** HMPANN model, which has been trained with three hidden layers, can reasonably predict the fatigue life of the car coil spring.

Similarly, the plotted graph in ***Figure 5.29 (c)*** illustrates the correlation analysis and comparison between the target FL and the anticipated FL generated by the **SWT** HMPANN model, which has three hidden layers. Two data points deviate from the borders delineated by the 1:2 or 2:1 correlation line, although remaining in close proximity to the top boundary. Based on the analysis, it can be inferred that the **SWT** HMPANN model, which has been trained with three hidden layers, can forecast the FL of the coil spring. However, its predictive accuracy is somewhat inferior to the **CoM** and **Mo** HMPANN models.

Figure 5.29 (d) illustrates the correlation analysis and comparison between the target FL and the anticipated FL generated by the **I-Kaz** HMPANN model, which has three hidden layers. Two data points deviate from the borders delineated by the 1:2 or 2:1 correlation line, although remaining close to the top boundary. Based on the analysis, it can be inferred that the **I-kaz** HMPANN model, which has been trained with three hidden layers, can forecast the FL of the coil spring with very high accuracy. The HMPANN that was suggested was validated using a collection of five experimental datasets gathered from real-world testing of cars. According to ISO 2631-1:1997, the automotive spring FL vehicle vibration was included in these datasets. This usage was performed to determine whether or not the suggested HMPANN was accurate.

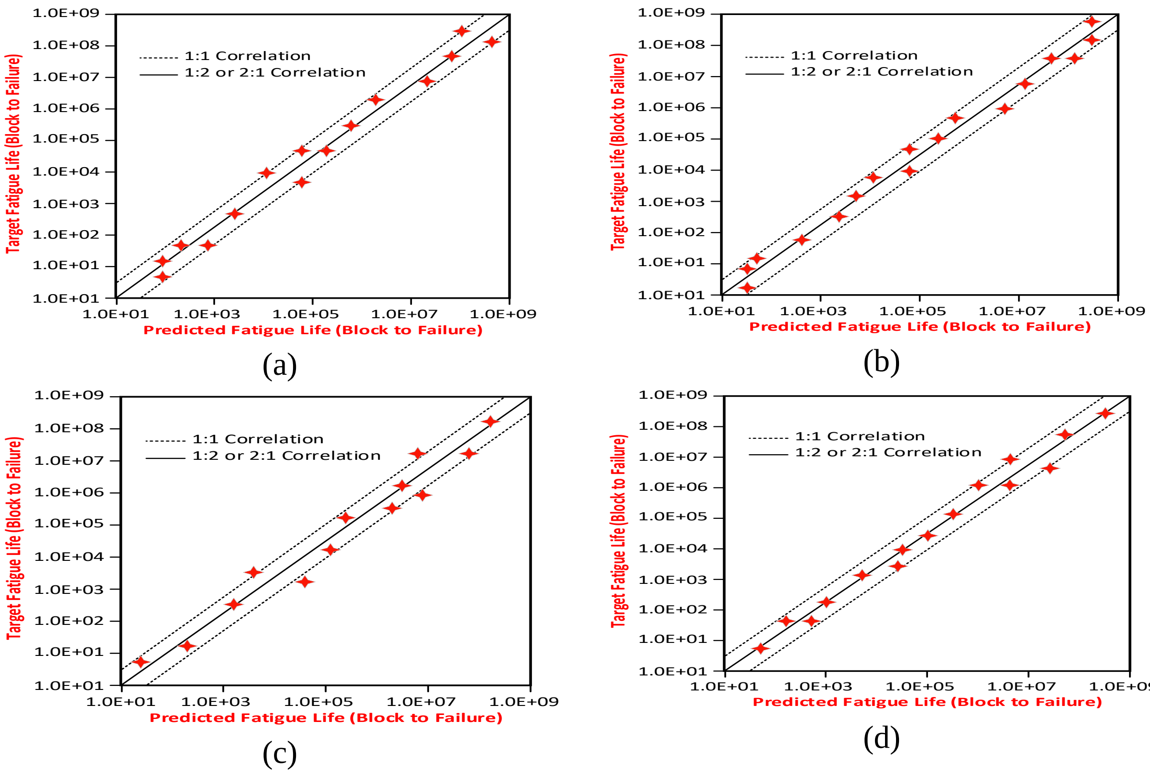


Figure 5.29 (a) CoM, and (b) Mo with 2 HLs, (c) SWT, and (d) I-Kaz with 3 HLs

Figure 5.30 (a) illustrates the correlation analysis and comparison between the target FL and the anticipated FL. It was easy to include all data points inside the predetermined boundaries. The findings suggest that the **CoM** HMPANN model appropriately predicted the FL of the spring. It is important to note, however, that the **Mo** HMPANN model contains three fatigue data points outside the constraints indicated by the 1:2 or 2:1 correlation line, as shown in ***Figure 5.30 (b)***.

Additionally, the **SWT** HMPANN illustrates the correlation analysis and comparison between the target FL and the anticipated FL. The **SWT** HMPANN model has shown promising results but not as promising as **I-kaz**, displayed in ***Figure 5.30 (c)***. ***Figure 5.32 (d),*** on the other hand, the **I-kaz** HMPANN model has shown promising results in terms of its ability to forecast the future, as proven by the fact that all of the data points are contained inside the boundaries. Through experimental data validation, this work aimed to evaluate the efficacy of the currently available HMPANN models in estimating the FL of springs when applied to real-world automotive applications.

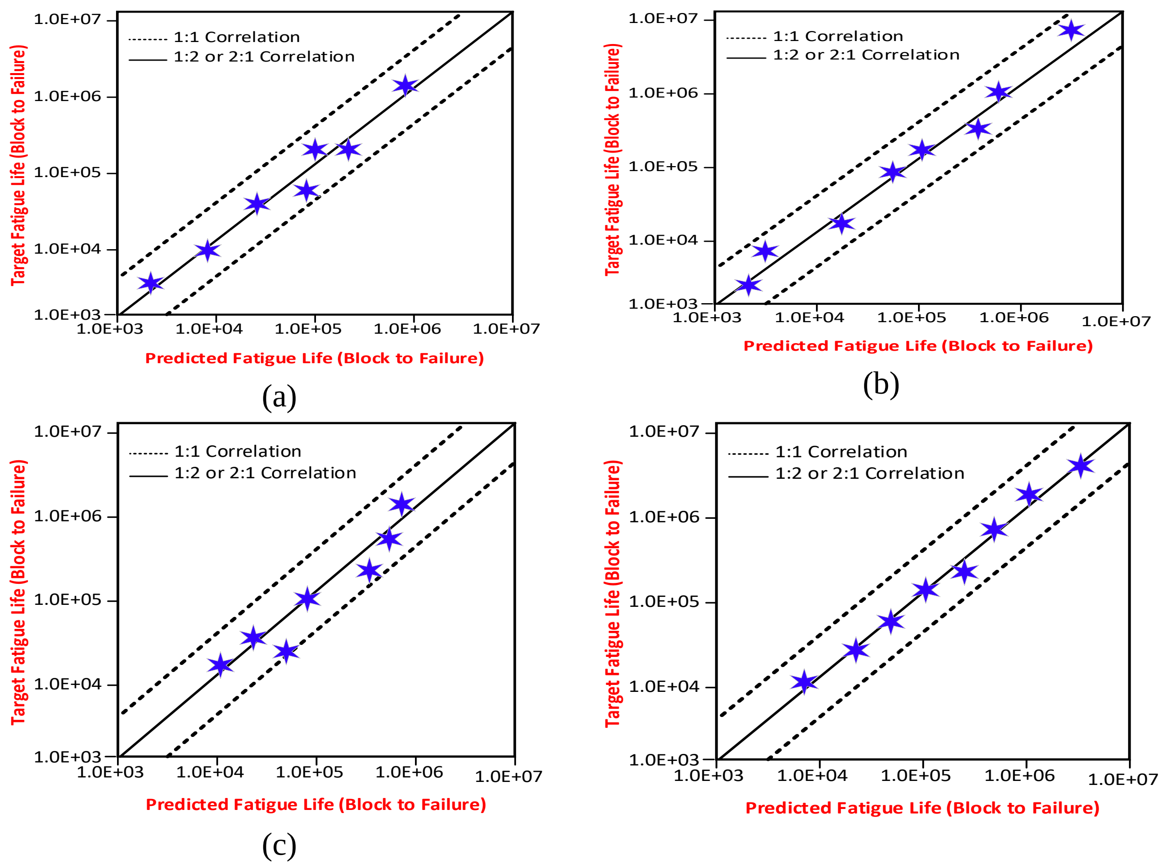


Figure 5.30 (a) CoM, and (b) Mo with 2 HLs, (c) SWT, and (d) I-kaz with 3 HLs

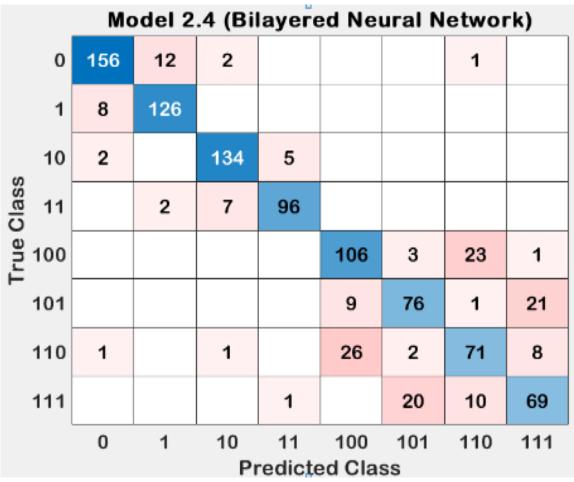
Because of its exceptional effectiveness in emulating the human brain's cognitive processes, ANN modelling is widely employed in vehicle engineering. This resolves complex problems possible. However, improving the performance of ANN models is of the utmost importance. This performance improvement may be accomplished by reducing the mean squared error values, abbreviated as MSE. Therefore, in the current inquiry, the effectiveness of the ANN models was boosted by using the Levenberg-Marquardt approach, an acknowledged optimum training strategy [494]. In addition, the author of this thesis manipulated the number of neurons included in the FANN models' hidden layers to locate the optimum number of neurons [484].

The hyperbolic tangent sigmoid transfer function was used to connect the input layer with the hidden layer/s. However, to maximise the usefulness of ANN models, it is often necessary to use more complex methods. This is accomplished via the adaptation of ANN design blueprints to the requirements of a certain application. Altering the number of neurons in the hidden layers is not the only way to enhance the predictive ability of ANN models. Constructing new types of ANN models is also feasible rather than just adjusting the total number of neurons in the hidden layers [495]. The current study includes the selection of optimum HMPANN models, which were chosen by considering a variety of parameters including the number of neurons present in the hidden layer(s), the number of hidden layers, and the particular architecture used.

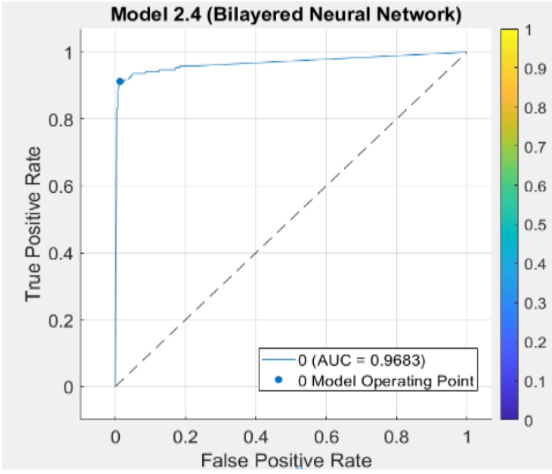
According to the results, the HMPANN models used in this study are anticipated to substantially assist designers and engineers in their capacity to predict the FL of vehicle coil springs. The findings of this research demonstrate that ANN is an appropriate tool for analysing vibrations and determining the FL of components used in automotive applications. It has been shown that using HMLPANN models can accurately anticipate the FL of vehicle coil springs. The time required for the design, development, and testing of prototypes may be significantly cut down due to this, which is a significant benefit.

As a consequence of this, the use of this strategy may result in cost reductions during the manufacturing of fresh iterations of car suspension systems. When it comes to the design and development of vehicle suspension systems, one of the key challenges that designers and engineers have is the application of knowledge obtained from an earlier version of the vehicle to a newer version [496]. When optimum HMPANN models are used, it is possible to quickly and easily forecast the fatigue life of a unique kind of automotive coil springs. This is made possible by the use of optimal modelling. When taking into consideration the ISO 2631-1:1997 vertical vibrations of the vehicle as well as the natural frequencies of the suspension system, it is possible to estimate the FL of the automotive coil spring, and it is also possible to obtain an immediate influence on the spring's stiffness. It is believed that using optimum HMPANN models may substantially aid designers and engineers in determining the durability of automotive coil springs and carrying out vibration analysis for vehicle suspension systems.

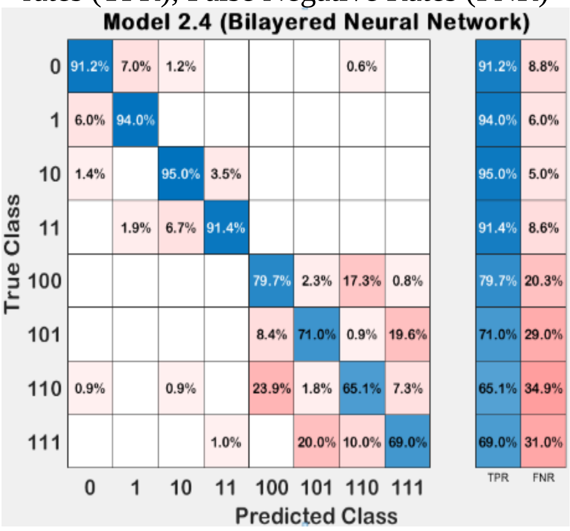
ANN confusion matrices



ROC Curve Validation



83.8 % ANN Confusion matrix true positive rates (TPR), False Negative Rates (FNR)



83.8 % ANN Positive predicted values (PPV), False Discovery Rates (FDR)

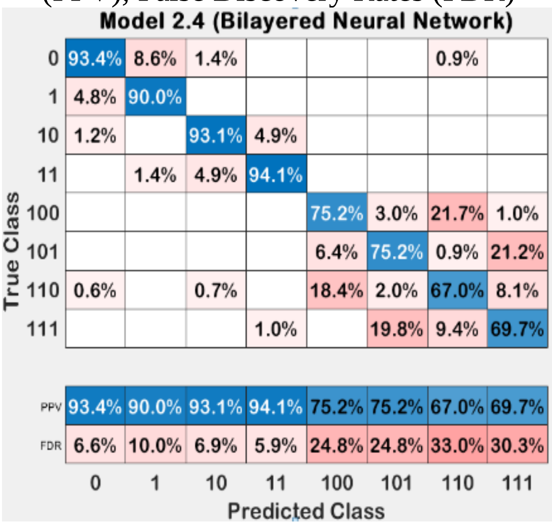
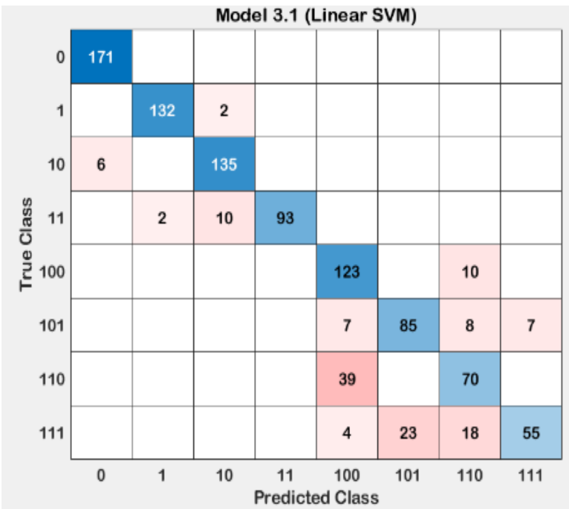
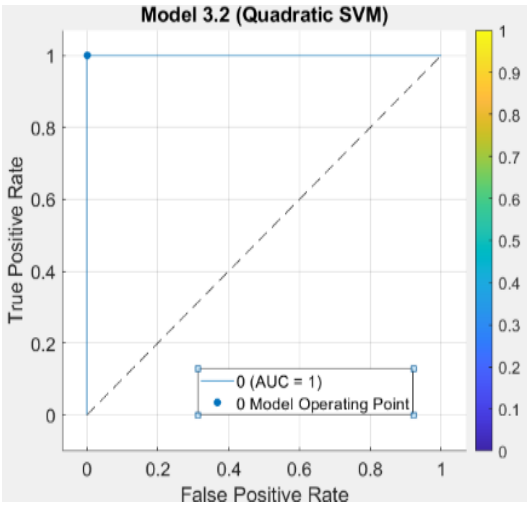


Figure 5.31 Confusion matrices and the ROC curve validation for the ANN

SVM Confusion matrix



ROC Curve Validation



87.6% SVM Confusion matrix true positive rates (TPR), False Negative Rates (FNR)

87.6% SVM Positive predicted values (PPV), False Discovery Rates (FDR)

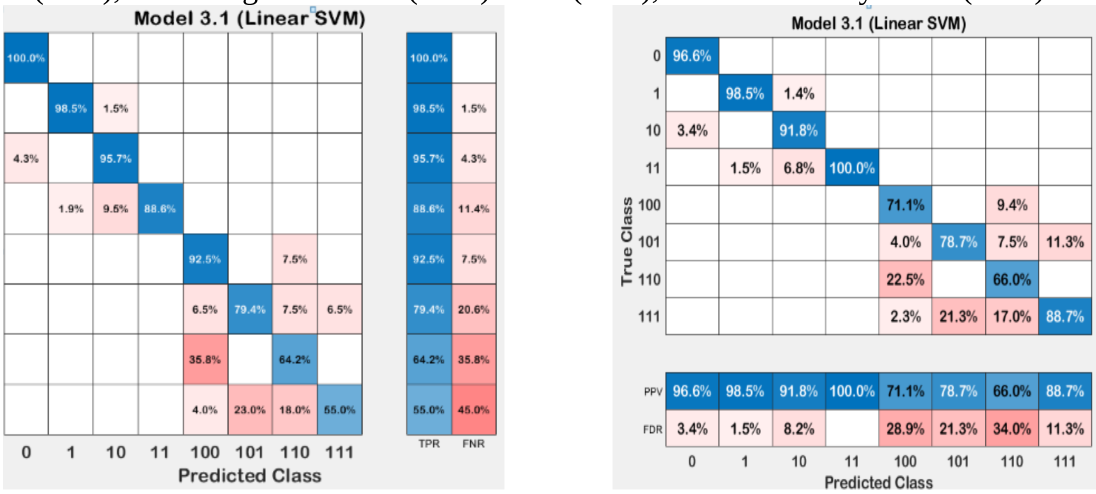


Figure5.32 Confusion matrices and the ROC curve validation for SVM

4.1 *ADTM Accuracy Validation*

The model's accuracy can be measured by examining how closely the predicted outcome value corresponds to the actual value and then comparing those two to the values that occurred. Because of the model's multidimensional structure generated by the seven factors supplied, it is impossible to represent the output as a function of the input in this particular instance. Evaluating the model's performance will be easier if we plot the output the model predicts and then compare it to the actual output. Consequently, it is feasible to display the projected output as a function of the true output using the code plot (YTrainTrue, YTrain, 'x'). The axis that represents the true output is called the X axis, and the axis that represents the predicted value is called the Y axis. The line graph depicts how the model's projected values match the true values, demonstrating that the model is great for predicting and picking the most suitable applicants for the post. ***Figure 3.33*** below illustrates an ideal linear relationship between the expected values and those obtained.

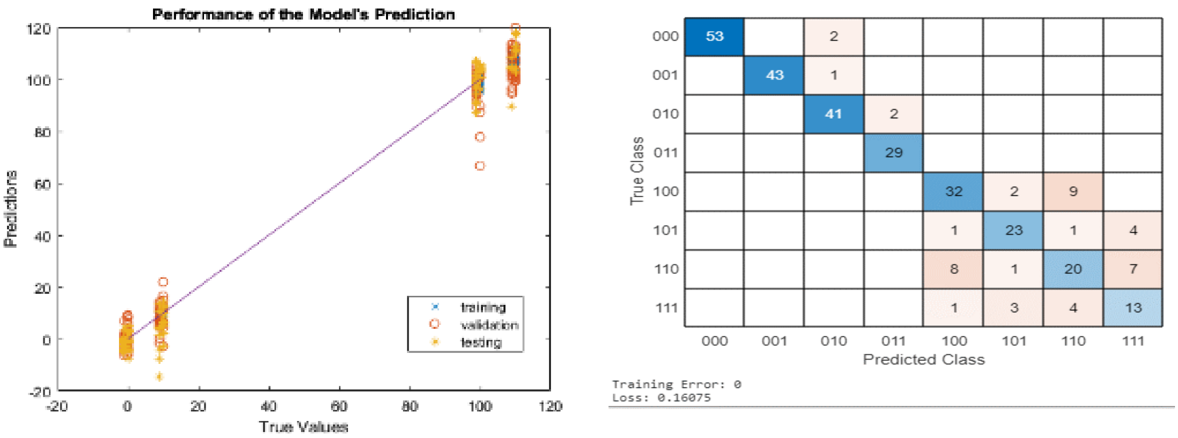


Figure 5.33 Performance of the ANN model with the confusion matrix

4.2 *Regression, Performance and Error Histogram Validation*

A statistical modelling method known as linear regression can quickly and efficiently fit and evaluate even the most complex non-linear models. The linear regression of the complicated relationship between the input data and the output demonstrates the model's exceptional dependability with a value of R = 0.99986. These results show that the model perfectly fits and performs exceptionally well across all training, validation, and test sets. The ANN model of 0.01726 of the training aligned with three epochs displays its greatest performance in ***Figure 5.33***, which can be found below. Because the validation and test data have the best fit exactly in the middle where it has been green ringed, the mean square error of logs can reach up to 103 on the Y axis, whereas the mean square error of logs can only reach six epochs on the X axis. The following graphic depicts the occurrences compared to the errors, where the errors, in this particular scenario, are equivalent to the targets, which are the outputs. Because it is equivalent to 0.06514, a zero-error value, the error is so minute that it is essentially insignificant.

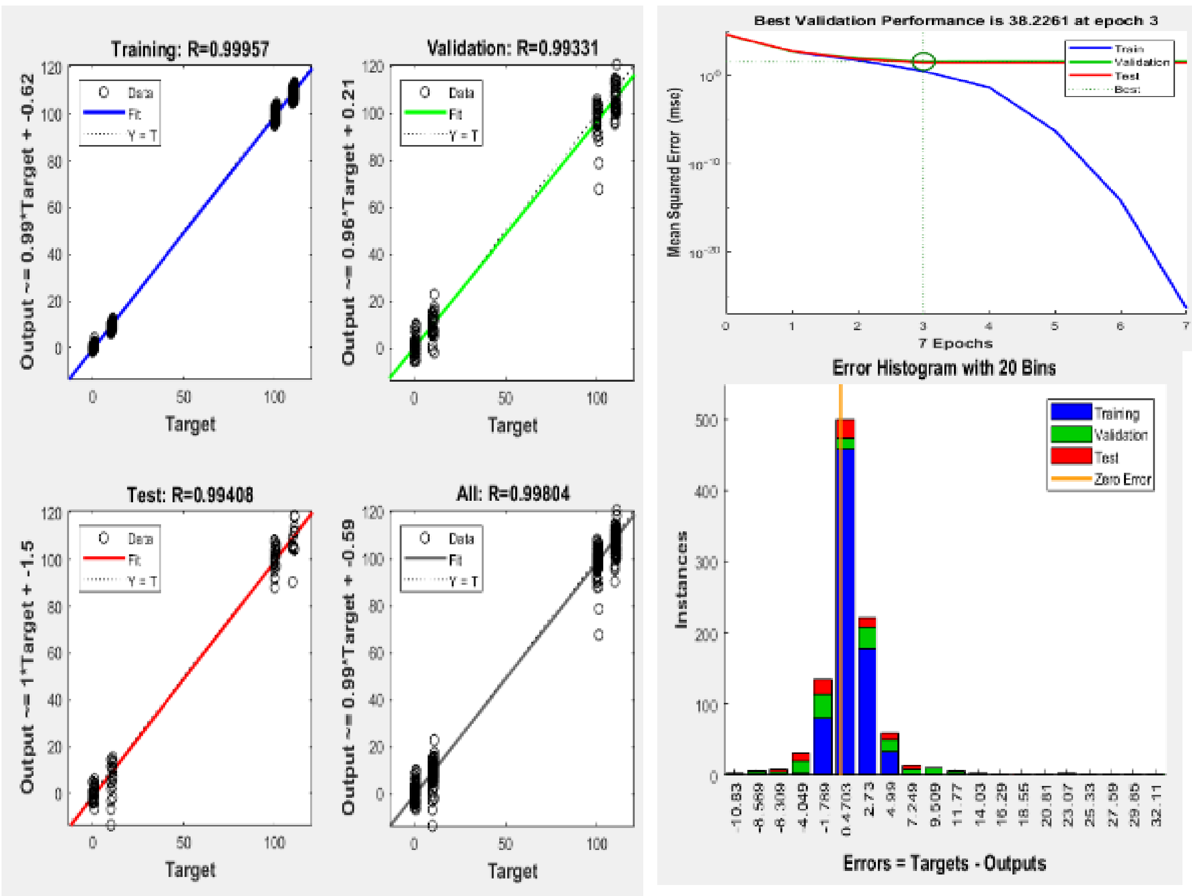


Figure 5.34 Improved regression, performance, and EH for the ANN

5 CHAPTER SUMMARY

This chapter aimed to enhance the accuracy of predicting the FL of automobile coil springs by integrating HMPANN topologies with the **I-kaz, CoM, Mo,** and **SWT** SL models. In order to ascertain the optimal HMPANN models that provide the lowest MSE values, the number of neurons inside the hidden layer(s) and the number of hidden layers were systematically manipulated. The optimal **CoM** HMPANN model is determined to include two hidden layers. The first hidden layer consists of three neurons, while the second hidden layer consists of seven neurons. The MSE for this model is calculated to be 0.0237. The optimal models proposed by **Mo** and **SWT** for the HMPANN architecture have three hidden layers, with MSE values of 0.2353 and 0.2462, respectively.

The validation findings demonstrate that most of the data points projected by the optimal HMPANN models strongly align with the 1:1 and 1:2 or 2:1 correlation, as shown in the **I-kaz** method. The results indicate that the optimised HMPANN models can accurately forecast the fatigue life of automobile coil springs. These models provide the potential to simplify the design and development of car suspension systems by substantially reducing the need for prototype construction and testing. This will tremendously benefit designers and engineers working in the automotive sector.

ADTMs can accurately customise Industry 5.0 for each industry because an algorithm learns from machine data ANN. The potential to collect CRT and historical suspension system data was built into the model when it was initially developed. The findings will assist in developing a model that can further diagnose individual parts and subsystems and help industries and individuals use simulation technologies to diagnose, treat, and anticipate systems faults. The current focus of the ADTMs is on discovering difficulties and developing solutions to those problems to assist the users. This ADTM capability is one strategy that can be used to remedy the problem; however, in the future, the platform will help minimise the risk factors for suspension systems faults and produce live condition monitoring to prevent these faults. We solved the problem of real-time supervision with high accuracy in decision-making and prediction of future crises by proposing a framework called ADTMs. This framework was combined with an ANN. The feasibility of ADTMs is demonstrated using a case study of a suspension system. The accuracy of the training, validation, and testing phases were respectively 0.99997, 0.99954, and 0.9993, and the overall accuracy was 0.99986. The proposed ADTMs framework and the ANN model’s creation can record historical and CRT data and manage and predict current and future machine systems faults.

CHAPTER 6 **CONCLUSION**
CONCLUSION AND FUTURE WORK

CONCLUSION

This thesis conducted detailed research about the concept and technologies underlying DTs technology due to the ***gaps*** shown in the literature. The thesis is also organised to answer two main research questions. **Q1** What are the actual characteristics of the DT concept for standardisation across theory and practice? Furthermore, **Q2:** How to implement ADTs into PdM of mechanical springs used in suspension systems? So that it can predict the FD and RUL.

CHAPTER ONE presented the Background of DTs and fatigue analysis methods used for coiled springs, Problem analysis, Project aim, Research questions, Project limitations, and Motivations.

CHAPTER TWO Presented ***First Contribution*** of the thesis in the form of ***a*** comprehensive systematic review analysis and includes the publication contribution of a paper titled "***Comprehensive Systematic Analysis of Digital Twins: History, Concepts, Development, Applications, Challenges, Gaps and Future Work***".

Additionally, the literature showed a need for more shared understanding between theory and practice and a lack of standardisation, leading to misconceptions about the DTs. In addition, there needs to be more development and integration of actual DTs into the system. Moreover, the DTs do not correspond to the description provided in the relevant literature. Furthermore, there needs to be more mathematical design experience, and lifecycles are still formulated using estimates and hypothetical best cases. The findings from the research published in the academic literature indicate that during the system's operation, there needs to be more attention paid to the simulation during operation. Moreover, there was no integration of DTs and AI into systems.

The heterogeneity in the distribution of DT applications worldwide is palpable, echoing the variances in technological advancements, industrial focus, and developmental strategies among countries, as shown in ***Table 2.5***. The future trajectory would likely witness an escalated integration of DTs across industries, with a potential tilt towards achieving sustainability, enhancing productivity, and fostering innovative developments underpinned by harmonising global standards and practices. As shown in ***Table 2.5*** *and* ***Figure 2.12***, the global application of DTs encapsulates myriad implementations, reflecting the respective technological prowess, economic focus, and developmental needs of different regions and countries. It heralds a realm where virtual and physical realities converge, offering insights, foresight, and enhanced management across various domains. The scope and impact of these applications continue to evolve, shaping and being shaped by the global technological, economic, and developmental trajectories of regions.

While PAv and DT inhabit the sphere of digital representation, understanding their distinct functionalities, applications, and focus is pivotal, as shown in ***Table 2.6***. Clarity in these concepts allows businesses and industries to leverage them aptly, ensuring they extract optimal value in enhancing user experiences and operational efficiencies. Though DTs and CPS harness the confluence of physical and digital worlds, understanding their distinctive focal points, functionalities, and applications is crucial, as shown in ***Figure 2.13***. Unpacking these nuanced distinctions aids in avoiding misconceptions and ensures their apt and effective deployment in various technological and industrial realms, as shown in ***Table 2.7***. Consequently, this enables organizations and researchers to harness their specific capabilities, driving innovation and efficiency in respective applications.

Figure 2.14 and ***Table 2.8*** Understanding the intrinsic differences between DMs and DTs is pivotal to harnessing their respective capabilities aptly in varied domains. While DMs offer value in design and visualization, DTs unfold advanced possibilities in monitoring, analysis, and optimization, catering to different spectra of requirements in the digitalization journey of entities and systems. This discernment clarifies conceptual misconceptions and guides toward informed application in practical scenarios across diverse industries. ***Figure 2.15*** and ***Table 2.9*** deciphering the distinctive attributes between DS and DTs is pivotal to negating misconceptions and deploying them aptly in varied domains. The static, non-interactive nature of DS makes it suitable for basic visualization and documentation, whereas the dynamic, interactive, and analytical prowess of DTs unlocks avenues for advanced applications like real-time monitoring and predictive analysis. Understanding these differential functionalities enables technologists and organizations to implement these digital replicas effectively, aligning them with specific requirements and applications in the digitalization journey of physical entities and systems.

Figure 2.16 and ***Table 2.10*** present an understanding that the conceptual and functional differences between DTs and DTW are fundamental to eliminating misconceptions and effectively harnessing their respective capabilities. The isolated, focused capabilities of a DT and the collaborative, network-oriented functionalities of a DTW cater to different requirements and applications within the digital transformation landscape. Recognizing these distinctions ensures accurate implementation and maximizes the potential benefits of these advanced technological concepts in various industrial domains. ***Figure 2.17*** and ***Table 2.11*** present discerning the conceptual and practical differences between DT and a hypothetical notion like PT, which is vital to negate misconceptions and strategically deploy them in their pertinent domains. While the DT capitalizes on digital replication, real-time monitoring, and virtual control, a PT would theoretically centre around tangible representation and physical experimentation. These distinctions enable organizations and individuals to apply these concepts judiciously, optimising their characteristic advantages in relevant applications and scenarios.

Figure 2.18 and ***Table 2.12*** present the IoT and DTs as pivotal components in smart technologies and digital transformation; their distinct functionalities, purposes, and applications must be acknowledged to eliminate misconceptions and optimize their respective potentials. IoT primarily anchors on inter-device connectivity and data exchange, while DTs emphasize creating a dynamic digital replica for simulation, analysis, and control of physical entities. Understanding these distinctions ensures that both concepts are leveraged effectively in their relevant domains, augmenting various sectors' digitalization and intelligent operational capabilities. The marriage of AI and DTs unfurls a canvas where DEs and PEs coalesce, fostering a reality where data-driven insights, predictive intelligence, and intelligent autonomy are not merely theoretical but pragmatically achievable and observable. This fusion elevates operational efficiencies and predictive capabilities and heralds a future where technological entities are not merely tools but collaborative partners in decision-making and operational management, thereby redefining the contours of smart operations in Industry 4.0. the integration characteristics between AI and DTs can be summarised as follows:

A. *Intricate Data Analysis*

The integration converges the physical and digital realms, allowing the multidimensional data from the DTs to be selectively analysed by AI algorithms. This symbiosis paves the way for sophisticated data analysis, ushering in enhanced predictability and insightful discoveries by understanding patterns, anomalies, and possible futures outlined by historical and RT data.

B. *Proactive Decision-Making*

With AI infusing its predictive and cognitive capabilities into DTs, decision-making transcends from being reactive to proactive. The AI algorithms, enriched with data from DTs, can anticipate issues, propose solutions, and even initiate preventive actions autonomously, elevating the operational reliability and efficiency of the physical entity.

C. Amplified Innovation

In the landscapes of design and development, AI-empowered DTs facilitate simulated testing and validation of prototypes in a risk-free digital environment. This intersection enables innovators and engineers to explore, iterate, and validate scenarios digitally before physical implementation, substantially reducing costs and nurturing innovation by providing a platform to test and learn from failures without tangible consequences.

D. Dynamic Synchronization

AI and DTs collectively establish a dynamic, synchronized relationship between physical and virtual worlds. AI leverages the data from DTs to optimize operations and predict trends, while the Digital Twin mirrors these optimized strategies in the virtual model, continuously aligning itself with the evolving physical entity, thereby establishing a bi-directional feedback loop.

E. Human-AI Collaboration

The collaborative environment between human experts and AI data-driven DTs facilitates shared intelligence and decision-making, where AI's data-driven insights and predictive capabilities complement human intuition and expertise. This synergy fosters an enhanced decision-making matrix, ensuring that decisions are insightful, validated, and holistically devised.

The review and analysis carried out in ***Chapter 2*** identified four characteristics/dimensions of the actual DT technology to be standardised and implemented across theory and practice as follows:

9- Physical Asset / Entity (PE)
10- Virtual Replica/ Entity (VE) (3D modelling)
11- Connections between the PE and its VE
12- Current Real Time (CRT) data

Therefore, this research proposes these characteristics or dimensions to standardise the concept of DTs technology across theory and practice and identifies DTs as a "***Four dimensions virtual replica that continuously simulates the entire behaviour of anything.***"

CHAPTER THREE presented the ***Second Contribution*** of the thesis in the form of a Physics-Based DT Model titled "***Physics-Based Digital Twins for Vibration Fatigue Analysis and Modelling from Theory to Concept Implementation***".

Additionally, the approach to problem-solving was outlined using Euler's mathematical theories for the prediction used in the DTs technology. ***Chapter Three*** proposed a novel numerical concept of the DT based on EM. The DT model successfully replicated the mechanical behaviour and virtually represented the mechanics of materials for the physical coiled spring. This thesis successfully developed a numerical way to validate the proposed idea of the DT. The technique suggested still has limitations and is subject to further research. This chapter proves that DT is a virtual replica of anything, where the replication must mirror the entire internal and external mechanical behaviour of the replicated thing in the Current Real Time (CRT) with four dimensions. The DT model virtually represented all stresses acting internally on the spring. While the resulting strains and stresses are accurate based on EM, this paper proposed a novel concept for DT.

The DT model captured all the variations of the normal and maximum induced shear stress in CRT. Additionally, the model showed the instant representation of the system's behaviour and showed that vibration behaved similarly concerning the rough time compared to the conduct of the Linear SFV system in the case of free force. The damping effect in the system mentioned in the undamped linear TFV system section leads the output response to be slightly distorted compared to the rest of the spring's motion within the first few seconds of the spring's motion movement observed. The Non-Linear steady and transient forced vibration used in the un-damped case illustrates all measurements' output response (deflection, strain, maximum normal and induced shear stresses). The output for each of the four springs behaves harmonically with the same NF, with different values concerning the time due to the other geometric properties of each spring. Non-linear SFV Systems (Damped) are the same as the undamped system. The only difference is that throughout the analysis of springs' motions within the system, which is attached to the base, neither gets extended nor gets compressed.

The model shows the overall displacement of the coils and the displacement between each coil. The model still has some limitations and is open for further research; fatigue analysis is one of the types of failure that accrues to mechanical systems. Since all the stresses shown in the model's interface are in the current real-time, improving the model further for fatigue analysis is essential.

CHAPTER FOUR Presented ***Third Contribution*** of the thesis in the form of a published paper titled "***Digital Twins for Live Condition Monitoring, Diagnosis and Predictive Remaining Lifecycles"***. Additionally, it presented an Implementation, Evaluation, Validation, and

Verification of the proposed method through a case study used to compare and validate the proposed mathematical analysis. Additionally, it includes the third publication contribution of a paper titled. ***Chapter Four*** validates the proposed physical modelling method used in DTs of the coil springs introduced in ***Chapter Three***.

Chapter Four uses an experimental design for the validation through a cost-effective and straightforward DT model for LCM and PdM based on four dimensions instead of five. The first dimension is the Digital Entity (DE); DE is the Digital Model (DM). The second dimension is the Physical Entity (PE); the PE is the primary physical springs used in an existing suspension system and the integrated intelligent sensors (load and strain). The third dimension is the Connection Entity (CE) between the PE and the sensors, sensors and Internet of Things (IoT) platforms, IoT platforms and the DE. The fourth entity is the Current Real Time (CRT) data flow between all entities.

The experimental validation in this chapter contributes to the knowledge as follows:

- Fatigue analysis is based on CRT data that considers the impact of specific factors that cause systems' deterioration throughout a given period. Compared to the existing methods to analyse Fatigue Lifecycles (FL) where factors of systems' deterioration are based on predetermined empirical calculations, estimation or not considered.
- DT method is used to improve systems' empirical predetermined loads and lifecycles.
- The entire mechanical behaviours of systems are visualised in CRT.

The proposed DT model improves the empirical predetermined average load for simulation and experiment by 35.7 % (1.6 times more). Based on the actual load that the system experiences in the real-life case study, the DT model improves the empirical predetermined average lifecycles of the system by 12 times compared to the simulated results and nine times more compared to the experimental results. The proposed DT model still improves the average lifecycles of the system by 19.7% (1.2 times more) compared to the wireless DT model results based on the actual load applied to the system. A real-life case study of a suspension system in a Peugeot 3008 is used to demonstrate the proposed DT model's high accuracy and efficiency.

CHAPTER FIVE Presented the ***Fourth Contribution in the form of*** a paper titled "***Advanced Digital Twin Modelling for Predictive Fatigue Lifecycles of Coil Springs Based Machine Learning***". Additionally, it presented the integration between DT models and ML to advance the DT technology and bring the self-learning models as a revolution in industry 5.0. Additionally, includes the fourth publication contribution of

Chapter Five enhanced the accuracy of predicting the FL of automobile coil springs by integrating HMPANN topologies with the **I-kaz, CoM, Mo,** and **SWT** SL models. In order to ascertain the optimal HMPANN models that provide the lowest MSE values, the number of neurons inside the hidden layer(s) and the number of hidden layers were systematically manipulated. The optimal **CoM** HMPANN model is determined to include two hidden layers. The first hidden layer consists of three neurons, while the second hidden layer consists of seven neurons. The MSE for this model is calculated to be 0.0237. The optimal models proposed by **Mo** and **SWT** for the HMPANN architecture have three hidden layers, with MSE values of 0.2353 and 0.2462, respectively.

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ADTMs can accurately customise Industry 5.0 for each industry because an algorithm learns from machine data ANN. The potential to collect CRT and historical suspension system data was built into the model when it was initially developed. The findings will assist in developing a model that can further diagnose individual parts and subsystems and help industries and individuals use simulation technologies to diagnose, treat, and anticipate systems faults. The current focus of the ADTMs is on discovering difficulties and developing solutions to those problems to assist the users. This ADTM capability is one strategy that can be used to remedy the problem; however, in the future, the platform will help minimise the risk factors for suspension systems faults and produce live condition monitoring to prevent these faults. We solved the problem of real-time supervision with high accuracy in decision-making and prediction of future crises by proposing a framework called ADTMs. This framework was combined with an ANN. The feasibility of ADTMs is demonstrated using a case study of a suspension system. The accuracy of the training, validation, and testing phases were respectively 0.99997, 0.99954, and 0.9993, and the overall accuracy was 0.99986. The proposed ADTMs framework and the ANN model’s creation can record historical and CRT data and manage and predict current and future machine systems faults.

FUTURE WORK

Future research should consider the additional requirements to develop digital twins to higher maturity levels. These additional requirements include integrating more machine and deep learning to enable simultaneous data collection and tying the physical production system to its digital replica to provide continuous data for maintenance forecasts. It is required to adapt the maturity levels for the generation of digital twins in greater detail in production systems with low production quantities and significant lead times. Our knowledge of this method for producing digital twins and its applicability to real-world production settings would significantly improve. Future research on digital twins and digitisation should unearth a larger understanding of both of these topics, which should improve the process for developing digital twins and raise the level of standardisation in the area as a whole.

A. *Technical Aspect*

Improving Real-Time Simulation with DTs: The real-time simulation that is more accurate allows engineers and operators to visualise the dynamic behaviour of systems better while the systems are in operation. This simulation, in turn, allows operators to predict failure and avoid unnecessary downtime. [289], [497], [498]. Potential research questions might be

Q1- How might standardised information architectures and models for DT concepts in simulation look like?

Q2- What are acceptable forms of communication and interaction with DT concepts?

Modelling Consistency and Accuracy: Knowledge reuse and increased interoperability of production systems are made possible by modelling consistency in production systems. As a result of improved model accuracy, DT functionalities are enhanced, resulting in more consistent decision-making outcomes. [73], [499]. Accordingly, the potential research questions might be: **Q1-** What are the specifics of DT concepts for different products and industries? Q2- What is the relevant information for internal and external stakeholders?

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