S.No.	Name of the Journal/ Special Issue	International/ National Journal	Frequency (Monthl/ Quaterly/ Half Yearly/ Yearly	Publisher	Indexed at Wos/ SCOPUS (Yes/No)	Indexed in UGC-CARE (Yes/No)	Any other Indexing (please specify) (Yes/No)
1	MAIT Journal of Management	National	Yearly	Maharaja Agrasen institute of Technology	No	No	No
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MAIT

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OF SCIENCE AND TECHNOLOGY

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Foreword by
Dr. Nand Kishore Garg

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Maharaja Agrasen Institute of Technology
(Maharaja Agrasen Technical Education Society, New Delhi)

MAIT Journal of Science and Technology

FOREWORD

Dr. Nand Kishore Garg
Founder and Chief Advisor, Maharaja Agrasen Technical Education Society, Delhi
Chancellor, Maharaja Agrasen University, Baddi, H. P.



Education must be accompanied by innovative research and development to hold true value for the community, especially in our globally interconnected world where contributing to global knowledge is essential. I am pleased by the enthusiastic response from contributors and fellow educational institutions towards the inaugural volume of the 'MAIT Journal of Science and Technology' from Maharaja Agrasen Institute of Technology.

I commend the Editorial Board for their successful effort in compiling the diverse ideas and aspirations of our students and faculty into a cohesive publication. Additionally, I am delighted to see that this marks the third publication from Maharaja Agrasen Institute of Technology within just six months. Congratulations to its Office Bearers and Chief Editor for this remarkable achievement.

Dr. Nand Kishore Garg

MESSAGE

Shri Vineet Kumar Gupta
Chairman, Maharaja Agrasen Technical Education Society, New Delhi

Prof. (Dr.) Vikram Bali
Director
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NNurturing creativity and sparking innovation are essential pillars of effective education, and an Institute Journal embodies this perfect blend. It captures the creative spirit of the academic community, distilling their inspired ideas in a remarkable manner.

I am delighted to announce the forthcoming publication of the 'MAIT Journal of science Technology'—an Annual Refereed Journal from Maharaja Agrasen Institute of Technology, Delhi.

I extend my heartfelt congratulations to the Editorial Board for achieving this milestone as per schedule, which is truly commendable considering the dedication and effort invested. May our students continue to ascend to new heights, bringing honor to the world and their professions through the power of education!

Vineet Kumar Gupta

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Table of Content

Editorial Committee (MAIT Journal of Science and Technology) ..... *iii*

Journal Information……*iv*

Table of Content..... *v*

About the Journal..... ...1

Selection and CAE Analysis of Suspension System For 4-Wheel Efficycle.....3

The VASS Method of Communication: Romanticising the Professionally Unscripted Ad-libs…11

Comparison and Selection of Steering Geometry for 4-Wheel Efficycle…….16

Supercapacitor-Powered Urban Train: A Cost-Effective Alternative……..22

Dynamic Distribution Locational Marginal Pricing Strategy from Electric Vehicles…….29

RFID Technology Based Smart Shopping Cart……39

Vision-Guided Autonomous Holonomic Robot for Dynamic Indoor Environments……..46

Voice-Operated UAV System Using AI with Live Two directional Communication……59

ADVANCEMENT OF THIN FILM SOLAR CELLS……68

Aware Spatio-Temporal Graph Neural Network for Turbine-Level Wind Power Prediction…77

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ABOUT THE JOURNAL

The MAIT Journal of Science and Technology stands as a premier forum for publishing original research contributions and comprehensive technical review articles, emphasizing interdisciplinary and pioneering research across a wide range of engineering topics. The journal invites contributions from seasoned and emerging researchers, professionals, and other stakeholders to disseminate their knowledge and experiences. Published bi-annually, it spans all areas of Science, Technology, and Management, offering a rich repository of original research, comprehensive technical reviews, detailed analyses, critical evaluations, and investigations into innovative technologies, devices, systems, materials, processes, operations, performance, maintenance, and control within the engineering and management fields. As a leading peer-reviewed platform and an authoritative source of information, the journal caters to a diverse audience, including researchers, professionals, and industry stakeholders. We are thrilled to announce that Volume 2, Issue 1 of the MAIT Journal of Science and Technology will be available online in December 2025, furthering our commitment to sharing groundbreaking advancements and innovative research across multiple disciplines.

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Selection and CAE Analysis of Suspension System For 4-Wheel Efficycle

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Abstract

This research paper overviews how a suspension system can be selected, designed and simulated for a four-wheeled vehicle. This research paper discussed the purpose and selection criteria of suspension systems. This study also shows the calculation required under different conditions such as acceleration, braking and cornering. The calculations were further used for Computer-aided engineering (CAE) analysis to determine the total deformation, maximum stress and factor of safety.

For the analysis, we have calculated weight distribution under defined conditions, ride rate, tyre rate, spring stiffness and forces on suspension components such as suspension arms, mounting points, upright, etc. For CAE analysis we have used Ansys software because of its availability and ease of use.

Keywords: Computer-aided engineering (CAE), Suspension system, Efficycle, Ansys software, Spring stiffness, Ride rate, Tire rate

1. Introduction

A vehicle's suspension system connects the chassis to the wheels. The most important task of a suspension system is to maintain maximum contact between the wheel and the road in all driving conditions. The suspension system also provides comfort to the passengers by reducing the shocks and vibration on uneven roads. [1] There are three types of suspension systems: independent, dependent and semi-dependent. For our 4-wheel efficycle we have selected an independent double wishbone suspension system because of its increased handling and comfort.

CAE analysis is the most important part in the designing phase of the vehicle. With CAE analysis we can determine the performance of a suspension system under different loading conditions. It helps us to create the most optimal design and sets a benchmark for the manufactured product. We have used ANSYS software to find out the maximum stress, total deformation and factor of safety of components of the suspension system.

2. Literature Review

A Lot of research has been done on suspension systems including its type, optimizing methods, material and analysis process [2, 13]

2.1. Suspension system types: Suspension systems can be divided into three types which are independent, dependent and semi-dependent. This can be determined by the performance requirement of the vehicle. For heavy-bearing vehicles dependent suspension system is optimal and for a high-performance race car independent suspension system is preferred because of its high handling and and ride comfort. Semi semi-independent suspension systems can have the benefits of both dependent suspension systems and independent suspension systems.

2.2 Material selection: The selection of material has the most impact on the designing of a suspension system. It determines the weight, durability and performance of the vehicle. Lightweight material such as aluminium can have better performance in comparison to steel because it reduces unsprung mass which increases the overall performance of the system. [3]

2.3 CAE Analysis: We have done Finite element analysis to determine the maximum stress and total deformation of suspension components. For the analysis, we have calculated weight distribution, ride rate, wheel rate, spring stiffness and forces on suspension system components under different conditions such as acceleration, braking and cornering.

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3. Methodology

3.1. Functions of Suspension Systems [2]

- The most important function of the suspension system is to maximize the contact between the wheel and track. Greater contact between the wheel and track improves handling and control.
- The suspension system also distributes the vehicle weight across all wheels
- It also improves the driver comfort by reducing the bumps

3.2. Selection criteria of suspension system

For the selection of suspension system geometry, we have to consider the weight of the vehicle, performance required, driving conditions, cost etc.

- The suspension system should be lightweight so that the unsprung mass can be minimized but still be durable to support the vehicle weight, passenger weight and additional load.
- The suspension system should be able to provide maximum grip between the wheel and the track to ensure ride comfort and handling
- The suspension system should be cost-effective. An efficient design and analysis can reduce the material used without sacrificing the durability of the vehicle.
- The suspension system component should be durable and last a long time.

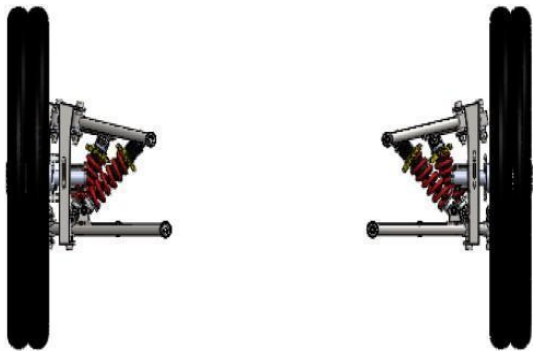


Figure 3.1: Front view

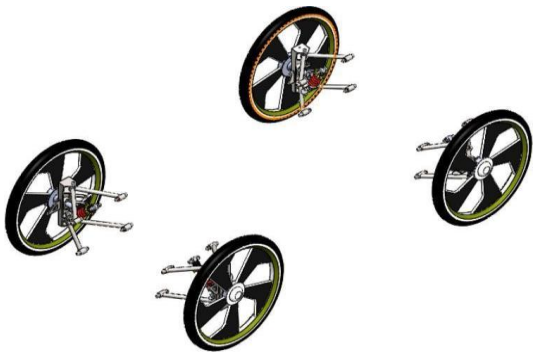


Figure 3.2: Isometric view

3.3. Finite element analysis (FEA):

- Mesh Generation: We imported the 3D suspension model into finite element software, such as ANSYS [4]. Create a mesh of the model, ensuring adequate element quality and density for accurate results.
- Boundary Conditions and Load Cases: Based on the expected operational scenarios and the requirements for the vehicle, define the proper boundary conditions and load instances. Load situations include static loads brought on by the weight of the vehicle, dynamic loads brought on by the unevenness of the road, and braking or turning forces.
- Analysis Setup: Configure the finite element analysis settings, such as solution type, material properties, and solver options.
- Structural Analysis: To assess the stress, strain, and displacement of suspension components under varied loading circumstances, perform linear or nonlinear static and dynamic analysis.
- Fatigue Analysis: Consider material parameters, stress concentrations, and loading cycles while doing fatigue analysis to determine the lifespan and durability of suspension components.

4. Numerical and CAE analysis

$Front\ Track\ width$: 939. $8mm$

$Rear\ Track\ width$: $1016mm$

$Wheelbase$: 1219. $2mm$

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$Weight$: 200 kg, 1960 N

$COG\ height$: 600mm

$Weight\ on\ front$ = w_f = 40%

$Weight\ on\ rear$ = w_r = 60%

4.1. Dynamic weight distribution

4.1.1. During acceleration

$$Longitudinal\ mass\ transfer\ on \text{ single } rear \text{ wheel} = \frac{(mass\ of\ car)\times(acclerationıs\ g)\times(COG\ height)}{wheel\ base\times 2} \quad (1)$$

$Longitudinal\ mass\ transfer\ on$ single $rear$ wheel lm_r= 334.715N
$Vertical\ Load\ transfer\ on\ rear\ wheel$ = $(weight \times w_r \times g) + lm_r$ = 842.719N

4.1.2. During braking

$Longitudinal\ mass\ transfer\ on$ single front wheel = 339.57N

$Vertical\ Load\ transfer\ on$ front $wheel$ = $(weight \times w_f \times g) + lm_f$= 1071.14N (2)

4.1.3. During cornering

$$Lateral\ mass\ transfer \text{ (front) } lr_f = \frac{(front\ mass\ of\ car)\times(corneringıs\ g)\times(COG\ height)}{track\ width\times 2} = 601.15\text{N}$$

$Vertical\ load\ on\ front\ corner$ = 993. 15N

$$Lateral\ mass\ transfer \text{ (rear) } lr_r = \frac{(rear\ \ mass\ of\ car)\times(corneringıs\ g)\times(COG\ height)}{track\ width\times 2} = 694.48\text{N}$$

$Vertical\ load\ on\ front\ corner$ = 1282.48N

4.2. Front spring stiffness

Ride Rate $k_r = 21.08Nmm^{-1}$

Tire Rate $k_t = 75Nmm^{-1}$

Installation ratio $IR^2 = 0.66$

Spring Stiffness $k_s = \frac{k_r \times k_t}{k_t - k_r} = 43.75Nmm^{-1}$ (3)

4.3. Rear spring stiffness

Ride Rate $k_r = 25.24Nmm^{-1}$

Tire Rate $k_t = 75Nmm^{-1}$

Installation ratio $IR^2 = 0.66$

Spring Stiffness $k_s = 87.32Nmm^{-1}$

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MAIT Journal of Science & Technology
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4.4. Forces on upright

height of lower ball joint = h_1

height of upper ball joint = h_2

lateral load = $w_{lateral}$

$$f_{top} = \frac{w_{lateral} \times h_1}{h_2} \quad (4)$$

$$f_{bottom} = \frac{w_{lateral} \times (h_1 + h_2)}{h_2} \quad (5)$$

For front,

f_{top} = 867.37N

f_{bottom} = 1575.58N

For rear,

f_{top} = 824.92N

f_{bottom} = 1494.35N

Radius of tyres R = 254mm

$w_{1brake} = 832.3N$

$w_{2brake} = 148.7N$

Torque on one front wheel = $w_{1brake} \times R = 211.4Nm$

Torque on one rear wheel = $w_{2brake} \times R + torque\ of\ motor = 102.96Nm$

4.5 Forces on arms

For front,

Upper arm $F_{upper} = F_{top} = 867.37N$

Lower arm $F_{lower} = F_{bottom} = 1575.58N$

For rear,

Upper arm $F_{upper} = F_{top} = 855.79N$

Lower arm $F_{lower} = F_{bottom} = 1540.78N$

4.6 Analysis of suspension components

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4.6.1 Front upright

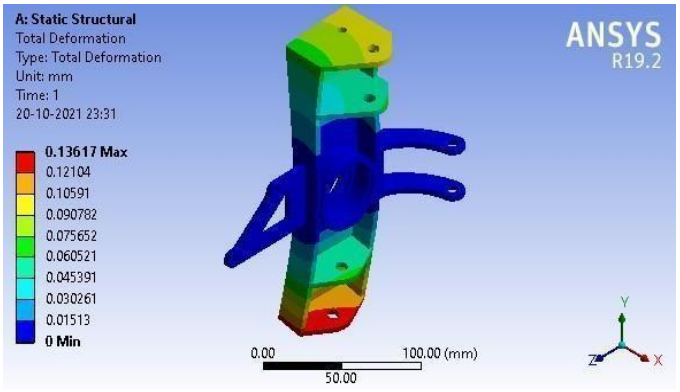


Figure 4.1:Maximum Total Deformation

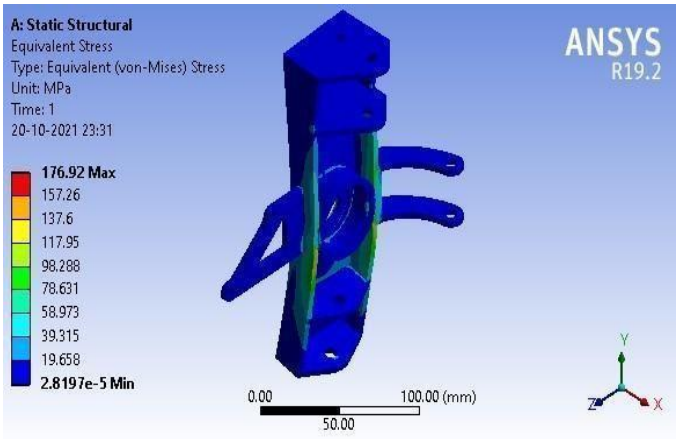


Figure 4.2:Maximum Stress

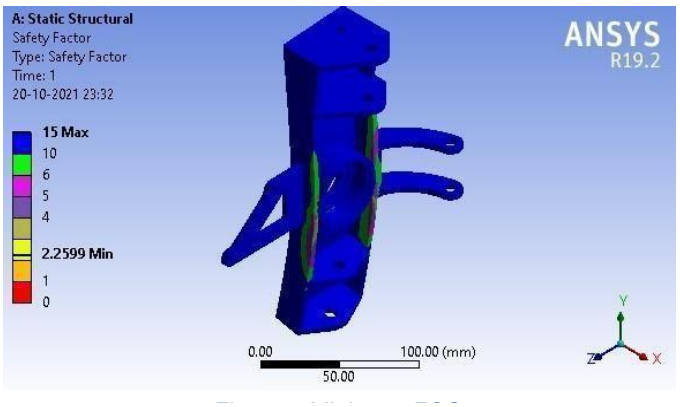


Figure 4.3: Factor of safety

- The maximum total deformation analyzed on the front upright is 0.13mm.
- The maximum stress analyzed is 176.92MPa.
- The minimum factor of safety analyzed is 2.25 for the front upright.

4.6.2 Rear upright

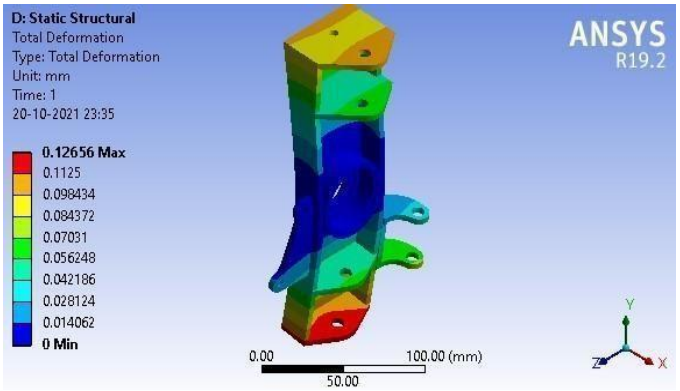


Figure 4.4:Maximum Total Deformation

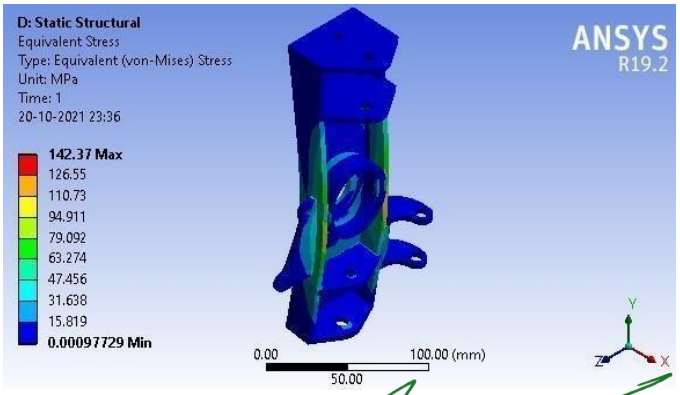


Figure 4.5:Maximum Stress

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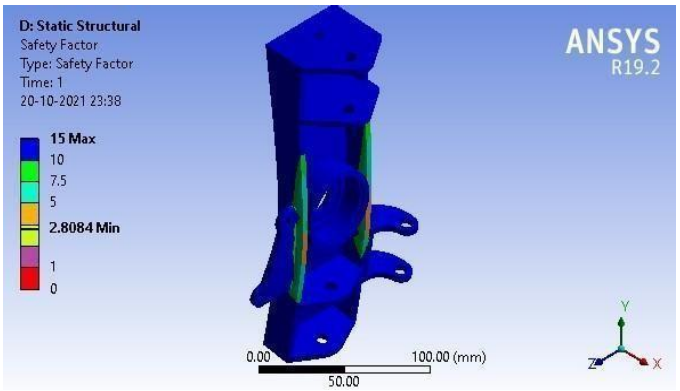


Figure 4.6: Factor of safety

- The maximum total deformation analyzed is 0.12mm
- The maximum total deformation analyzed is 0.12mm
- The minimum factor of safety analyzed is 2.80 for the rear upright.

4.6.3 Front upper arm

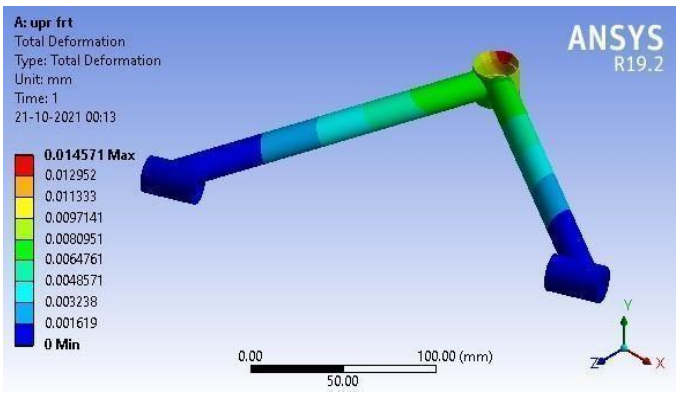


Figure 4.7: Maximum Total Deformation

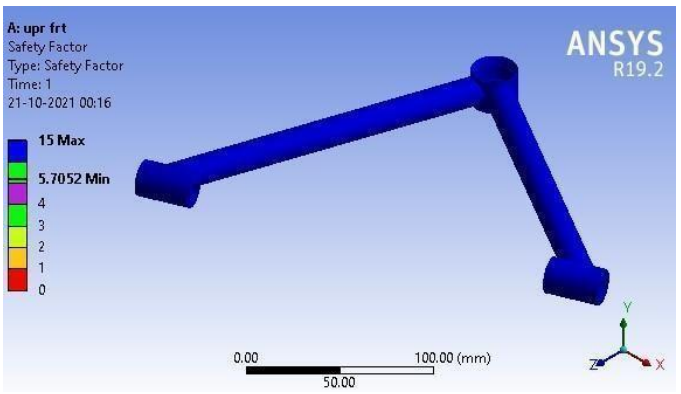


Figure 4.8: Minimum Factor of Safety

- The maximum total deformation analyzed is 0.014mm.
- The minimum factor of safety analyzed is 5.70

4.6.4 Rear upper arm

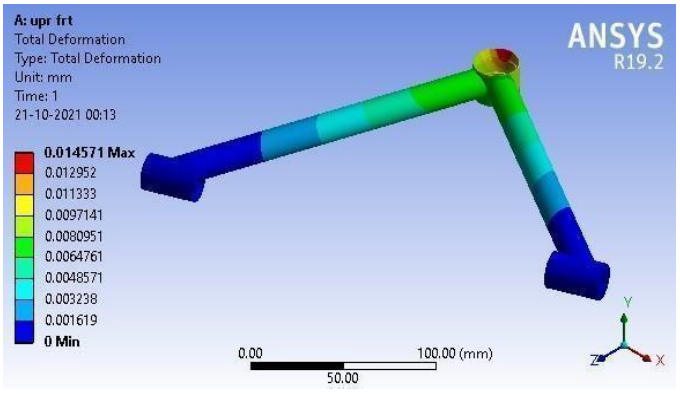


Figure 4.9: Maximum Total Deformation

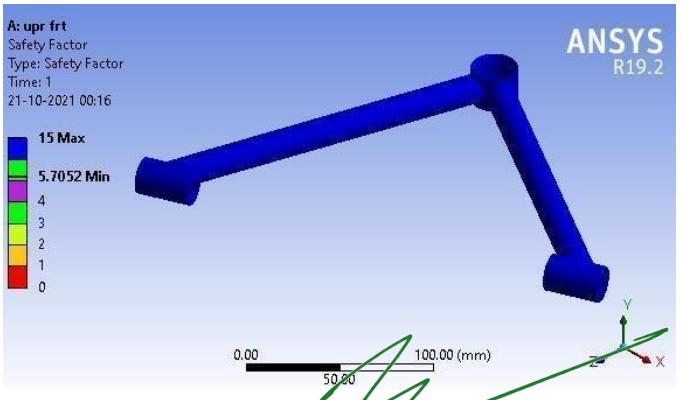


Figure 4.10: Minimum Factor of Safety

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- The maximum total deformation analyzed is 0.012mm.
- The minimum factor of safety analyzed is 5.62

4.6.5. Front lower arm

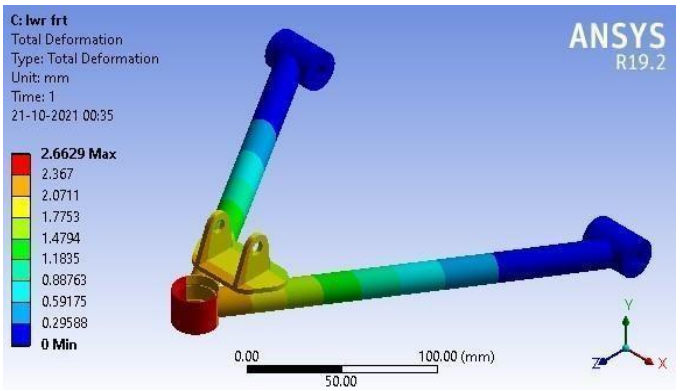


Figure 4.11: Maximum Total Deformation

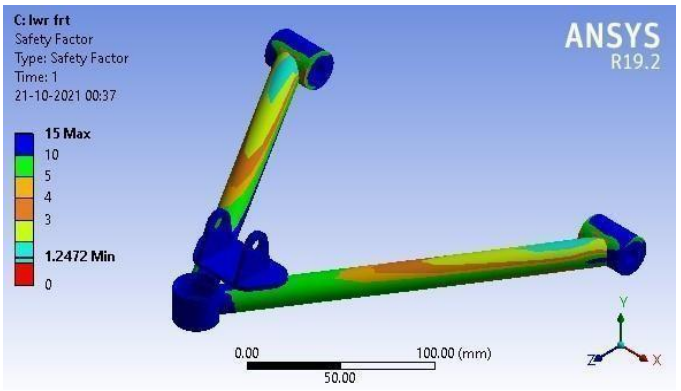


Figure 4.12: Minimum Factor of Safety

- The total deformation analyzed is 2.66mm.
- The minimum factor of safety analyzed is 1.74

4.6.6 Rear lower arm

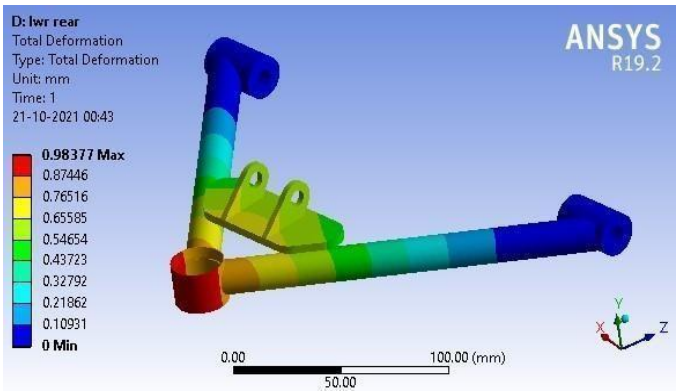


Figure 4.13: Maximum Total Deformation

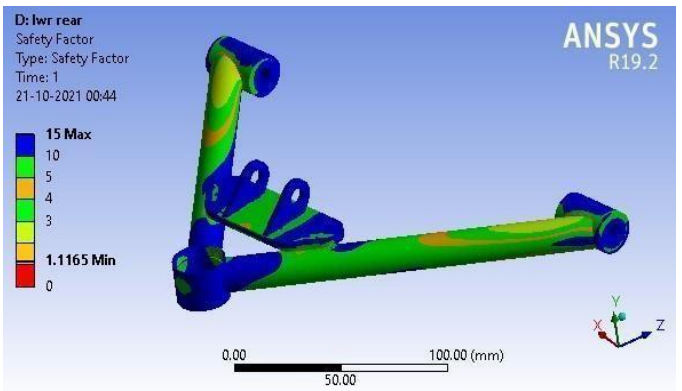


Figure 4.14: Minimum Factor of Safety

- The maximum total deformation analyzed is 0.98mm.
- The minimum factor of safety analyzed is 1.51

5. Results

On researching different types of suspension systems, the selected suspension system for our vehicle is a double wishbone suspension system based on the factors:

- It is high-performance and provides better handling and ride comfort than a dependent suspension system.
- It can handle high loads compared to some other suspension systems.
- Double wishbone suspension can provide greater control over wheel alignment parameters such as camber, caster and toe.

The materials selected for based on analysis are:

- Front upright is EN8 with a minimum FOS of 2.25
- Rear upright is EN8 with a minimum FOS of 2.80
- The front upper arm is AISI 1018 with a minimum FOS of 5.70

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- The rear upper arm is AISI 1018 with a minimum FOS of 5.62
- The front lower arm is AISI 1018 with a minimum FOS of 1.74
- The rear lower arm is AISI 1018 with a minimum FOS of 1.51

5. Conclusion

The combination of proper suspension system selection and CAE analysis enables the development of a well-tuned suspension system that meets the specific requirements of a vehicle. By considering factors such as vehicle type, intended use, and desired performance characteristics, we can select the most suitable suspension system. The subsequent CAE analysis aids in refining the design and ensuring that it meets the desired objectives, resulting in a suspension system that provides excellent ride comfort, handling, and stability.

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The VASS Method of Communication: Romanticising the Professionally Unscripted Ad-libs

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Abstract: *The proposed research paper aims to elaborate on a communicative strategy that can enable scripted and unscripted professional interactions. To be impressive, and to offer content that has depth, is to understand professional communication. VASS is a method of communication that I have conceptualised to summarise the heavy factors of creating, memorising and improvising communicative instances in both personal and professional spaces. The paper discusses a method that is systematic and derives inspiration from effective communicative strategies that have been prominent in the 21st century. To speak effortlessly and fluently on unscripted topics is a desire for many youths, and the proposed methodology may aid their attempts to be authentic and vibrant amongst a crowd of generic conversations.*

Keywords: Communicative Strategy, Visual aids, Subjectivity, Specification, Professional Relational Dynamics

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1. Introduction

Ever growing introverted instances, especially in the post-covid era, are forcing many Gen-Z youths to deny aspects of communication for which they are not prepared. Social shyness, awkwardness and denial have gradually seeped through many individuals who wish to conceptualise and concretise what they have to speak or write in unscripted or scripted conversations, especially in a professional space.

With the dominantly increasing concept of on-campus placement drives, matters of communicative angst have twirled towards precise questionnaires that are endlessly asked about career and personality to a multitudinal group of freshers at a stretch, which is tiresome and tedious nonetheless. Communication, in its rawness, is closer to an attempt to transfer ideas, thoughts and emotions from one source to another. More often than not, it is wrapped taut around the intent to develop relational dynamics. If an individual developed friendship with another human being at any stage of life, one of them would have initiated a conversation with the other. Without that communicative initiation, whether it be an inquiry of where the canteen was located or about the means of commute to and from college, their relation would have never been recognised, let alone culminated.

It is often surprising to many socially shy individuals that communication is beyond the verbal, and densely includes a deep accord with the visual and the vocal. If one positions a subtle doubt on the claim that meaning is carried forth by mediums other than words, it can be easily comprehended and verified by shrieking harshly at the top of one's voice while praising father's cooking at home after dinner, or reclining back on a chair in an interview while earnestly answering the questionnaire. Albert Mehrabian, a researcher of body language, was the first to break down the components of a face-to-face conversation and he found that communication is primarily 55% nonverbal, 38% vocal, and only 7% words.

Such ratio of the role of verbal and nonverbal in a face-to-face conversation always-already surfaces as a profoundly surprising fact to many young individuals in the contemporary era as major communicative functionality is through mails, messenger apps, or social media platforms that heavily involve typing. Thus, nonverbal negotiations have declined sharply for many and their inclusion in communication appears more as an optionality rather than a necessity. A calm and distinct social awkwardness in interaction has creeped in many individuals who stand in metros or classrooms, for example, and await a favourable moment to converse rather than create one.

The concern is not entirely personal suffrage. It has pinnacled professional ad-libs and scripted interactions to be uncomfortable, undesirable and untackable, especially when they are face-to-face and beyond the preparedness and comfort of typing which allots plenty of time to think, rethink, and reconstruct the randomised flow of thoughts. Locating oneself in the dire situation of conversing without preparation has a haste and gap which is similar to the one endured even in prepared instances like interviews, group meetings and discussion, the agenda and questionnaire of which is usually served in advance or at least holds a probability of being asked.

The VASS method offers an improved chance at negotiating not only prepared occurrences of interaction or content development, but its gradual practice and decor in daily routine heightens competence of negotiating unscripted professional ad-libs as well. VASS stands for an effective communicative strategy for formulating content where emphasis is on Visually-Aided Subjectivity and Specification while trying to conjure thoughts, ideas and emotions, and channelising them through words in articulation or writing.

2. Visually-Aided

There is a two-dimensionally essentiality to visually-aided thinking: it gives observational depth to the content that is being developed, and it helps in retaining content, like a memorised speech to be delivered in an orientation program. An individual prepares a speech on poverty, for example, and the approach is to define poverty, government claim on property, quotes on property, and thus, the thought process gradually succumbs to an individual's thought process churning on words. It is like the repetition of the sentence in the question itself while writing the first line of an answer during the college examinations. It is an easy approach but depends heavily on remembering the sequence of words, the chronological development of writing, and becomes generically hollow. But the dynamics would be altered slightly if the speech was prepared through visual thinking. The individual may recline back, imagine what poverty looks like to her, and then proceed to a space like a traffic signal where beggars are most commonly found by her and she wishes to initiate her content from that image itself. Her development of thought will retain that thought even when she will be delivering that speech, many weeks later, because that image is part of her reflexive thinking and is easy to retain.

Instructions to make instant noodles, for instance, are written boldly on the pack itself but they always-eternally use tender images to depict the process where there is a source of heat, a pan, procedure of pouring ingredients visually demonstrated and the completion of the process as well. The directions are very well writ but the retaining factor of making instant noodles shall remain a recollection of the visual demonstration printed on the packet. Recollecting childhood memories through the images of maternal grandmother's house is the reason that childhood experience remains intact and taut to such an extent that one can write about it at length even though many, many years have been added to their catalogue of memories.

A fifteen minute presentation to be delivered in front of a client holds similar dynamics. What prominently worsens the situation is when the presenter dedicates his energy in retaining the chronology of words. First line of introduction, then first line of product description, and then first line of conclusion are usually memorised in a parrot-fashion which have a higher

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probability of being forgotten amidst the hustle, bustle and anxiety of meeting a client who has arrived from a foreign country especially for the presentation. Remembering words would be existentially more tedious while describing childhood or the product. Visually-aided thinking provides a platform to recollect and retain data that is varied and dynamically categorised which seldom, or never, leads to confusion or stuttering. If the first line of the product description paragraph is forgotten by the presenter, for example, then there is a concrete chance that the sequentiality of the paragraph in itself will be deeply compromised.

To introduce a product, one may break the image of the product into parts, like those diagrams in the biology and physics books, assign functionality to each part like the screen or the fuel tank, its bulleted specifications and start from the top/left/bottom of the product and proceed in a clockwise or anticlockwise mannerism while delivering the details. To introduce a person, one may place that person in an office space through imaginary images, put a name plate with designation on the table, hang 3 plaques on the wall highlighting the prestigious awards earned by the person, position a calendar on the side table highlighting the year 1982 which is the year the person started working as an engineer, and other such designated triggers of information by being creative and innovative to suits one's own fondness.

The visual dissection of content to be remembered and the visual dissection of thoughts, ideas and emotions when content is to be developed, are aesthetically similar in their communicative dynamics.

3. Subjectivity

Amongst the diverse types of writing, descriptive writing is a marvel for professional and personal communicative methodologies as they blend facts and fiction, which is the true beauty of human experiences. To comprehend it fully, one must grapple with its dynamics in experiential reality. Suppose an individual notices a dead-lock on a traffic signal because of an accident. She then visits a tea shop around the corner, orders a tea for herself and casually inquires about the cause and concern of such an accident. She might hear a narration from someone sipping tea that two cars colliding is no big occurrence in a metropolitan like Delhi. What will interest her though, would be reiteration of the event that is not exclusively argumentative or expository in nature. That means that the account should not be holistically opinionated or factual. It should cover the reality of what happened along with an attempt to recreate the same.

The tea-seller herself chose to describe the events with the swift movement of her hands while depicting the swirling speed with which one car dramatically nudged another car (depicted with a soft movement of the shoulder) and then bumped into a motorcyclist (demonstrated through an exaggerated clap) who was thrown into the air, and who stood almost immediately, unharmed by the bitter surprise of the car playing hide and seek with him. An event's singularity, one should comprehend, is deciphered through connotations and denotations. The congestion at the traffic signal is a singular event in the spatio-temporal curvature but one person observes it through the opinionated disenchantment that he has with the city and one observed it solely to reiterate it to customers who will flock her shop throughout the day.

A painting in an art gallery is an event that will be aesthetically deciphered by individuals where few might claim it imposes patriarchy and many might associate it post-war-trauma that affected a huge population after the world wars. A concert is an event that holds singularity but if the reporter holds minimalistic knowledge or liking of music, or even if she does but is inexperienced, the content developed about the event shall be denotative derivation from the totality of the event, not its entirety or even distant connotative attempt as it will lack fundamental concepts of music, its functionality and deliverance.

Along with the visual-aid of recollecting how the event progressed, how the crowd swayed or how the motorcyclist was flung into the air, the mere intent of subjectivity ensures authenticity. Depth of description is enabled by visual-aids and the weight of authenticity, organicity and originality is asserted by the subjectivity of an individual. It is similar to a less than perfect assignment that a student earnestly attempts with regard to his/her understanding of the subject, and is easily noticed by the teacher who is evaluating majority of assignments that are impeccable in their content which in turn leads to a doubt that it might have been compiled from a web browser rather than the webbing of one's own understanding.

4. Specification

In an interview, on being enquired about commuting, a candidate answered that she has travelled far to reach the placement campus. However, another candidate specified that the travel of more than 28 kilometres was tiresome for him. 'A crowd gathered around the accident-site' and 'Nearly 200 people bundled together as the traffic crawled' are sentences which arguably hold a small variation but the variation does succeed slightly in offering specification that is highly observational and enchants the dislocation of the audience, be it a reader or a listener. For the audience to confidently dislocate from the current position and actually relocate to the accident-site, there should be specific building blocks where they will be setting their metaphorical feet and watching the event alongside the speaker. It is a common strategy employed, for example, by stand-up comedians.

The dislocation and relocation of the audience, be it while reading a novel about wizards studying in a distant campus or a comedian explaining humorous blabbering of hawkers in a local Delhi market, is a crisp amalgamation of VASS method itself. Audience can witness the magical campus even though it does not exist, strongly agree with the connotative authenticity of the writer about magic and also know the power of each and every, specific child wizard in the imaginary campus.

The VASS method emphasises a dominant impression where the writer does not tell but rather shows. Vivid sensory

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details enhance the affiliation of meaning the reader can hold and choose through denotative and connotative capacities. Through the intent of specification, instead of saying that the relation between person A and person B is no longer good, one can state their relation has turned bitter. Success is always already described by its sweet taste. Rather than telling the reader, what is offered is the sense of taste, for example, and what one associates with it, and thus, success is associated as desirable because it is sweet and not despicable through the taste of bitterness.

Specification decors heavily through sensory description which uses sight, sound, smell, touch and taste to sketch an impression. Consider three statements: 'he gave her a hug', 'he gave her a warm hug', and 'he gave her a cold shoulder'. The association is etched through the specification which shows the warmth of a hug instead of telling whether it was a comfortable, affectionate hug or a denouncing rejection through body language of shoulder. It is the close association with what is being said or written that the audience accepts as clutches to relocate themselves towards the thoughts, ideas and/or emotions that are being described.

5. Empirical Verification of VASS methodology

If a candidate is asked about their graduation experience in an interview and the candidate replies, 'It was a good experience ma'am, I learnt a lot and had fun as well. It has improved me as a human being'. It is a strongly compiled and composed content as an answer. To consider a different answer, however, through the VASS method would modify such a reply to be slightly more aesthetic. If the candidate approaches the reply through the VASS methodology, their reply would be attuned and morphed as a visual approach of their college campus. The candidate would obviously visualise the college space, and with each space like the classroom, playground or canteen, a different idea, thought and/or emotion may be experienced.

The depth and scaling of these experiences, for example, is foddered by the step of tapping in visual-aids of the campus space which would provide two prominent things- a multidimensional vibrancy to what the content can negotiate while avoiding being a singularity of experience being called campus, college or graduation, and a memorising pattern when the individual enters the placement drive after being prepared to tackle a question about campus life as it has a higher probability of being asked to freshers and interns.

Then the subjectivity of the candidate would move away from being generic and towards a personalised connotative experience of college by being authentic and organic through statements which would sway more like 'Initially I was…' or 'It boosted my self-image that was distraught after JEE'. Through prominent social media platforms and recruitment portals, many employers of leading multinational corporations have recently emphasised that they professionally crave for an authentic resume which has mundane human errors of spacing or grammatical mistakes as they hold heavy a view of application which is original, and not oriented or compiled by an AI driven engine.

The singularity of the designation for which the candidate has applied for is staunchly similar to the singularity of being a student. Through an interview process of more than 300 students in a single stretch, jingled versions of monotonous experiences of college life being 'good' offer a generic attempt made by each consecutive candidate. The sheer moment a candidate articulates an authentic experience which is truly subjective, the negotiation is broadly unconcerned whether the answer is correct or incorrect, but the answer is definitely much appreciated as it is staunchly organic and not processed through templates that are easily and endlessly available on innumerable online platforms.

One may consider a probable statement like 'I believe I have spent the best half-century of months of my life in college; the clamouring lectures, bustling canteens and stinking toilets; they make me glow with a warm memory of my college days'. It decorates as an impressive attempt to justify the expectations aligned with the interview question, and creates a subtle association through specifications that can relocate the panlist(s) to their own college days which were majorly dedicated to the classroom, canteen and playground spaces. They might even smile or smirk.

It is a softly exaggerated articulation solely to emphasise that a slight, yet prominent, caressing effect of specification can effort into an impressive charm, especially when the monotonous nature of conversations, in most professional spaces, has worn down authentic interactions. 'I have been teaching for many years' and 'I have more than two decades of teaching experience' is a difference in content that enables subtle escalation in articulation strategy.

6. Conclusion

The VASS method is an intent to efficiently negotiate communicative situations that are scripted and especially those that are unscripted. Visual-aids provide depth, vibrancy and scaling of memory to content, while subjectivity offers authenticity and originality that is organic, and specification ensures an improved chance of association, possible relocation of the audience and long-lasting impression.

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Comparison and Selection of Steering Geometry for 4-Wheel Efficycle

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Abstract

In this research paper, we have discussed different types of steering geometry such as Ackerman, anti-ackerman and Davis steering geometry. We have also discussed the advantages and disadvantages of all three types of geometry and implemented the best steering geometry for our four-wheel effic-ycle. We have done three iterations to determine the best Ackerman percentage, critical velocity and steering ratio.

Keywords: Steering Geometries, Ackermann Steering, Anti-Ackerman Steering, Davis Steering, critical velocity

1. Introduction

The steering system is a part of vehicle dynamics which helps to control the direction of the vehicle according to the driver's input. It influences the vehicle handling, control and cornering performance. There are multiple types of steering systems such as power steering, and mechanical steering but all of them are based on the geometry of the steering system. Geometry can be divided into three types that are Ackerman, Anti-Ackerman and Davis steering geometry.

Furthermore, we have discussed all three types of steering geometry and their advantages and disadvantages in the upcoming paragraph. This research paper can help other students to have a profound understanding of steering geometry and how they can opt for the most optimal geometry while designing their vehicle

2. Literature review

Engineers have done a lot of research to optimize all the steering geometry and further innovations are being done to improve the handling, and control of high-speed vehicles. In this review, we have

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discussed the advantages and disadvantages of Ackerman, Anti-Ackerman and Davis geometry respectively. [2, 3, 4]

2.1 *Methodology*

Ackermann geometry: In Ackerman geometry both front tyres while cornering have different radii. It is done to avoid sideways slippage as the wheels while turning form different circles with a common center point. It improves the grip of the wheels.

Advantages of Ackermann Geometry:

- To avoid the sideway slip of the wheel while cornering.
- Ackerman geometry is easy to understand and it makes designing the steering easy.
- It solves the problem of the wheels turning around a different radius.

Disadvantages of Ackermann Geometry:

- It is highly unstable at high speeds.
- Ackermann geometry causes uneven tyre wear.
- It is highly unstable at high speeds

The Davis steering mechanism consists of two arms or rods that connect the front wheels to the steering wheel. The arms are angled inward toward each other, and the steering wheel is attached to a pivot point where the arms meet. As the steering wheel is turned, the arms pivot around this point, causing the front wheels to turn at different angles. This mechanism ensures that the wheels turn at different angles reducing the slip and scrub and improving vehicle stability.

Advantages of Davis Geometry:

- It is stable at high speeds.
- It provides a smaller value of turning radius.
- Reduces Slip and Scrub.

Disadvantages of Davis Geometry:

- Causes more wear on the steering gear
- The friction produced is more due to sliding pairs

Anti-Ackermann geometry is a type of geometry designed for high-speed vehicles to reduce slip angles at front tyres during cornering. It is the opposite of Ackermann steering geometry as the

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outer wheel turns at a greater angle as compared to the inner wheel, therefore, covering less distance.

It is majorly used in Race cars where Traction and Vehicle stability are the main aspects to be considered rather than turning radius.

Advantages of Anti-Ackermann Geometry:

- Maximum traction is achieved.
- Reduces the value of slip angle at front tires providing stability

Disadvantages of Ackermann Geometry:

- Increases the value of the Turning radius.
- It makes the vehicle less manoeuvrable in congested corners.

3. Numerical analysis

4.1 Anti-Ackermann Steering Geometry Calculations
The turning angle for the outer wheel in Anti-Ackermann geometry can be expressed as:
tan(θ_outer) = L / (R + (t/2))
tan(θ_inner) = L / (R - (t/2))
where L = wheelbase, R = turning radius, t = track width.

4.2 Davis Steering Geometry Calculations
In Davis steering, the steering arms are inclined, and the relation can be derived as:
tan(θ) = L / (R ± (t/2))
where the plus sign applies for the inner wheel and minus for the outer wheel.
This mechanism ensures that both wheels trace different circles with a common center, reducing slip and scrub.

$$L_{wheelbase} = 1.27\ m$$
$$W_{track\ width} = 0.93\ m$$

$Considering\ turning\ radius = R$

$To\ find\ the\ perfect\ Ackermann\ geometry\ for\ our\ vehicle\ we\ performed\ various\ iterations\ by\ varying\ the\ values\ of\ the\ turning\ radius\ (under\ 4m\ as\ per\ the\ figure\ of\ 8\ test).$

$We\ performed\ three\ iterations\ for\ which\ the\ results\ are\ as\ mentioned\ below:$

$$For\ R = 2\ m$$
$$Inner\ angle = 39.658^0 \quad Outer\ angle = 27.216^0$$
$$Ackermann\ \% = 99.58\%$$
$$For\ R = 2.5\ m$$

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$$Inner\ angle\ = 32.005^0\ \ Outer\ angle\ = 23.122^0 \quad (1)$$

$$Ackermann\ \%\ =\ 100.175\% \quad (2)$$

$$For\ R\ =\ 3m$$
$$Inner\ angle\ =\ 26.6^0 \quad Outer\ angle\ =\ 20.10^0$$
$$Ackermann\ \%\ =\ 100.21\%$$

As for turning radius of 2. 5*m we were getting* 100. 175% *Ackermann % in reference to* 100% *or perfect Ackermann percentage.*

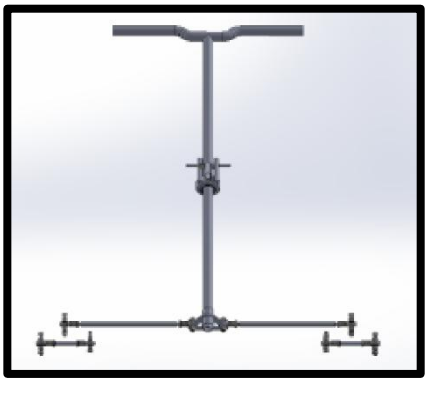
$$Critical\ Velocity\ =\ \sqrt{\mu g r}$$

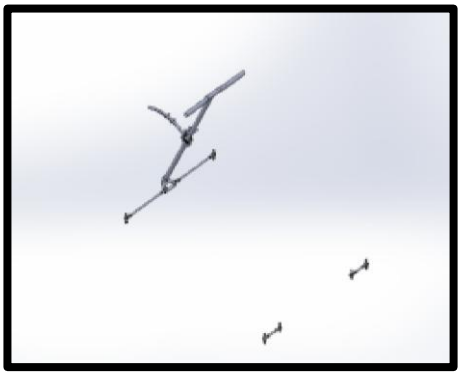
$$\mu\ =\ 1.2$$
$$g\ =\ 9.8\,m/s$$
$$R\ =\ 2.5\,m$$

$$So\ critical\ velocity\ =\ 5.42\,m/s$$

Steering ratio$(S.R)$ *refers to the ratio between the turn of the steering wheel and the turn of the wheels.*

$$S.R\ =\ \frac{Lock\ to\ lock\ angle\ of\ steering\ handle}{Inside\ angle + Outside\ angle} =\ 1.08 \quad (3)$$





4. Results

On studying and researching three types of steering geometries, the Geometry that suits the best for our vehicle best is Ackermann Geometry based on factors such as ease of manufacturing and

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basic mathematical Calculations and as the speed of the vehicle is low, this geometry suits the best. The numerical calculations we have done provide all the desired results.

The turning radius calculated is $2.5\,m$ with inner and outer angles as 32.005^0 & 23.122^0 respectively. The steering ratio calculated is 1.08

5. Conclusion

The implementation of the idea of comparing different steering geometries based on their applications, advantages & disadvantages has been successful in selecting the steering geometry of our vehicle. Through a thorough evaluation of different steering geometries' behaviour, this research aims to contribute to the development of a simple and efficient steering system to achieve maximum vehicle handling.

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Supercapacitor-Powered Urban Train: A Cost-Effective Alternative

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***Abstract**: This paper investigates the role of supercapacitor technology in enhancing traction efficiency and reducing infrastructure costs in metro rail systems by replacing conventional track-based electrification. Traditional metro systems rely heavily on continuous electrification through overhead lines or third-rail systems, leading to high capital expenditure, complex infrastructure requirements, and significant energy losses, especially in urban environments with frequent stops. Whereas, the quick charging, adequate regenerative braking, and longevity of supercapictor powered trains enables them preferred choice for local railroad lines.*

Keywords: Supercapacitor, Electrification, Third-Rail System, Regenerative Braking, Overhead catenary systems.

1. INTRODUCTION

The need for a sustainable and efficient public transport system is to deal with the problems that come up because of more people living in cities, less fossil fuel reserves, and the effects on the environment. Electric trains, trams and tram buses are the main types of sustainable transportation. The Delhi metro is the largest metro train system in the world [1]. The metro rail network system includes 25 kV AC overhead catenary systems and 750 V DC third-rail systems [2]. These systems contributes speedy transit, but with significant funds and operational expenditures. Moreover, the electrification infrastructure includes high installation cost, complex maintenance requirement, especially in densely populated areas are challenging.
The urban metro trains have frequent stops, thus, requires continuous acceleration and deceleration . Which leads to considerable energy consumption and wear on mechanical components. This results in increased maintenance costs and reduced system efficiency.

The alternative method to run the metro trains are required to improve efficiency, reduce costs, and mitigate environmental impact to cope up these challenges. Supercapacitor based technology is an emerging solution, known for its fast charging capability, high power density, and durability. This provides on-board energy storage, thus, reduces reliance on conventional electrification of track.

The electrification cost is reduced and efficiency is improved and train is powered through pre-charged supercapacitor.

2.LITERATURE REVIEW.

Delhi Metro operates primarily using a 25 kV AC overhead catenary system for electric supply. In this configuration, electrical energy is transmitted through overhead supply line commonly referred to as the Overhead Equipment (OHE), which is suspended above the tracks. The rolling stock (train) is equipped with pantographs—mechanical devices mounted on the roof of each train car—that maintain continuous contact with the overhead wire. The pantograph collects current and transfers it to the train's power systems, enabling propulsion and mobility, lighting, air conditioning, and control systems.
The cost of electrification infrastructure in metro rail systems forms a substantial portion of the overall capital expenditure. The component of the metro train systems are overhead catenary lines to feed electric powers to train through pantographs, traction substations to feed the catenary lines, and the related transmission equipment and accessories.

The electrification cost of metro rail systems at various part of the globe varies such as, Mexico City's Line B had a total US$970 million capital expenditure, US$50.4 million which is approximately 5.2% of total expenditure is for the power system. Whereas Caracas Metro's Line 3 budget is US$372 million, and it spent US$33.1 million, which is 8.9% of total budget on electrification infrastructure. Similarly, Santiago Metro's Line 5 extension, which is of 2.8 km in length, is given US$5.5 million to metro rail electrification components. Which is 2.8% of its total budget of US$197 million. These figures confirm that electrification regularly consumes between 2% to 9% of a metro system's capital budget, depending on the complexity, train, and system voltage **[3]**.

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In the Indian context, metro electrification costs are even more pronounced due to the scale and engineering challenges in densely populated urban areas. According to the Sub-Committee on Traction System, Power Supply & Energy Efficiency under the Ministry of Urban Development, the estimated electrification costs are:

- For a 25 kV AC Overhead Catenary System:
  - Elevated corridors: ₹9.51 crore per km
  - Underground corridors: ₹11.26 crore per km
- For a 750 V DC Third Rail System:
  - Average cost: ₹13.36 crore per km
- For a 1500 V DC Overhead Catenary System:
  - Elevated corridors: ₹10.51 crore per km
  - Underground corridors: ₹12.26 crore per km

The above figures emphasises that the selection of traction system has a considerable impact on capital expenses **[4]**. The electrification cost depends on length of electrification network and the configurations used. The Delhi Metro, which is a large network of over 390 km length, the total electrification cost exceeds ₹4,000 Crore. This causes heavy financial burden on urban infrastructure projects, and raises long-term issues of operation and maintenance costs.

3.PROBLEM STATEMENT

The conventional metro train system due to dependence on rail electrification depends on significant capital and operational expenditure. These systems are costly to install and maintain, particularly in densely populated areas,. This research aims to explore alternative propulsion strategies, specifically supercapacitor-based onboard energy systems, to substantially reduce the cost of electrification infrastructure and enhance overall system efficiency, reliability, and sustainability

4. PROPOSED SOLUTION

The metro train systems based on conventional electrification are characterized by frequent halts at stations located closely, usually every 1 to 2.5 kilometres **[5]**. Which causes the train to accelerate, cruise, brake, and decelerate frequently. Thus, most of the time train remains in transient states rather than in steady-state cruising **[6]**. This causes repeated high power demand for traction motors and hence, substantial electrical loading on the overhead catenary system. Additionally, shorter distance between the halting stations causes little opportunity for the energy generated due to regenerative braking to be efficiently absorbed or reused except adequate energy storage or grid susceptibility exists [**7]**.

The problems of costly track electrification systems is overcome by the integration of supercapacitor-based on-board energy storage units in metro rolling stock **[8]**. Supercapacitors, which are also known as ultracapacitors, are high power density, quick charge-discharge characteristics, and minimal energy loss electrochemical energy storage devices. The supercapacitors due to extremely low equivalent series resistance (ESR) in contrast to batteries gains high levels of charge in seconds and delivers large bursts of current **[9]**.

In the proposed system, supercapacitor modules is integrated within the train cars and designed to recharge at every station stop. Since metro dwell times typically range from 20 to 40 seconds [**10]**, this stationary window is sufficient for partial or full recharging of supercapacitors, especially when paired with high-efficiency power interfaces. Furthermore, regenerative braking energy—currently underutilized in many systems due to lack of on-board storage—can be captured and stored directly into the supercapacitor bank during deceleration.

Once charged, the supercapacitors feeds the traction system during acceleration phase, thereby reducing the instantaneous demand on the overhead line or third-rail system. through fully offloading peak power requirements from the main transmission infrastructure, the overall grid load decreases and more predictable, enabling reduced infrastructure ratings and improved system stability.

Additionally, the mechanical simplicity, long cycle life, and temperature tolerance of supercapacitors make them highly suitable for the stop-and-go operational profile of urban metros **[11]**. Their negligible ESR (equivalent series resistance) allows for efficient energy transfer with minimal heat generation, ensuring high performance

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even under frequent charge-discharge conditions. The super capacitors bridges the gap between conventional capacitors and batteries by storages energy electrostatically, thereby, significantly, higher power densities and larger cycle lives **[12].**

5. METHODOLOGY

The supercapacitor are considered as electric double-layer capacitance (EDLC). When a voltage is placed across the electrodes of an EDLC, charges develop on the surfaces within the electrode materials and in some instances along the region adjacent to electrolyte which is thought of forming Electrical double-layer at interface **[13]**. This mechanism is non-faradaic (redox) which enables fast charging and discharging cycles **[14].**
The material and structural advancements are reasons for supercapacitors to store large energy including reasons mentioned below as,
1. Porous electrodes include large surface area materials of activated carbon, graphene or carbon nanotubes. These materials have a large specific surface area (often > 2000 m^2/g) which allows for a huge amount of charge storage due to ion adsorption on the surface **[15]**.
2. Electric Double Layer Effect EDLCs are different from the traditional capacitors, which utilizes physical polarization of current carriers enclosed within a dielectric layer to increase capacity. In this way a truly massive capacitance per unit volume is achieved.
3. Some supercapacitors uses metal oxide or conducting polymer based electrodes, these mechanisms offer additional capacitance on the surface through the reversible redox reactions of Faradaic charge The pseudocapacitance is quite similar to double-layer capacitance and may be easily integrated into a standard electrolytic capacitor. This is referred to as pseudocapacitance which serves in conjunction with the EDLC mechanism **[16]**.
4. Dielectric Engineering: The use of advance dielectrics material like GO, RGO and even layer materials such as MXene has triggered the higher energy densities because it enhances the conductivity and decreases ESR. Graphene, in particular, possesses high electrical conductivity and mechanical properties that are superior to any other state-of-the-art materials today which makes graphene a very promising candidate for next-generation supercapacitors **[17]**.
High power output due to low ES, This is because supercapacitors have an extremely lower equivalent series resistance (ESR) as compared with the batteries which allows fast delivery of energy. This is essential for use cases ranging from urban metro systems, which have low energy requirements in terms of the required bursts during frequent accelerations and deceleration cycles.

6. SIMULATED RESULTS

Fig. 6.1 depicts the implemented MATLAB Simulink model of supercapacitor powered metro train. The model replicates the energy flow from a supercapacitor to a Permanent Magnet DC (PMDC) motor, which acts as an approximate representation of an actual train traction system. Fig. 3.2 illustrates the performance of the developed prototype of the supercapacitor powered permanent magnet DC motor system.

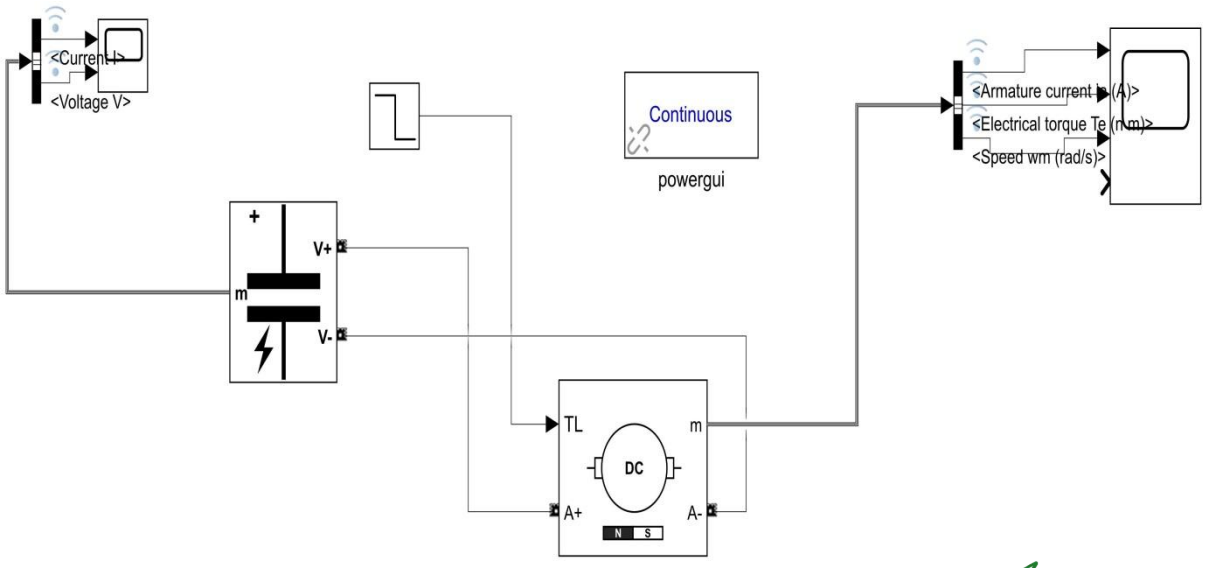


Fig 6.1 Supercapacitor powered metro train block diagram

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6.1 **Supercapacitor Block**
This block models the behavior of an idealized supercapacitor with parameters corresponding to a typical high-capacitance, low-ESR energy storage device. In this model:

- The supercapacitor provides initial energy to drive the train.
- It mimics the quick discharge and rapid recharge capability inherent to Electric Double Layer Capacitors (EDLCs).

6.2 PMDC Motor Block
While real-world metro trains employ 3-phase induction or permanent magnet synchronous motor, a PMDC motor is used here for simulation due to its simplicity and ease of control. It serves as an effective approximation to demonstrate dynamic responses like torque generation, acceleration, and energy draw from the source.

6.3 Power Measurement Blocks
To track system performance, the following outputs are measured:

- Armature Current (ia): Shows the current drawn by the motor during acceleration.
- Electrical Torque (Te): Reflects the torque developed, which spikes during the initial phase.
- Speed (w_m): Indicates the angular speed rise over time as the vehicle accelerates and coasts.

6.4 Load Torque (TL)

This represents the mechanical load applied to the PMDC motor shaft, simulating the resistance of vehicle weight and friction forces.

It constitutes of two-state step function to depict the static and dynamic friction of the train wheel. Where dynamic friction < static friction.

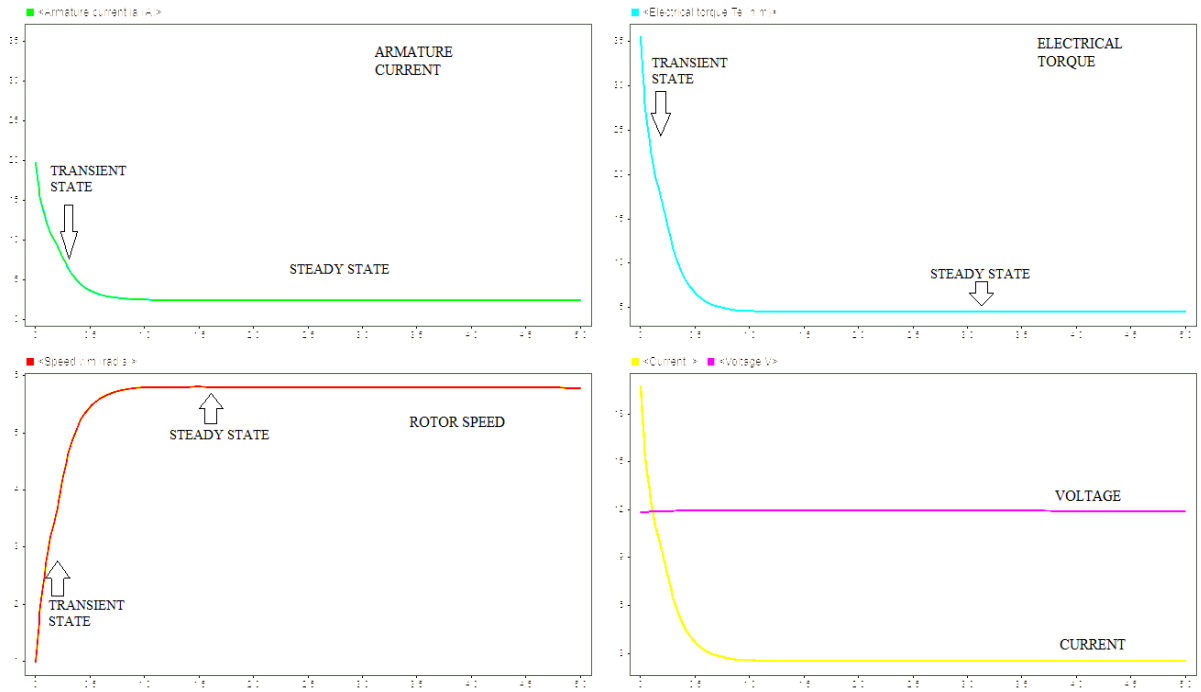


Fig 6.2 armature current (a), electrical torque (b)speed (c), capacitor voltage and (d) current

Key observations from the results are:

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- The Armature Current and Electrical Torque exhibit a sharp initial spike within the first second (0–1 s), indicating high current and torque demand during the start-up and acceleration phase — a characteristic behavior in urban metro operations where frequent stops and rapid accelerations are typical.
- The speed of the motor (in rad/s) shows a smooth and rapid increase, reaching steady-state conditions shortly after 1.5 seconds, demonstrating the supercapacitor's ability to deliver fast-response power delivery and efficient motor startup.
- The voltage across the supercapacitor remains relatively stable throughout the simulation, with a minor drop, validating the low Equivalent Series Resistance (ESR) and minimal energy loss characteristics of supercapacitors.

7. REALIZED PROTOTYPE PERFORMANCE

Fig. 7.1 illustrates the block diagram of proto type developed in the laboratory. A scaled-down prototype of a supercapacitor-powered metro train is successfully developed to experimentally validate the feasibility of supercapacitors as the primary energy source for rail-based transportation. The working prototype emulates the actual traction system behavior using components selected for their functional similarity to real-world systems.

The traction drive of the prototype uses a 775 V DC motor as an equivalent substitute for a full-scale traction motor. Power delivery is managed via a BTS7960 high-current H-bridge driver module, which is capable of bi-directional motor control. The energy storage system consists of five 2.7 V, 500 F supercapacitors connected in series to achieve a combined voltage rating of 13.5 V. Two such series banks are connected in parallel, resulting in an effective capacitance of approximately 200 F at 13.5 V.

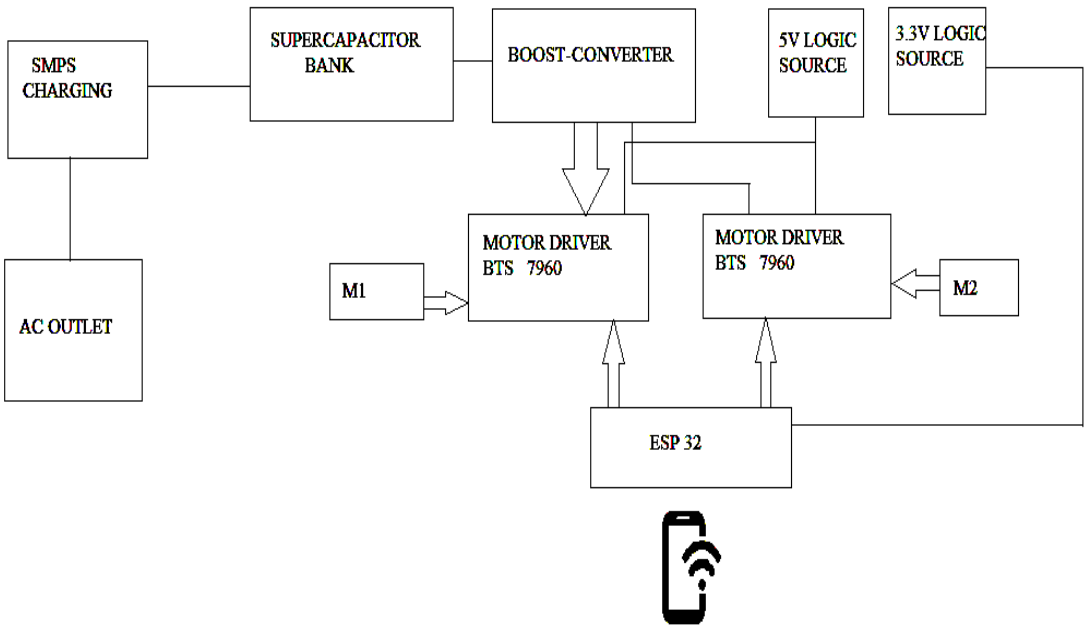


Fig 7.1 block diagram of prototype

The charging of the supercapacitors is done through a 1200W SMPS, and discharge is controlled through the boost converter which is connected to BTS7960, which in turn is governed by an ESP32 microcontroller. The ESP32 manages switching logic, speed control, and directional operation. During operation, the system demonstrates:

- High current discharge at start up, similar to real-world train acceleration conditions.
- Rapid attainment of peak motor speed, validating the high power density and low ESR (Equivalent Series Resistance) of the supercapacitor bank.

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- Stable performance during low-load cruising and effective deceleration behavior during motor shutdown.

This prototype, while scaled for laboratory testing, successfully simulates the core behavior of a supercapacitor-driven metro rail, proving the concept and offering a low-cost and accessible platform for further research into regenerative braking, charge control algorithms, and energy efficiency optimization.

Table 7.1 backup time of motor at various speed

SNO	MOTOR SPEED	BACKUP TIME
1	70 %	205 SEC
2	30%	430 SEC

Table 7.2 chargin time of super capacitor for various range of voltage

SNO	VOLTAGE RANGE	CHARGING TIME
1	0-12 V	~40 SEC
2	6.5-12	~15 SEC

7.1 Limitations of Prototype

While the prototype successfully demonstrates the fundamental working of a supercapacitor-powered rail traction system, several limitations exist due to scaling and component constraints are as,

1 Scaled-Down Voltage and Power Levels:
The prototype operates at low voltage (12–13.5 V) and current levels, which do not fully represent the high-voltage environment (750 V to 25 kV) of actual metro systems. Thus, real-world power handling behavior is only approximated.

2 Use of PMDC Motor Instead of Traction Motor:
The 775 DC motor lacks the torque, speed range, and control complexity of AC traction motors (such as induction or permanent magnet synchronous motors) used in metro trains. This limits the dynamic fidelity of the prototype.

3. **Simplified Control Strategy**:
The ESP32 microcontroller operates the motor using basic control logic without advanced features such as regenerative braking, vector control, or real-time load adaptation, which are common in real systems.

4. **Limited Energy Storage**:
The supercapacitor bank (approx. 200 F at 13.5 V) provides only a brief energy window, insufficient for continuous or long-duration runs. This limits test durations and real-world applicability.

5. **Absence of Regenerative Braking Simulation**:
The prototype is not included mechanisms to recapture energy during braking or deceleration, a key advantage of supercapacitor-based systems in rail transport.

6. **Simplified Load Modeling**:
The mechanical load is idealized, without incorporating realistic parameters like , gradient, passenger mass variation, or environmental factors like wind resistance.

7. **Thermal Effects Ignored**:
Heating of the motor, capacitor bank, or driver circuitry under repeated cycles is not modeled, though it's a critical consideration in real-life systems.

8. **Inability to Include Certain Components in Simulation**:
MATLAB Simulink model has not included the real-world components like the BTS7960 motor driver and

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ESP32 controller, which means hardware-specific behaviors are not present in simulation results.

8. CONCLUSIONS

This work explore different ways to improve the energy efficiency and cost-effectiveness of urban metro systems through the integration of supercapacitor-based propulsion system. The development of a scaled-down prototype using a 775V DC motor, BTS7960 motor driver, ESP32 controller, and a 13.5 V, 200 F supercapacitor bank successfully demonstrated the feasibility of capacitive energy storage for short, frequent transit operations characteristic of urban rail systems.

Simulation and prototype test results indicate that supercapacitors, due to their rapid charging, high cycle life, and low internal resistance efficiently deliver burst energy required during acceleration phases and recharge during station stoppages. However, the limitations of the system—such as reduced energy density, limited storage duration, and scaling constraints—suggest that it is currently more suited for short-distance urban applications rather than long-haul or high-speed rail systems.

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Dynamic Distribution Locational Marginal Pricing Strategy from Electric Vehicles

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Abstract

This paper presents a single Quadratic Unconstrained Binary Optimization (QUBO) model of the combined optimization of both active and reactive power dispatch of an Electric Vehicle Aggregator (EVA). Its methodology integrates a new tri-layered, nested optimization framework that streamlines the process of selecting an optimum timetable of the EVA, checking its feasibility with grid limits at the Distribution System Operator (DSO) tier, and then distributing the ultimate schedule to each EV. The resulting framework results in a multi-level, comprehensive evaluation of the system, which generates (a) economically optimal results of both the EVA and the DSO, (b) detailed active and reactive power schedules on the cluster level of the electric vehicles, and (c) in-depth verification of the grid stability in the form of the voltage profiles, power factor, and system losses. Comparative studies indicate that this technique is easily better than benchmark techniques, and results in the reduction of up to 70.5% in total system cost and 29% in active power losses. The findings prove that the suggested QUBO framework can be effectively used as a strong, economically beneficial, and scalable approach to the problem of the demand management of electric vehicles in modern power systems.

Keywords: Demand Response, Electric Vehicle Aggregator, Locational Marginal Pricing, Quadratic Unconstrained Binary Optimization

1. INTRODUCTION

DLMP is a market-based mechanism to determine dynamic location-specific prices based on energy delivery marginal costs (i.e., network congestion losses), which provide the economic signals needed to manage resources efficiently ensure grid reliability [1, 2]. At the distribution level, the DSO first determines an EVA's operational boundaries (i.e., collective battery capacity charging constraints) to leverage distribution-level services [3]. Using dynamic DLMP pricing guidance, the aggregator can then intelligently schedule charging during low-price periods provide vehicle-to-grid (V2G) services during high-price events [4]. Thus, EVs are transformed from passive loads into active, dispatchable assets that can reduce local congestion enhance system resilience. For example, the work of Canizes et al. demonstrated this by using DLMP as a dynamic pricing tool to quantify how much EV users would voluntarily adjust their charging behavior in order to reduce their costs and those of the grid operator [5].

In addition, electric vehicles offer more than just management of active power. With advanced chargers containing voltage source converters, EVs can also supply or absorb reactive power [6]. This means that EVs can provide reactive power even while absorbing zero active power; thus, they have significant potential to provide localized voltage support participate in ancillary service markets [7]. The problem of DLMP-directed reactive demand response from EVAs is a large area of research; studies have utilized various techniques to optimize the DSO–EVA interaction. Traditional modeling approaches typically rely on bilevel programming [10] and hierarchical programming [9]. These bilevel problems have been converted to single-level formulations using the KKT conditions and the strong duality theorem [8, 9, 11]. Other models have utilized quadratic programming [12], Bender's decomposition to solve a Mixed-Integer Nonlinear Program (MINLP) that co-optimizes network reconfiguration with EV user behavior simulation [5], or nonlinear optimization to solve for system-wide social welfare [13]. While these classical optimization methods are well-established, their limitations in handling increasingly complex, discrete, and stochastic environments motivate the exploration of novel computational paradigms. Alongside these established MINLP methods, another class of optimization models, known as binary optimization, has gained prominence in various fields. Among these, QUBO is particularly versatile, with demonstrated success in diverse domains such as finance, cryptography. The primary method for mapping constrained optimization problems, like those found in power systems, into the QUBO format is the use of penalty techniques—a process that involves integrating the problem's constraints directly into the objective function as penalty terms [16, 17].

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Although its underlying importance has been recognized, the current literature reveals numerous gaps in research that underpin the need to conduct the inquiry. First of all, the popularity of classical optimization methods can be mentioned. When used on multi-level problems, such techniques typically involve a significant computational cost and, in contrast to other computational frameworks, they do not guarantee global optimality, making it challenging to explore alternative frameworks with potentially faster and stronger convergence properties[18]. In order to address these deficiencies, the current study proposes a new approach with a unique optimization design and less biased performance criteria. The key element of the suggested solution is the unified Quadratic Unconstrained Binary Optimization (QUBO) framework that involves two salient methodological developments. It initially reverses the traditional optimization path by initially setting up an upper-level problem posed in the EV Aggregator (EVA) viewpoint, thus arriving at an optimum power plan via consideration of the existing day-ahead locational marginal prices (DLMPs). Secondly, it replaces classical Karush-Kuhn-Tucker (KKT) duality transforms with a specific QUBO model to break down the nested tri-level optimization problem of coordinated power flow among EV clusters. This detailed information of the methodology is outlined in Section 2.

The main contributions of this study, stemming from these methodological and analytical innovations, are summarized as follows.

- Formulation of the DLMP-driven optimization problem as a QUBO model, with penalty factors derived from Lagrangian Multipliers.
- A rigorous evaluation designed to isolate and quantify the benefits of dedicated reactive power (Qeva-only) support from EVAs for improving grid voltage stability and system efficiency.
- A comprehensive performance evaluation across scenarios designed to test the adaptability of the proposed framework under diverse operational conditions.
- A novel directional power flow visualization that provides an intuitive blueprint of network loading and stress resulting from EV placement during peak hours.
- Benchmarking of the proposed framework against a state-of-the-art method to demonstrate significant improvements in economic efficiency, system performance, and grid stability.

2. PROPOSED METHODOLOGY

In the proposed framework as shown in Figure 1, an EVA optimization at the first level and a DSO optimization at the second level are coordinated through DLMPs. The DLMPs for active and reactive power in each bus and time slot, denoted as $\lambda^{P}_{i,t}$&$\lambda^{Q}_{i,t}$ sensitive price signals reflecting the marginal cost of power delivery. Binary encoding of power variables is achieved, and the resulting output includes cluster-level optimal active and reactive power schedules $P^{eva}_{c,i,t}$ & $Q^{eva}_{c,i,t}$ across time and location. In the second stage, the DSO receives the aggregated active and reactive power schedule from the EVA's optimization and solves its own QUBO problem. The DSO's objective is to minimize the total cost of grid operation, which includes dispatch from distributed generators (DGs), renewable energy sources (PV and wind), and power drawn from the transmission-distribution (TD) interface. All DSO operational constraints—including active and reactive power balance, voltage limits, TD interface power factor, and generator limits—are encoded as penalty terms within the objective function of QUBO. In case the DSO confirms feasibility, the final stage involves EVA Individual Load Allocation, where the aggregated cluster schedule is distributed across individual EVs attached to the specific buses in the system. This is handled through another QUBO optimization, with the corresponding objective. The allocation seeks to minimize reference tracking error and intra-cluster charging interruption cost, subject to constraints including cluster-level tracking, charging smoothness, individual EV energy satisfaction, and rated power limits. The output of this step is the individual EV-level power schedule, specifies how much power each EV should draw at each time slot.

3. OPTIMIZATION FRAMEWORK

A standard QUBO problem is represented by the following function:

$$\min_{\eta} H(J, h) = \sum_{i,j} J_{i,j}\eta_i\eta_j + \sum_{i} h_i\eta_i \tag{1}$$

where $\eta \in \{0,1\}^N$ is a vector of N binary decision variables, J is a symmetric matrix representing the quadratic interaction weights between variables, and h is a vector of linear biases [15].

The hierarchical framework is discussed in the following subsections.

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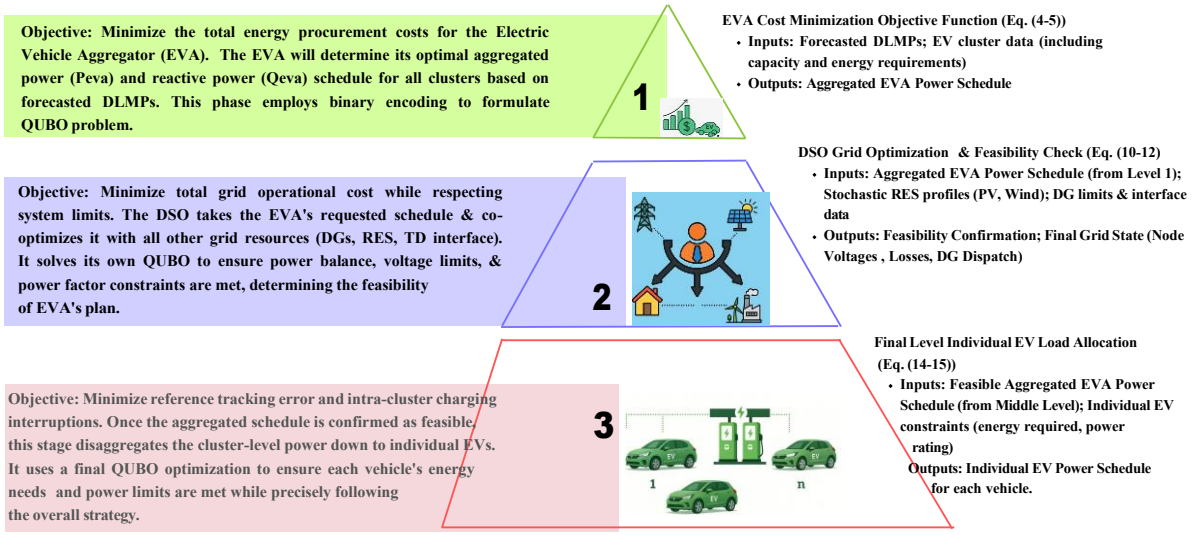


Figure 1: Proposed Hierarchical Optimization Methodology.

3.1 EVA Optimization Problem (Upper-Level)

Minimization of objective function, O_{eva} is subject to a set of constraints that represent the physical and operational limits of the EV fleet, including the instantaneous power limits, total energy requirements for each cluster, the apparent power capacity of the chargers, and the allowable range for reactive power injection or absorption.

$$\min_{P,Q} \quad O_{\text{eva}} = \sum_{c\in C}\sum_{i\in I}\sum_{t\in T} P^{\text{eva}}_{c,i,t}\cdot\lambda^{P}_{i,t} + Q^{\text{eva}}_{c,i,t}\cdot\lambda^{Q}_{i,t} \tag{2}$$

subject to constraints:

$$\begin{aligned}
&\underline{P}_c \le P^{\text{eva}}_{c,t} \le \bar{P}_c, && \forall c,t\\
&\underline{E}_c \le \textstyle\sum_t P^{\text{eva}}_{c,t} \le \bar{E}_c, && \forall c\\
&P^{\text{eva}\,2}_{c,t} + Q^{\text{eva}\,2}_{c,t} \le S^{\text{Rated}\,2}_{c,t}, && \forall c,t\\
&\underline{Q}^{\text{eva}}_{c,t} \le Q^{\text{eva}}_{c,t} \le \bar{Q}^{\text{eva}}_{c,t}, && \forall c,t
\end{aligned}$$

To adapt the constrained problem (refer Equation (2)), we must first transform its continuous power variables into a binary format QUBO formulation. This is done by approximating any real-valued variable P as a weighted sum of binary variables x_k:

$$P = \sum_{k=0}^{d-1} x_k \cdot 2^k, \qquad \text{where } x_k \in \{0,1\} \tag{3}$$

In this new formulation, the original constraints are embedded within the objective function as quadratic penalty terms, each weighted by a coefficient ρ_j. The resulting unconstrained objective function to be minimized is:

$$\min \quad Z = \underbrace{\sum_{c,t,k} x^{P}_{c,i,t,k}\cdot 2^k\cdot\lambda^{P}_{i,t} + x^{Q}_{c,i,t,k}\cdot 2^k\cdot\lambda^{Q}_{i,t}}_{\text{Operational Cost}} + \underbrace{\sum_{j=1}^{7}\rho_j\cdot\text{Penalty}_j}_{\text{Constraint Penalties}} \tag{4}$$

The individual penalty terms, which correspond to the seven original constraints, are defined as follows:

$$\begin{aligned}
&\text{Penalty}_{1,2} = \left(P^{\text{eva}}_{c,t} - \bar{P}_c\right)^2\cdot\Theta\left(P^{\text{eva}}_{c,t} - \bar{P}_c\right) + \left(\underline{P}_c - P^{\text{eva}}_{c,t}\right)^2\cdot\Theta\left(\underline{P}_c - P^{\text{eva}}_{c,t}\right) && \text{for Active Power Bound}\\
&\text{Penalty}_{3,4} = \left(\textstyle\sum_t P^{\text{eva}}_{c,t} - \bar{E}_c\right)^2\cdot\Theta\left(\textstyle\sum_t P^{\text{eva}}_{c,t} - \bar{E}_c\right) && \text{for Energy Requirement}\\
&\text{Penalty}_{5} = \left(P^{\text{eva}}_{c,t}\right)^2 + \left(Q^{\text{eva}}_{c,t}\right)^2 - \left(S^{\text{Rated}}_{c,t}\right)^2 && \text{for Apparent Power Limit}\\
&\text{Penalty}_{5,6} = \left(Q^{\text{eva}}_{c,t} - \bar{Q}_c\right)^2\cdot\Theta\left(Q^{\text{eva}}_{c,t} - \bar{Q}_c\right) + \left(\underline{Q}_c - Q^{\text{eva}}_{c,t}\right)^2\cdot\Theta\left(\underline{Q}_c - Q^{\text{eva}}_{c,t}\right) && \text{for Reactive Power Bound}
\end{aligned} \tag{5}$$

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3.2 DSO Optimization Problem (Lower-Level)

$$\min O_{\text{dso}} = \sum_{t\in T}\sum_{g\in DG} \alpha^{P}_{g,t} P_{g,t} + \alpha^{Q}_{g,t} Q^{\text{abs}}_{g,t} + \sum_{i\in TDg} \Gamma^{TDg}_{i,t} P^{TDfx}_{i,t} - P^{TDg}_{i,t} + L^{TDg}_{i,t} Q^{\text{abs}}_{i,t} \quad (6)$$

subject to constraints:

$$\sum_g P_{g,t} + \sum_i P^{TDg}_{i,t} + \sum_i P^{PV}_{i,t} + \sum_i P^{WG}_{i,t} = \sum_j P_{i,j,t}, \quad \forall i,t$$

$$\sum_g Q_{g,t} + \sum_i Q^{TDg}_{i,t} - Q^{\text{inflex}}_{i,t} + \sum_c Q^{eva}_{c,i,t} = \sum_j Q_{i,j,t}, \quad \forall i,t$$

$$\underline{V}i \le Vi,t \le \bar{V}_i, \quad \forall i,t$$

$$\underline{\theta}i \le \theta i,t \le \bar{\theta}_i, \quad \forall i,t$$

$$Q^{TD}_{j,t} - \tan(\arccos(0.9)) \cdot P^{TD}_{j,t} \ge 0, \quad \forall i,j,t$$

The QUBO formulation of DSO optimization. Here, the objective is to minimize a single function comprising operational costs and penalties for any constraint violations.

$$\min \quad Z = \underbrace{\sum_{g,t,k} x^{P}_{g,t,k}\cdot 2^k \cdot \alpha^{P}_{g,t} + x^{Q}_{g,t,k}\cdot 2^k \cdot \alpha^{Q}_{g,t}}_{\text{Operational Cost}} + \underbrace{\sum_{j=8}^{13} \rho_j \cdot \text{Penalty}_j}_{\text{Constraint Penalties}} \quad (7)$$

where x are the binary decision variables of the QUBO problem. The various system constraints are embedded into the objective function as quadratic penalty terms. These penalties are defined as follows:

Here, Penalty terms are defined as:

$$\begin{aligned}
&\text{Penalty}_8 = \Big(\sum_g P_{g,t} + \sum_i P^{TD}_{i,t} + \sum_i P^{PV}_{i,t} + \sum_i P^{WG}_{i,t} - \sum_j P_{D,j,t}\Big)^2 && \text{Power Balance Constraint}\\
&\text{Penalty}_{9,10} = (V_i - \bar{V}_i)^2 \cdot \Theta(V_i - \bar{V}_i) + (\underline{V}_i - V_i)^2 \cdot \Theta(\underline{V}_i - V_i) && \text{Voltage Limit Violation}\\
&\text{Penalty}_{11} = Q^{TD}_{i,t} - 0.484 \cdot P^{TD}_{i,t}{}^2 \cdot \Theta(\text{violation}) && \text{TD Interface Power Factor}\\
&\text{Penalty}_{12,13} = (P_{g,t} - \bar{P}_g)^2 \cdot \Theta(Pg,t - \bar{P}_g) && \text{Generator Limit Violation}
\end{aligned} \quad (8)$$

3.3 EVA Individual EV Load Allocation

$$\min O_{\text{evla}} = \sum_{t=1}^{T}\sum_{c=1}^{C} \delta^{eva}_{c,t} \cdot \omega_1 + \gamma^{\text{intrup}}_{c,t} \cdot \omega_2 \quad (9)$$

where, $\delta^{eva}_{c,t}$ is the difference (error) between the scheduled total and $\gamma^{\text{intrup}}_{c,t}$ refers to what was allocated across EVs and total intra-cluster power fluctuation or interruption cost for EVA. The constraints can be given by:

$$\begin{aligned}
&P^{\text{eva}}_{c,t} - \sum_{n=1}^{N} \hat{P}^{\text{eva}}_{n,t} = \delta^{\text{eva}}_{c,t}, && \forall c,t\\
&\sum_{n=1}^{N} \hat{P}^{\text{eva}}_{n,t} - P^{\text{eva}}_{n,t+1} = \gamma^{\text{intrup}}_{c,t}, && \forall c,t\\
&\sum_{t=1}^{T} \hat{P}^{\text{eva}}_{n,t} = E^{\text{eva}}_{n}, && \forall n\\
&0 \le \hat{P}^{\text{eva}}_{n,t} \le P^{\text{rated}}, && \forall n,t
\end{aligned} \quad (10)$$

The QUBO formulation of equation (9) is given below.

$$\min \sum_{t,c} \delta^{eva}_{c,t} \cdot \omega_1 + \gamma^{\text{intrup}}_{c,t} \cdot \omega_2 + \sum_{j=13}^{15} \rho_j \cdot \text{Penalty}_j \quad (11)$$

At the dispatch level, the Electric Vehicle Aggregator (EVA) uses the following penalty terms to ensure both aggregate and individual EV charging targets are met: The penalty terms for the EVA dispatch level are defined as follows:

$$\begin{aligned}
&\text{Penalty}_{13} = \Big(P^{\text{eva}}_{c,t} - \sum_n \hat{P}^{\text{eva}}_{n,t}\Big)^2 && \text{Aggregator Reference Tracking}\\
&\text{Penalty}_{14} = \Big(\sum_t \hat{P}^{\text{eva}}_{n,t} - E^{\text{eva}}_{n}\Big)^2 && \text{Individual EV Charging Fulfillment}\\
&\text{Penalty}_{15} = \hat{P}n,t^{eva} - P^{\text{rated}}_{n}{}^2 \cdot \Theta\ \hat{P}n,t^{eva} - P^{\text{rated}}_{n} && \text{EV Maximum Charging Rate Violation}
\end{aligned} \quad (12)$$

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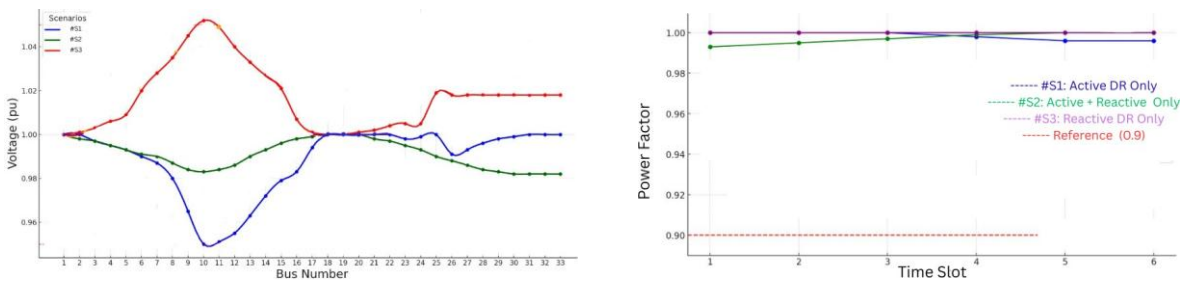
where, P^{eva} is the reference power schedule for the entire aggregator; $\hat{P}^{eva}_{c,t}$ is the dispatched charging power to an individual EV n at time t; E^{eva}_{n} is the total energy required by EV n; $P^{rated}_{n,t}$ is the maximum rated charging power for EV n.

Table 1: Comprehensive Simulation and Computational Setup.

Parameter	Description	Value
System & Network Model		
System	IEEE standard radial distribution network	33-bus
Time Horizon	Total simulation duration and discretization	24 hours (6 slots × 4h)
Assets & Loads		
EV Population	Number and aggregation of electric vehicles	1000 (20 spectral clusters)
Optimization & Pricing		
Optimization Model	Framework for scheduling active/reactive power	QUBO
QUBO Encoding	Binary variable precision for scheduling	8 bits (primary) + 4 bits (sensitivity)
DLMP Scheme	Pricing for active and reactive power	
Base Case	Fixed hourly prices for active power	λP: [40, 50, 60, 70, 100, 60] $/MWh
	Price range for reactive power	λQ: [4–10] $/MVArh
Computational Environment		
Execution Platform	Primary environment for reported results	Google Colaboratory (Colab)
Runtime Type	Processor used on Colab	*CPU (Standard) / GPU (Tesla T4)**
Development Machine	Local machine for coding and initial tests	Dell G15
CPU / RAM		Intel i5-11260H / 8 GB
GPU	(Part of dev. environment, not core calc.)	NVIDIA GeForce RTX 4060
Software	Core language and key libraries	
Language		Python 3.10
Core Libraries	Numerical, Data, and Network Modeling	NumPy, SciPy, Pandas, NetworkX
Visualization	Plotting and data visualization	Matplotlib, Seaborn
Utility	Progress tracking during optimization	TQDM

4. SIMULATION RESULTS AND DISCUSSION

This section includes the performance evaluation of the optimized structure of the proposed optimization framework for the IEEE 33-Bus System modified with a single 500 kW Photovoltaic (PV) System located at bus 15 and three 500 kW Wind Turbines located at bus 7. The purpose of this simulation study, as shown in Table 1 and described in detail, is to evaluate how well the system can perform under increasingly complex conditions. The research begins with a relatively simple evaluation (Scenarios S_1-S_2), and continues through to add complexity in two stages; first through the introduction of Reactive Power Dispatch (#S_3), and second through the inclusion of Adaptive Pricing (#S_4) into the previous stage of analysis. The ability of the proposed optimization to keep the critical grid parameters within acceptable bounds is demonstrated by the ability to maintain each buses' voltage levels within a standard operating range of 0.95-1.05 p.u. during peak periods (see Figure 2a) thereby providing a stable base upon which to minimize losses. Additionally, the power factor at the T-D interface is maintained constant and close to unity at all times (as shown in Figure 2b). These results indicate the optimization's effectiveness in keeping the critical grid parameters within acceptable limits; this can be seen in Figure 2 for each of the cases studies. To ensure that the primary needs of maintaining acceptable voltage levels at the T-D interface and acceptable current flow through each distribution line are met, secondary performance metrics were evaluated. These include Power Deviation (PD), i.e., the deviation of the total power delivered over a time period from the reference schedule (i.e., the difference between the actual amount of energy delivered during the same time frame



(a) Voltage Profile at Peak Hour. **(b)** Power Factor at T-D Interface.

Figure 2: Validation of the proposed optimization approach across different scenarios, showing (a) the bus voltage profiles and (b) the power factor at the T-D interface.

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and the scheduled amount of energy); and Line Loading, i.e., the time varying percent of power flow on a given distribution line relative to the lines rated maximum allowable capacity. In addition, the impact of the different scenarios on the characteristics of the system is also explored, specifically the network topology with power flow. This is the representation of the grid's structure, which shows the buses (nodes), lines (edges), and the direction and magnitude of the power flow.

4.1 Performance Analysis of System

This section provides a performance analysis for two scenarios ($§_1$–$§_2$) to compare our proposed framework with another approach given in [8].

4.1.1 Scenario $§_1$: Baseline Case without Demand Response

The results of the simulation in the case of the baseline scenario ($§_1$), where the EVA receives only active power and demand response (DR) is not carried out, are presented in this section. Figure 3 in the appendix shows that optimization results in a continuously constant active power consumption of 3.3325 MW through the whole day. This constant rate of charge supports the fact that there is no load shifting, as specified in the scenario. This observation is further confirmed by Figure 3a, which shows that all electric vehicle (EV) clusters have a fixed rate of charging over the time horizon. As a result, there are no adaptive charging policies and responsive power control. The charging schedule is fixed and immobile, which brings about severe network inefficiency and stress. The line-loading distribution shown in Figure 3b indicates that the load distribution is highly skewed: most of the lines are lightly loaded, and some of them are heavily overloaded. This kind of arrangement is the sign of the inefficient use of resources and the appearance of bottlenecks due to the stagnant flows of power. In order to explain the cause of such an imbalance, it is instructive to examine the network topology (Figure 3c) alongside the EV demand profiles (Figure 3d). The overall examination elucidates the loci of stress. An example would be a cluster with heavy energy requirement at a distance (a bus) far away to the substation which automatically induces large power flows and power losses which are directly traced in the highly stressed lines that are defined by the histogram.

Further examination of the simulation outcome indicates the operational disadvantages of this method. Figure 3e indicates considerable differences between the actual and reference charging patterns, particularly during the transition phases between off-peak and peak demand (slots 1 and 6). These reference patterns, described by Equation 2, are used as penalty functions in the QUBO objective function. The differences indicate a lack of temporal synchronization in cluster charging, despite the constant total load. At the same time, Figure 3f indicates the total system line losses, which increase over time during peak periods. Since this case does not offer reactive power compensation, the system inherently suffers from higher I^2R losses; without reactive compensation, the system requires greater current injections for grid balance, which is solely addressed by active power dispatch.

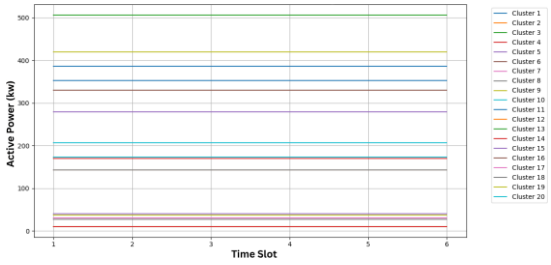
4.1.2 S_2:With Active and Reactive DR

In this case, the EVA functions as a prosumer by engaging in both active and reactive DR with substantial improvements over the baseline scenario (S_1). Unlike in the previous scenario, the optimized active power consumption, P^{eva}, is now time-varying and optimally varied over time intervals (Figure 4a), while the EVA also injects reactive power, Q^{eva}, into the grid (Figure 4b). This synchronized control directly enhances the health of the network by ensuring more balanced line loading (Figure 4c) across the topology of the system (Figure 4d) and ensuring voltage stability at the buses, as reflected by the small variations on the heat map (Figure 4e). The main effect of this optimized control is a substantial reduction in total active power losses compared to the baseline (Figure 4f). These system-level benefits are achieved by optimally dispatching individual EV clusters according to their energy demand and availability (Figure 4h), with their individual active and reactive contributions shown in Figure 4i. Another indication of the support role of the EVA is reflected at the T-D interface, where P^{eva} is constant while Q^{eva} reduces during peak hours to offer ancillary services (Figure 4g). Although this optimized control schedule varies from the initial reference given by Equation 2 (Figure 4j), it is this flexibility that makes it possible to achieve substantial improvements in the efficiency and stability of the grid.

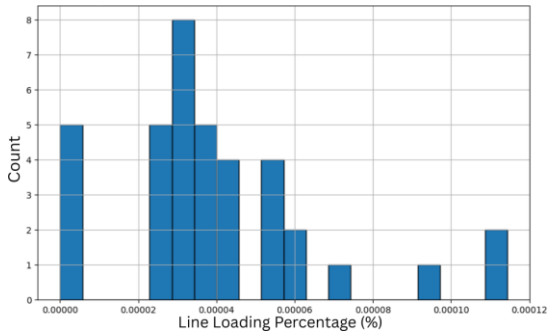
Even for the two similar scenarios, the proposed study offers a more comprehensive analysis by considering a broader set of metrics. This includes a thorough analysis of the grid performance (such as line loading histogram analysis, voltage profile analysis), optimization process (such as convergence analysis, bit depth analysis), and model-specific criteria (such as quality of clustering and EVA profitability) as indicated in Table 2 and explained in the next section. The comparative performance analysis of the proposed approach with [8] for the two scenarios, namely S_1 and S_2, is as follows: S_1 is concerned with cost minimization, whereas S_2 also considers reactive support for the grid.

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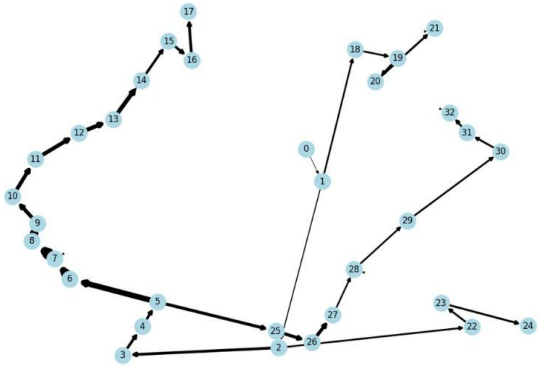
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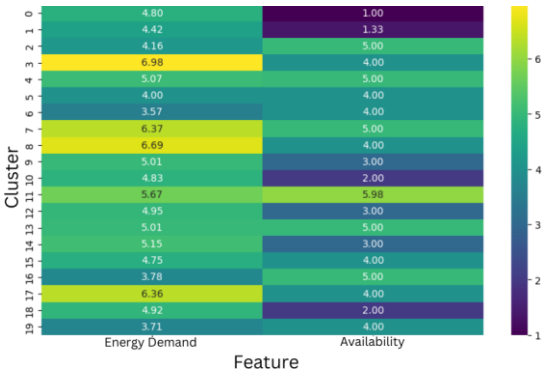
(a) Cluster-wise Charging Profiles



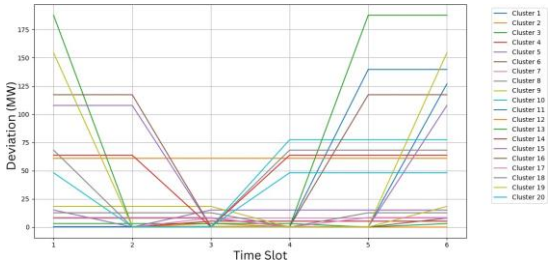
(b) Line Loading Percentage at Peak Hour (Time Slot 5)



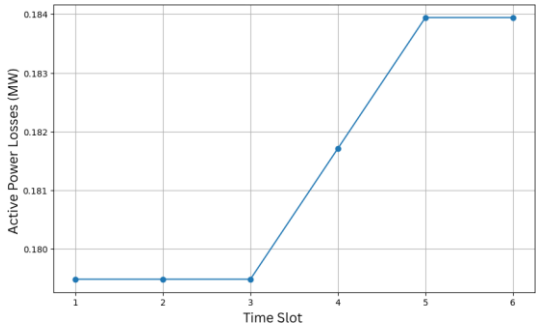
(c) Network Topology with Power Flow at Peak Hour (Time Slot 5)



(d) Cluster Distribution Heatmap



(e) Power Deviation Schedule across Time Slots

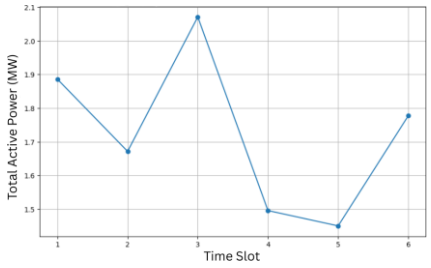


(f) Active Power Losses across Time Slots

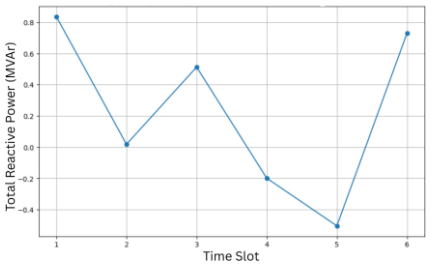
Figure 3: System response and grid performance under the conditions of S_1

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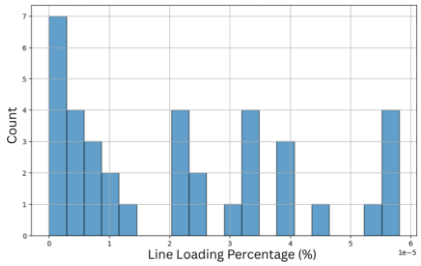
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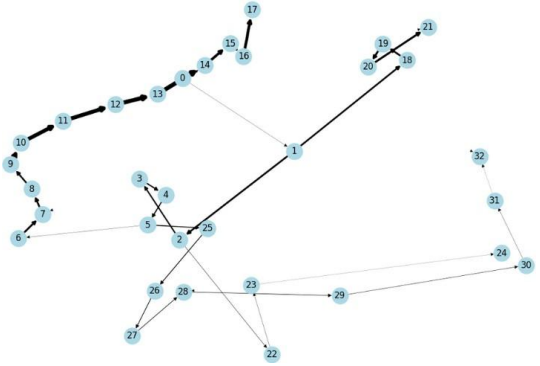
(a) Total Active Power across Time Slots



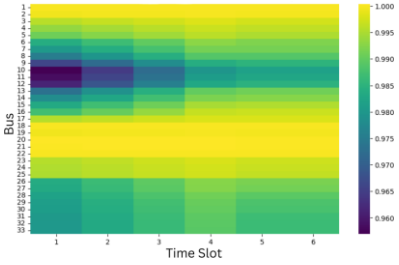
(b) Total Rective Power across Time Slots



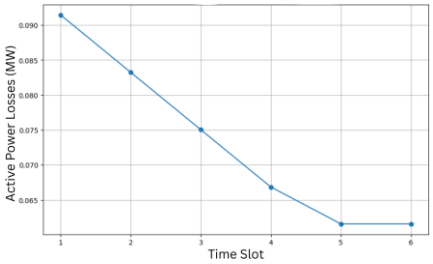
(c) Line Loading Percentage at Peak Hour (Time Slot 5)



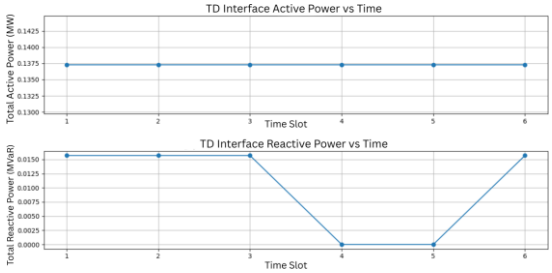
(d) Network Topology with Power Flow at Peak Hour (Time Slot 5)



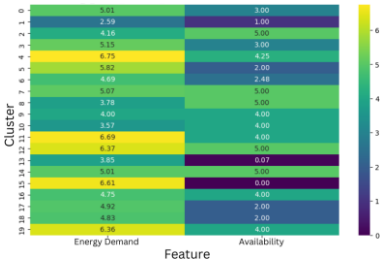
(e) Voltage Heatmap (p.u.)



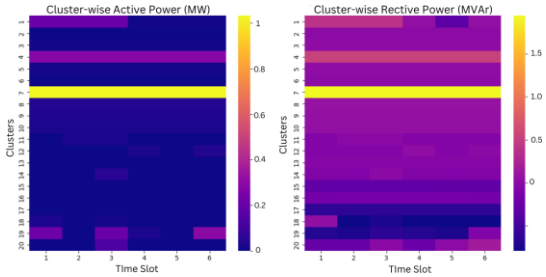
(f) Active Power Losses



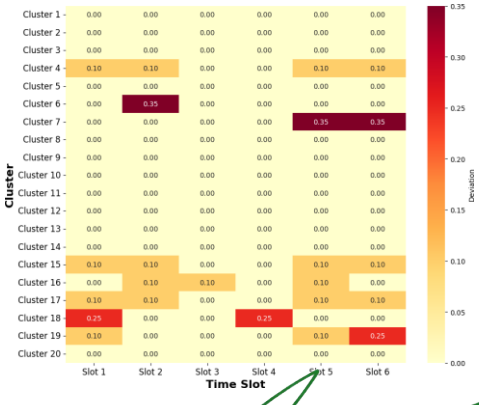
(g) T-D Interface Active and Reactive Powers across Time Slots



(h) Cluster Distribution Heatmap



(i) Cluster-wise Active and Reactive Power



(j) Deviation from Reference Schedule

Figure 4: System response and grid performance under the conditions of S_2

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Table 2: Comparative Performance Analysis of the Proposed Method.

Performance Metric	S_1		S_2		Key Finding / Improvement
	[8]	Proposed	[8]	Proposed	
Methodological Setup					
No. of EVs	1000	1000	1000	1000	Baseline consistency
No. of Clusters	4	20	–	–	QUBO method has Finer granularity.
Clustering Score	0.4010	0.5501	–	–	**37%** Silhouette score
Bit Precision	Cont.	4/8-bit	Cont.	4/8-bit	Enables quantum/digital implementation
Economic Performance					
EVA Cost ($)	1634.80	1132.20	726.31	580.50	**30.7%** (S_1) & **20.1%** (S_2)
DSO Cost ($)	3994.79	526.06	472.20	276.30	**86.8%** (S_1) & **41.5%** (S_2)
Total System Cost ($)	5629.59	1658.26	1198.51	856.80	**70.5%** (S_1) & **28.5%** (S_2)
Reactive Compensation ($)	–	–	15.00	4.95	**67.0%** cost S_2
Grid Technical Performance					
System Active Losses (MWh)	1.75	1.09	0.62	0.44	**37.7%** (S_1) & **29.0%** (S_2)
Minimum Voltage (pu)	N/R	0.9500	0.9501	0.9570	**0.7%** floor in S_2
Avg. Voltage (pu)	~0.985	0.9890	0.9880	0.9905	Consistently closer to 1.0 pu
Voltage Profile Std Dev (pu)	~0.012	N/R	~0.012	0.0079	**34% smoother** voltage profile in S_2
Power Factor (TD Interface)	0.985	0.998	N/R	0.998	to near-unity
Total Reactive Energy (MVArh)	–	–	~110	136.27	**23.9%** reactive support
Operational Constraints & Runtimes					
Charging Interruptions	N/R	N/R	5	2	**60%** interruptions
Constraint Violations	N/R	66	N/R	75	Comparable constraint adherence
QUBO Runtime (4-bit) (s)	–	69.5	–	–	Fast computation time
QUBO Runtime (8-bit) (s)	–	326.6	–	–	Trade-off for higher precision

N/R: Not Reported; Cont.: Continuous variables; –: Not applicable

4.1.3 Comparison with Reported Work

The performance of the proposed QUBO optimization method is benchmarked against the reported work in [8]. The previous study has considerd two primary cases that correspond to our cost-minimization scenario (S_1) and reactive power support scenario (S_2). Consequently, a direct performance comparison for these two scenarios, with their respective results are summarized in Table 2. As detailed in Table 2, the proposed QUBO framework demonstrates substantial and multifaceted improvements over the benchmark approach. From an economic perspective, the framework drastically reduces costs for both the EVA and the DSO, leading to a remarkable reduction in total system cost - by more than 70% in the baseline scenario (S_1). These financial gains are underpinned by superior grid management, evidenced by significant reductions in active power losses and a markedly improved voltage profile, which is improved and more stable. Methodologically, performance gains are driven by a finer-grained clustering approach and the use of a bit-based optimization model. Operationally, the system achieves these benefits with fewer charging interruptions and computationally viable runtime, confirming the practical applicability of the proposed framework.

5. CONCLUSION

This paper introduced a new integrated three-level QUBO-based optimization model that was designed to address the demand response problem based on the DLMP. A sequential, modular framework offers an alternative to classical bilevel methods, which is both practical and scalable, and which attempts to capture the interaction between the EVA and the DSO in its hierarchical nature under diverse operational conditions. The findings prove the obvious excellence and flexibility of the suggested strategy. A direct comparison with an existing approach demonstrates that our framework is capable of lowering the overall price of the system using active demand response and using both active and reactive demand response, without exceeding the limits of the important parameters of the grid. The work affirms that EV flexibility intelligently operated through dynamic market information is a very crucial and economically viable asset in developing a more robust and stable distribution grid. The future work must be directed at improving the framework and making it more curtailment-reducing-strategy-specific to ensure the economic and environmental performance of such complicated energy systems is improved.

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RFID Technology Based Smart Shopping Cart

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Abstract: *Lately, navigating and selecting items in shopping centers has become a daily activity in urban areas, with a multitude of individuals engaging in shopping, particularly during holidays and weekends. The peak shopping periods coincide with special offers and discounts, leading people to purchase a variety of items and place them in shopping carts. Upon completing their purchases, customers are required to visit the billing counter for payment and invoicing. At the charging counter, the clerk readies the receipt utilizing a standardized tag scanner, a tedious cycle that frequently brings about lengthy lines. To overcome this problem, this paper proposed a smart shopping cart using RFID technology.*

Supermarket aisles with long lineups are not conducive to happy consumers. In actuality, the poll you cited presents a dismal image: Long lines are deliberately avoided by 86% of consumers, and 70% of them say they wouldn't even think about going back. The cause? It all comes down to annoyance. Consumers are frustrated by inefficiency and lost time, as they wish to finish their errand and go on with their lives. This affects a supermarket's bottom line directly; it's not simply a small annoyance. Revenue is lost and loyalty is weakened when clients depart. The good news is that there are workable solutions for this issue, all of them revolve on optimizing the checkout procedure.

This paper aims to address the issue of long lines at billing counters in malls. The proposed solution involves the use of a smart shopping cart that displays the total cost of the items stored within the cart. This allows customers to directly pay the amount either through a mobile application or at the billing counter, facilitating a quicker and more efficient checkout process. An Arduino Uno, an RFID Reader Module, an RFID Card, and a Bell are the hardware components. This framework wipes out the customary checking of items at the counter, essentially accelerating the whole buying process. In addition, the customer is made aware of the total amount that needs to be paid, which enables better personal savings-based financial planning.

Since the entire billing process relies on RFID technology, the likelihood of human errors is significantly reduced. The system also incorporates a feature that allows customers to remove scanned items, further enhancing the overall shopping experience. By adopting this innovative approach, customers can manage their shopping more efficiently, selecting items based on their budget.

Keywords: RFID, Arduino Uno

1. INTRODUCTION

The project integrates Arduino Uno, RFID sensing, and an Android-based mobile application to automate the end-to-end shopping workflow. Architecturally, the system is divided into two layers: electronic hardware and software. The Arduino Uno acts as an intermediary controller, bridging the RFID hardware layer with the software layer, specifically the Android application.

On the software side, users authenticate via secure login methods before accessing the system, thereby safeguarding personal data. The application additionally prevents accidental purchase of expired goods and grants shoppers instant access to rich product information—enabling side-by-side product comparisons directly on their phones.

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This information-rich feature empowers consumers to select the most suitable product within their budget. A dynamic in-app shopping list reflects selections in real time, adapting to priority changes or spending constraints, and also reminds users of pending purchases. A back-end server, linked wirelessly to the smart cart, handles data exchange with the mobile app from any point within the store, enabling untethered, seamless product information retrieval and a consistently efficient shopping journey.

2. HARDWARE COMPONENTS

Table 1 summarises the key hardware elements that constitute the proposed smart shopping cart system.

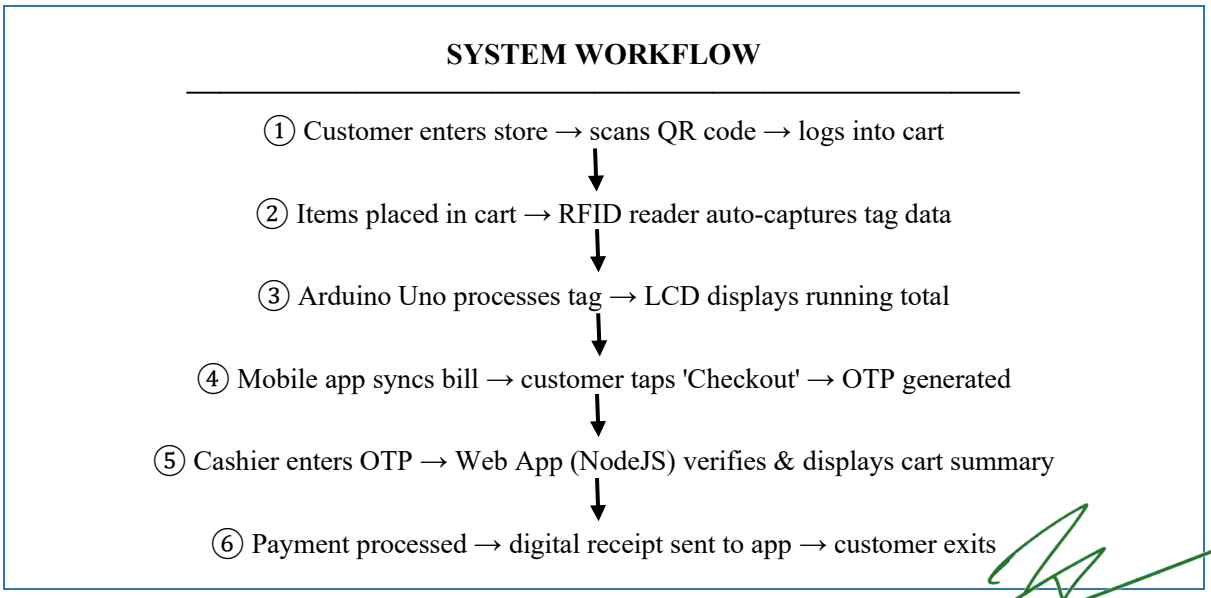
Table 1 Hardware Components of the Smart Shopping Cart System

Component	Model / Type	Function	Role in System
Microcontroller	Arduino Uno	Central processing unit	Coordinates RFID & software
RFID Reader	EM-18 Module	Reads RFID tags wirelessly	Captures item data
RFID Tags	Passive Tags	Stores item info	Attached to each product
Display	LCD Screen	Shows bill total	Real-time cost feedback
Alert	Buzzer / Bell	Audio confirmation	Item scan notification

3. SYSTEM WORKFLOW

Figure 1 below illustrates the step-by-step operational flow of the proposed RFID-based smart shopping cart system, from customer entry to final payment.

Fig. 1 End-to-End System Workflow Diagram



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3.1 Advantages of RFID system

Post-pandemic consumer behaviour has heightened sensitivity to hygiene and contactless interaction in public retail environments. The smart shopping cart directly addresses these expectations by enabling customers to shop with minimal physical contact with surfaces or other individuals. Variants such as the Super Mini smart cart even feature antibacterial handles rated at 99.99% effectiveness, reinforcing shopper confidence.

Beyond health considerations, RFID delivers substantial operational and commercial benefits across multiple domains. Table 2 provides a structured overview.

Table 2 Advantages of RFID Systems

Category	Advantage	Impact
Inventory	Near-flawless scan accuracy	Reduces human error; maintains ideal stock
Inventory	Real-time stock visibility	Prevents stock-outs and lost sales
Supply Chain	Automated contactless identification	Faster receiving, shipping & sorting
Supply Chain	End-to-end product traceability	Greater accountability & efficiency
Supply Chain	RFID-based theft deterrence	Reduces shrinkage & asset loss
Operations	Workflow automation	Less manual labour; lower costs
Operations	Real-time data analytics	Supports faster, informed decisions
Operations	Asset utilisation tracking	Minimises equipment downtime
Extras	Product authentication via tag data	Counters counterfeiting
Extras	Digital returns/exchange processing	Personalised, rapid customer service
Extras	Reduced paper-label printing	Smaller environmental footprint

Collectively, RFID systems generate measurable improvements in operational effectiveness, data accuracy, and supply-chain transparency across sectors as diverse as retail, healthcare, manufacturing, and logistics.

3.2 Limitations OF RFID System

One practical drawback specific to smart shopping carts is the absence of a child seating area—a concern for parents, particularly mothers who routinely bring young children to the supermarket. This design gap may influence adoption among that demographic.

At a broader technology level, RFID presents several well-documented constraints. Table 3 categorises these challenges for clarity.

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Table 3 Limitations of RFID Systems

Category	Challenge	Sub-Issue	Detail
Cost	High upfront investment	Tag cost	$1–$30 per tag vs. a few cents for barcodes
	High upfront investment	Reader cost	Roughly 10× the price of barcode scanners
	Integration overhead	Infrastructure	Existing systems need upgrades & software changes
Technical	Signal interference	Environment	Metal & liquids distort readings
	Tag collision	Density	Multiple nearby tags cause read conflicts
	Limited read range	Distance	Tags may be missed beyond rated range
Security	Privacy risk	Data breach	Encrypted protocols mandatory
	Hacking vulnerability	Cloning	Tags can be duplicated with off-shelf hardware
Misc.	Battery dependency	Active tags	Battery replacements add maintenance cost
	Environmental disposal	Hazardous	Some tags contain harmful compounds
	No universal standard	Protocol	Different frequencies hinder cross-system use

A thorough cost-benefit analysis is therefore essential before committing to RFID deployment. The specific application context, infrastructure maturity, and security requirements must all be weighed against the technology's clear operational merits.

4. APPLICATION

4.1 Application for client and cashier

The dual-app architecture—comprising a client-facing Android application and a cashier-facing NodeJS web interface—streamlines the checkout process for both parties.

4.2 Client App (Android Flutter)

Scan & Track: The mobile interface allows shoppers to scan RFID-tagged items using their smartphones. Each scan instantly populates the in-app shopping list with the product name, price, and image.

Real-time Tracking: The cumulative bill updates dynamically with every scan, giving users full budget visibility and eliminating price surprises at the point of payment.

Checkout & OTP: Once shopping is complete, the customer taps 'Checkout.' The app generates and displays a unique One-Time Password (OTP) for handoff to the cashier.

4.3 Cashier Web App (NodeJS)

OTP Verification: The cashier enters the customer's OTP into the web portal, which retrieves and displays the complete cart summary along with the total payable amount.

Swift Evaluation & Payment: The cashier reviews the itemised list, confirms accuracy, and processes payment via the customer's chosen method—eliminating the need for manual item-by-item scanning.

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Receipt & Done: A digital receipt is dispatched to the customer's app, and the transaction is closed without the customer ever having to stand in a conventional checkout queue.

5. RELATED WORK

Several prior studies have explored RFID and related technologies for retail automation. Table 4 compares these works against the proposed system.

Table 4 Comparative Analysis of Related Works

Author / Year	Technology Used	Billing Method	Key Contribution	Limitation
Sainath (2014)	Barcode	Central system via unique ID	Barcode-based automated billing	Requires line-of-sight scan
Budic (2014)	RFID	Checkout-counter queue	RFID queue optimisation	Still requires counter visit
KomalAmbekar (2015)	RFID + ZigBee	Central charging division	Wireless bill generation	Limited ZigBee range
Prateek Aryan (2014)	RFID + Bluetooth	Bill pushed to Android via BT	In-cart billing with Bluetooth	Short Bluetooth range
Proposed System	RFID + Arduino + Android App	OTP-verified, app-based payment	End-to-end automated checkout	Requires stable Wi-Fi

6. PROPOSED METHODOLOGY

RFID technology is increasingly supplanting traditional barcode systems owing to its capacity for automatic, line-of-sight-free identification. In the proposed design, every shopping cart is equipped with an RFID module, and all store products carry corresponding RFID tags. On entering the premises, a customer scans a QR code to authenticate and activate the cart session. As products are added, the RFID reader logs each item automatically. At checkout, the system computes and deducts the total directly from the customer's linked digital wallet, rendering manual cashier intervention unnecessary.

6.1. RFID (Radio-Frequency Identification)

RFID employs electromagnetic fields to identify and track objects via embedded tags. Each tag contains a miniature radio transmitter and a transponder. When energised by a reader's EM field, the tag broadcasts a unique serial number back to the reader for identification.

6.2. INTEL 8051 Microcontroller

The MCS-51 is a single-chip microcontroller developed by Intel in the 1980s for embedded applications. Designed by John Wharton, it achieved wide commercial adoption through the late 1980s and early 1990s, and binary-compatible derivatives remain in active use today.

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6.3. RFID Reader

An RFID reader retrieves data stored on RFID tags via radio-wave communication, enabling individual item tracking. Unlike barcodes, RFID tags require neither direct physical alignment nor line-of-sight access to the reader, significantly simplifying high-throughput scanning.

6.4. LCD Display

A Liquid Crystal Display (LCD) derives its name from the dual physical state of its active medium—simultaneously exhibiting properties of both a liquid and a solid crystal. It produces a visual output by modulating light through this liquid crystal layer.

7. FUTURE SCOPE

The RFID-based smart cart platform offers significant headroom for future enhancement. Table 5 outlines priority development directions.

Table 5 Future Development Roadmap

Enhancement Area	Proposed Development	Expected Benefit
Tagging Technology	Ultra-wideband (UWB) RFID tags	Longer range, greater precision
Data Security	AES-256 encrypted tag communication	Prevents cloning & data breaches
Personalisation	AI-driven product recommendations	Tailored shopping experience
Autonomous Carts	Self-navigating cart robots	Hands-free in-store assistance
Payment	Integrated UPI / contactless NFC payment	Zero queue, instant settlement
Standards	Adoption of ISO 18000-6C (EPC Gen2)	Cross-vendor interoperability

Employing the EM-18 reader alongside Arduino, the current system already makes notable strides in reducing billing delays and simplifying inventory oversight in high-footfall retail environments. Its potential to displace legacy barcode systems in the automation domain is considerable. Looking further ahead, autonomous carts capable of traversing store aisles and aggregating selected items represent a transformative horizon—one that advances in UWB tagging, data-security protocols, and AI-driven personalisation will progressively make attainable.

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Vision-Guided Autonomous Holonomic Robot for Dynamic Indoor Environments

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Abstract:*This work presents the design and development of an autonomous holonomic drive robot system with object detection capability, enabling movement in all directions using computer vision and Mecanum wheels. Computer vision-based object detection allows the robot to recognize its surroundings, categorize objects, and respond promptly, while the drive system facilitates smooth movement of the robot across its entire workspace. The capabilities of the robot are further enhanced using OpenCV and YOLO technology to enable effective movement and interaction in changing environments. A two-tier control architecture integrating a Raspberry Pi Zero 2W and an ESP8266 microcontroller effectively isolates sensitive vision hardware from high-current motor components through a dedicated driver circuit. Trajectory tracking and system validation are carried out through Gazebo simulation. The result is a successfully developed autonomous robot prototype capable of navigating dynamic indoor environments without reliance on GPS infrastructure, making it well suited for a range of real-world applications.*

Keywords: Autonomous Robots, Holonomic Drive, Computer Vision, OpenCV, YOLO.

1. INTRODUCTION

Robots are an integral part of automation that can work independently in complicated environments with ease. The main aim of robot is object detection to recognize barriers, allowing the robot to move around and steer clear of possible obstacles successfully. Holonomic drive systems integrated with computer vision overcome these restrictions by enabling robots to navigate smoothly in all directions and make intelligent choices based on their environment. These features are useful to deploy this robot to various fields, such as warehouse automation and aiding in rescue missions. This research is centered on creating a self-navigating robot with omnidirectional drive for identifying objects. The next section presents the literature survey, gaps identified, and main contributions of proposed work.

2. LITERATURE REVIEW

A literature survey has been conducted to check progress in autonomous robotics. There has been a notable advancement in holonomic drive systems, omnidirectional mobility. It has been reported that computer vision provides better navigation and perception. The review summary in Table 1 combines main findings from important works. From the reported work, the gaps are identified providing the motivation behind this present research.

Table 1: Summary of Reported Work

Ref. No. & Publication / Source	Title	Key Contribution
Doroftei et al. (2007) [1]	Omnidirectional Mobile Robot – Design and Implementation	Established foundational principles for the mechanical design and control of omnidirectional mobile robots; demonstrated that holonomic systems allow free directional movement without reorientation.
Mohd Salih et al. (2006) [2]	Designing Omni-Directional Mobile Robot with Mecanum Wheel	Explored the engineering challenges involved in building a Mecanum-wheeled mobile robot; highlighted the wheel's unique capacity for simultaneous lateral and forward motion.
De Silva & Munasinghe (2009) [3]	Development of a Holonomic Mobile Robot for Field Applications	Addressed the creation of a holonomic robot suited to outdoor/field conditions; emphasized the significance of terrain adaptability for practical autonomous deployment.

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Ref. No. & Publication / Source	Title	Key Contribution
Tatar et al. (2014) [4]	Design and Development of an Autonomous Omni-Directional Mobile Robot with Mecanum Wheels	Detailed the hardware–software integration of an autonomous omni-directional platform; contributed practical insights into sensor fusion and control algorithm design.
Piemngam et al. (2019) [5]	Development of Autonomous Mobile Robot Platform with Mecanum Wheels	Examined design considerations for a Mecanum-wheeled autonomous robot and demonstrated how computer vision enhances obstacle identification and avoidance capability.
Taheri et al. (2015) [6]	Kinematic Model of a Four Mecanum Wheeled Mobile Robot	Formulated the mathematical kinematic model relating individual wheel angular velocities to the robot's linear and rotational motion, providing a rigorous theoretical basis for Mecanum-based control.
Kowalczyk & Joon (2022) [8]	Design of One Degree of Freedom Rotating Platform for Leader-Follower Autonomous Robot Control	Introduced a rotating platform mechanism for coordinating multi-robot leader–follower behaviour; underlined the importance of inter-robot communication in distributed systems.
Tsiakas et al. (2023) [9]	An Autonomous Navigation Framework for Holonomic Mobile Robots in Confined Agricultural Environments	Proposed an adaptive navigation framework for holonomic robots operating in constrained agricultural spaces; highlighted challenges specific to domain-specific autonomous deployment.
Toribio et al. (2021) [10]	Mobile Robot Localization in Industrial Environments Using a Ring of Cameras and ArUco Markers	Demonstrated the use of ArUco marker arrays with a multi-camera setup for precise industrial robot localization; contributed robust positioning methods applicable to automation workflows.
Mutalib & Azlan (2020) [11]	Prototype Development of Mecanum Wheels Mobile Robot: A Review	Reviewed iterative prototype development practices for Mecanum-wheeled robots; offered practical guidance on testing methodologies during the engineering lifecycle.
Asus et al. (2020) [12]	Design and Control of a Motor Wheel System Controlled by Smartphone	Described a smartphone-controlled motor-wheel system and presented a torque/force calculation methodology that serves as a reference for drive system parameter design.
Kumar et al. (2020) [13]	Autonomous Navigation of Holonomic Mobile Robot Using Point-to-Line Algorithm	Introduced a point-to-line path-planning algorithm for holonomic robots; illustrated improvements in manoeuvrability and collision-free navigation over conventional approaches.
Sheth et al. (2018) [14]	Design and Development of Intelligent AGV Using Computer Vision and Artificial Intelligence	Combined AI with computer vision to build an intelligent automated guided vehicle; emphasised the critical role of object detection in enabling reliable autonomous movement.
Garrido & Panov (2023) [15]	Detection of ArUco Markers – OpenCV Tutorials	Provided a step-by-step technical guide for implementing ArUco marker detection using the OpenCV library; a foundational reference for vision-based robot localisation.

The proposed work is driven by the increasing need for self-sufficient robots that can efficiently move around

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in changing environments and complete tasks independently and accurately without the need of GPS. The following are main research gaps:

- Most studies (Doroftei et al., de Silva & Munasinghe, Tatar et al.) have focused on outdoor or open-space navigation. Very few addressed reliable autonomous navigations in unstructured, dynamic indoor spaces without GPS.
- The work of Piemngam et al. (2019) and Sheth et al. (2018) have separately explored computer vision and Mecanum-wheeled robots, a complete integration of holonomic drive with real-time YOLO-based object detection on a single lightweight embedded platform is still largely unexplored.
- Most of the referenced systems (Puthussery et al., Kowalczyk & Joon) have relied on expensive depth cameras and high-end processors for navigation. A cost-effective alternative using a standard camera module with ultrasonic sensing for distance estimation is not well addressed.
- Existing works have typically used a single controller for both vision processing and motor control. The isolation of high-level vision tasks from low-level motor operations using a dual-microcontroller setup (Raspberry Pi + ESP8266) is not explored in prior literature.
- Kumar et al. (2020) and Tsiakas et al. (2023) have proposed navigation algorithms but few works have demonstrated Gazebo-based simulation validation before actual hardware testing, creating a gap in systematic development methodology.

2.1 Contributions:

The main work carried out is as follows:

- Development of full kinematic model derived for a 4-Mecanum-wheel robot linking wheel angular velocities to robot motion in X, Y, and rotational directions and appropriate selection of motors and battery based on torque computation.
- Development of a two-level electronics architecture isolating sensitive sensors from high-current motor drivers.
- Provision of ArUco marker-based indoor navigation as a GPS-free alternative, combined with SLAM concepts.
- Real-time object detection using OpenCV + YOLO for obstacle recognition and path guidance, and conduction of simulation study using Gazebo to validate ArUco navigation before hardware testing.

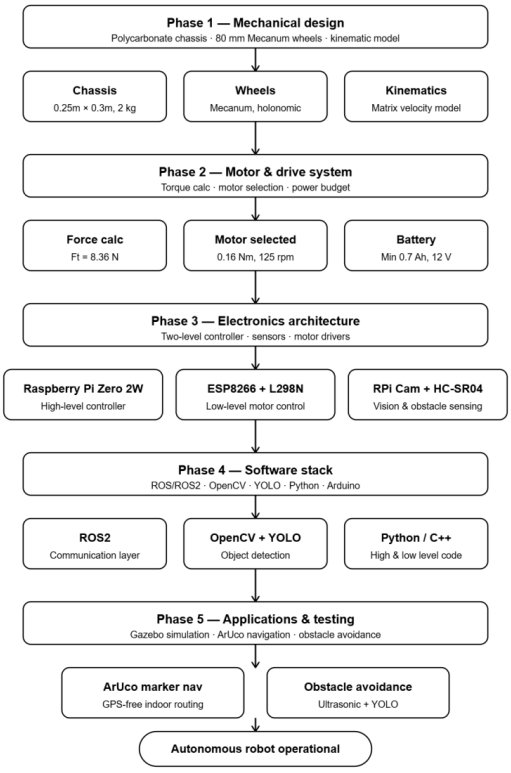


Fig. 1 Proposed Work Flow.

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3. Proposed Work

The different phases of work is illustrated with the help of Fig. 1 and discussed in coming subsections.

3. System Design

3.1 Mechanical Design

(a) Chassis design: The chassis structure must be robust and is designed to accommodate Mecanum wheels, allowing for omnidirectional movement. To have these features we made our robot chassis from polycarbonate sheet because it is lightweight to support the necessary hardware without hindering mobility. The dimensions of the chassis are: Length: 0.25 meters, Width = 0.3 meters, Height = 0.15 cm, weight of the bot: 2kg

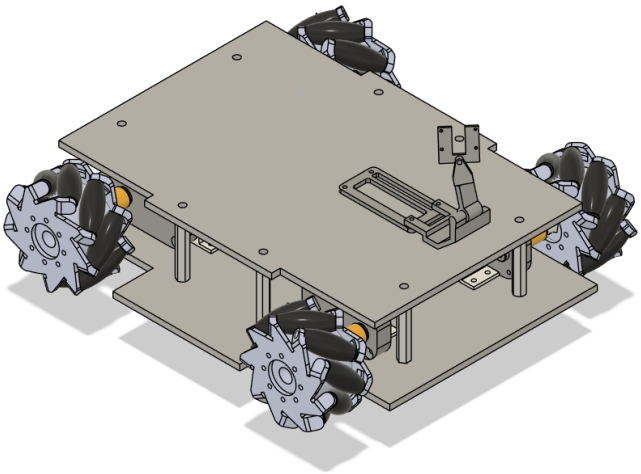
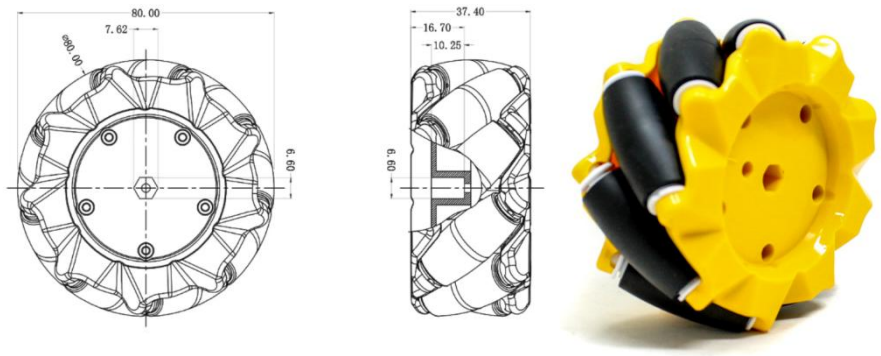


Fig 2 CAD Design of the Robot

a) **Wheel selection:** Mecanum wheels will be used to achieve holonomic motion, enabling the robot to move in any direction without changing its orientation. We have used 80mm Mecanum wheels:



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Fig 3 80 mm Mecanum rubber roller wheels

3.2 Kinematic modeling

The kinematic model of the robot is based on the velocities of the individual wheels and their contribution to the overall movement of the robot. The model uses a set of equations that relate the angular velocities of the wheels to the robot's linear and angular velocities in the X, Y, and rotational directions.

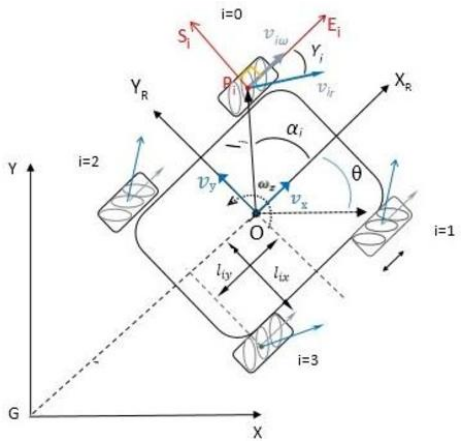


Fig 4 Wheels Configuration and Posture definition [6]

The robot's motion can be described by its velocity in the X (forward), Y (sideways), and θ (rotational) directions. The velocity of the robot $(\vec{V})$ is determined by the velocities of the individual Mecanum wheels (V_i), which are a function of their angular velocities (ω_i).

Each Mecanum wheel generates a velocity vector at a 45-degree angle to the wheel's plane. The robot's movement is the result of the superposition of these vectors. The kinematic model of the robot can be described using the following equations:

Let (V_x), (V_y), and (ω) represent the robot's velocity in the X (forward), Y (sideways), and rotational directions, respectively.

Let (ω_1), (ω_2), (ω_3), and (ω_4) be the angular velocities of the four wheels.

The relationship between the robot's global velocity vector and the individual wheel speeds is given by the following matrix equation:

$$\begin{bmatrix} V_x \\ V_y \\ \omega \end{bmatrix} = \frac{1}{4} \begin{bmatrix} 1 & -1 & -\dfrac{1}{L+R} \\ 1 & 1 & \dfrac{1}{L+R} \\ 1 & 1 & -\dfrac{1}{L+R} \\ 1 & -1 & \dfrac{1}{L+R} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix}$$

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Where, L is the distance between the front and back wheels, and R is the distance between the left and right wheels.

This matrix equation relates the angular velocities of the wheels to the robot's linear and angular velocities. By solving the inverse kinematics, we can determine the necessary wheel speeds to achieve a desired motion

3.3 Design of motor driver system parameters:

To calculate the torque required by the mobile robot to accelerate we first need to calculate the force required by the bot to accelerate. The primary criterion of designing a robot that carries load is to calculate the torque required to transmit the weight of the load from one point to another. Torque required for the system is calculated using the total tractive effort or force (F_t) of the system as in equation 1[12].

$$F_t = F_a + F_r + F_g + F_d \quad (1)$$

where, F_a = force due to acceleration, F_r = Force due to friction or wheel rolling resistance, F_g =force due to gradient resistance, F_d = aerodynamic drag. The wheel diameter is 80mm so the radius (r) will be 40 mm or 0.04 m. For one revolution of wheel, the robot will move a distance of:

$$2\pi r = 2 \times 3.14 \times 0.04 = 0.251m \quad (2)$$

The robot is designed to achieve a speed of 0.52 m/s.

In our experiment, we are assuming the robot is operating in an indoor environment and moving on a flat surface, so the F_g will be zero and aerodynamic drag is neglected due to an insignificant value. Therefore, the forces acting on the robot are F_a and F_r.

Force due to acceleration: $F_a = m \times a$ (3)

where, m = mass of the robot = 2kg; a = acceleration of the robot

assuming that the robot will achieve the desired velocity (V) of 0.52 m/s in time (t) 2 seconds, then the acceleration (a) of the robot can be calculated as:

$$a = V/t = 0.52/2 = 0.26m/s^2 \quad (4)$$

$$F_a = 2 * 0.26 = 0.52N$$

Force due to friction: $F_r = \mu \times N$ (5)

where, μ = coefficient of friction, N = Normal force

Assuming for coefficient of friction (μ) to be 0.4 for the floor and Normal force (N) acting on the robot is:

$$N = m * g \quad (6)$$

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where m = mass of the robot = 2 kg and g = acceleration due to gravity = 9.8 m/s^2

So, $N = 2 * 9.8 = 19.6N$

Therefore, $F_r = 0.4 * 19.6 = 7.84N$

The total tractive force (F_t) required by the robot is:

$$F_t = F_a + F_r \quad (7)$$

$$F_t = 0.52 + 7.84$$

$$F_t = 8.36N$$

We need to select a permanent magnet DC motor that can provide the required force. The torque (τ) provided by the motor can be calculated using the formula:

$$\tau = F * r \quad (8)$$

where F is the total force required by the mobile robot = 8.36 N, and r is the radius of the wheel = 0.04 m.

$$\tau = 8.36 * 0.04 = 0.33Nm$$

Since our design is an omni-drive system with four mecanum wheels, each motor only needs to provide a quarter of the total torque. Therefore, torque per wheel or torque required by each motor is:

$$\tau = 0.33/4 = 0.08Nm \quad (9)$$

Then, with a design speed (V*)* of 0.52 m/s and wheel radius (*r)* of 0.04 m, we can calculate the required rated speed of the motor (*n*) in rpm as:

$$n = V * 60/2\pi r \quad (10)$$
$$n = 0.52 * 60/0.251 = 124.3rpm$$

- To ensure that the robot can move reliably under all conditions, we would consider adopting a safety factor of 2, this means we will select a motor which can give a torque twice the calculated torque per wheel.

Therefore, on the basis of above calculations and our robot design we need to select a permanent magnet DC gear motor with a rated torque τ = 0.16 Nm and with a rated speed of 125 rpm.

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Fig 5 L-shaped permanent magnet dc gear motor

Based on the calculations above, assuming we select a permanent magnet DC motor with a rated voltage of E = 12V, rated torque of τ = 0.16 Nm, and rated speed of n =125 rpm, the required power of the motor can be calculated using the formula:

$$P = \tau \times \omega \tag{11}$$

where τ is the torque provided by the motor and ω is the angular velocity of the motor. Thus, Angular speed in rad/s (ω) of the motor and wheel will be:

$$\omega = n \times (2\pi/60) \tag{12}$$

$$\omega = 125 \times 0.104 = 13 rad/s$$

and, $P = \tau \times \omega = 0.16 \times 13 = 2.08W$

The above calculated required power is for one motor. The total power required for four motors is:

$$P_{total} = 4 \times 2.08 = 8.32W \tag{13}$$

and the rated voltage of the selected motors is E = 12V, we can calculate the required current (I):

$$I = P_{total}/E \tag{14}$$

$$I = 8.32/12 = 0.69A$$

Therefore, the minimum capacity of the power battery should be 0.7 Ah in order to power the robot for 1 hour of operation. If the robot needs to run for a longer period, a higher capacity battery should be selected.

From the above systematic calculation, we are able to select the right DC gear motor with 0.16 Nm, 125 rpm and battery capacity 0.7 Ah based on the torque computation.

3.4 Electronics Architecture

a) Microcontroller/Processor: A central processing unit, a Raspberry Pi zero 2W, will serve as the robot's brain, handling computations and decision-making.

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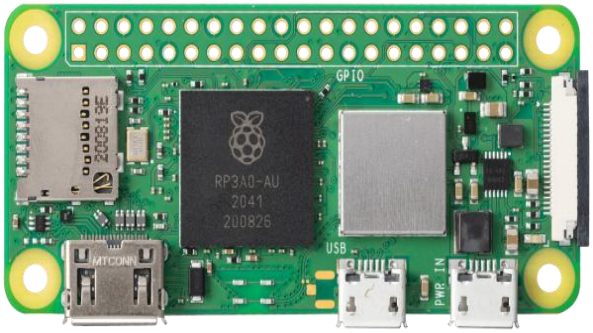


Fig 6 Raspberry Pi Zero 2W

b) Motor Driver Circuit: Motor drivers will be required to control the speed and direction of each Mecanum wheel independently. We have used two L298N Motor driver modules with ESP8266 for controlling the motors of our robot.

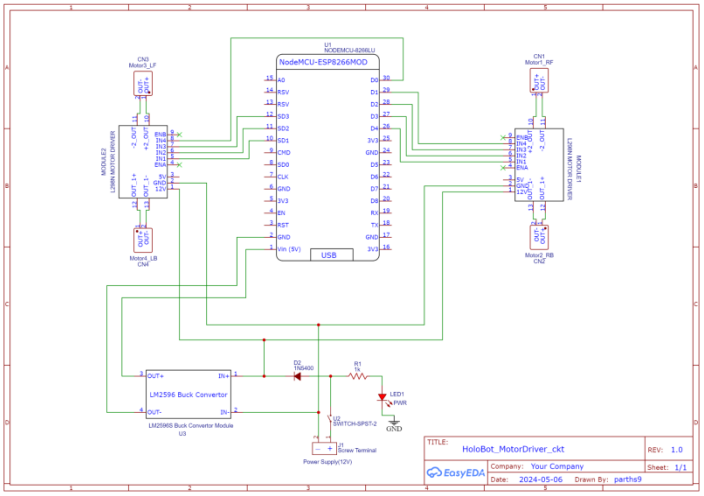


Fig 7 Motor Driver Circuit schematic

c) Sensors: A Camera module for object detection, we have used Raspberry Pi Cam for our project. We also have added an Ultrasonic sensor as an additional sensor for obstacle detection.

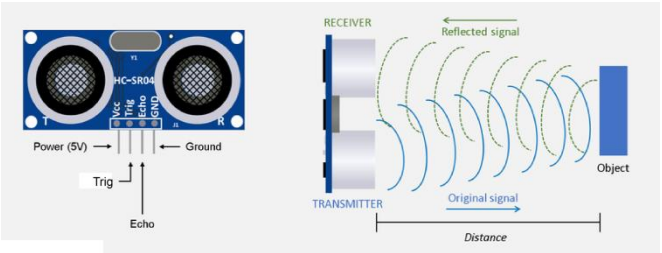


Fig 8 HC-SR04 Ultrasonic Sensor



Fig 9 RPi - CAM Module

Circuit:

The ultrasonic sensor and RPi - Cam module are connected to the Raspberry Pi Zero, which acts as a high-level controller, the Raspberry Pi can be connected to ESP8266 module either via WiFi or I2C interface. The motor driver circuit controlled

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by ESP8266 acts as a low-level controller. This two-level architecture helps in isolating sensitive sensor equipment from high-current components of the motor driver circuit.

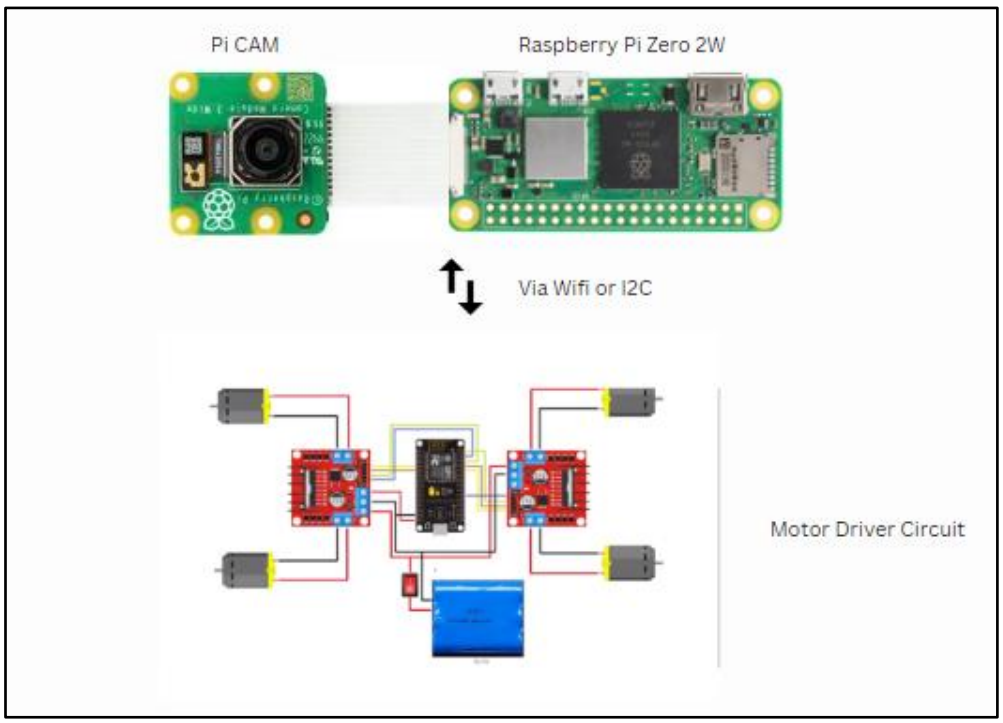


Fig 10 Electronics architecture of the robot

3.5 Software Stack

a) ROS/ROS2: The Robot Operating System (ROS) and ROS2 are middleware software packages for robotics that are open-source and offer services tailored for a diverse computer cluster. They provide resources and frameworks for acquiring, constructing, scripting, and executing code on various machines. ROS is commonly utilized in robotics research and development, offering an organized communication layer on top of the host OS in a diverse compute cluster.

b) OpenCV/YOLO: OpenCV is a wide-ranging open-source library used for computer vision tasks that provides a variety of functions for image processing and machine learning. YOLO, which stands for You Only Look Once, is a cutting-edge object detection system that operates in real-time and is built upon deep learning algorithms. As a pair, they are effective resources for assisting robots in accurately and quickly identifying objects and obstacles.

c) Python: Python is recognized for its simplicity and clearness, being a high-level, interpreted programming language. It is commonly selected for software development in different areas, like robotics, because of its wide range of libraries and frameworks like ROS and OpenCV, which make development and prototyping faster and easier.

d) C++/Arduino IDE Sketch: The ESP8266 microcontroller is programmed to control the motor driver circuit using Arduino IDE sketch, a subset of C++ programming language.

4. APPLICATIONS

4.1 ArUco Marker-Based Navigation

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This combines aspects of beacon-based navigation and Simultaneous Localization and Mapping (SLAM), offering a balance between the two approaches.These stages are described below and illustrated with the help of Fig. 10.

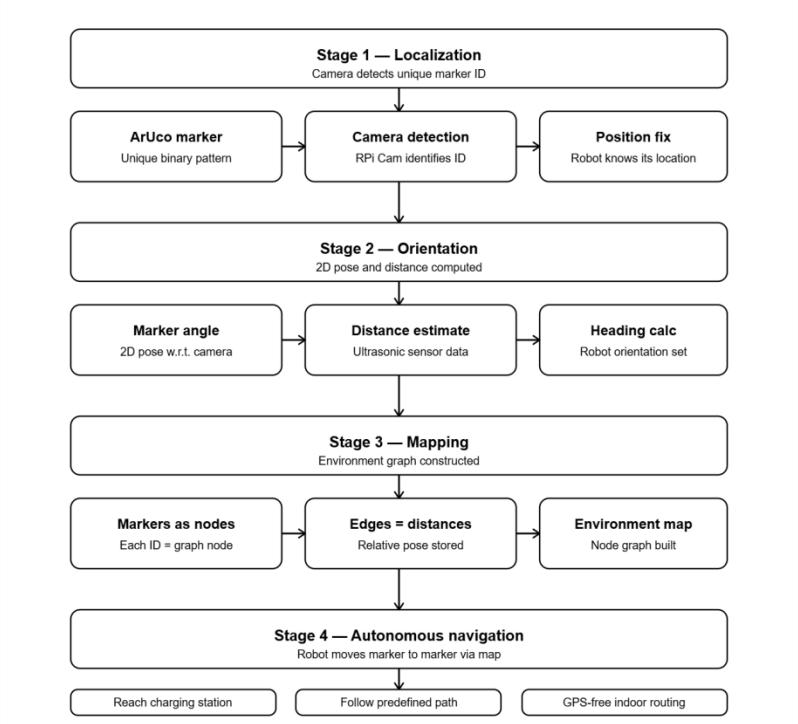


Fig 11 ArUco Marker-Based Navigation Stages

- **Stage 1** — Localization: camera detects unique marker ID
- **Stage 2** — Orientation: 2D angle + distance computed
- **Stage 3** — Mapping: node graph built from all detected markers
- **Stage 4** — Navigation: robot moves autonomously using the map

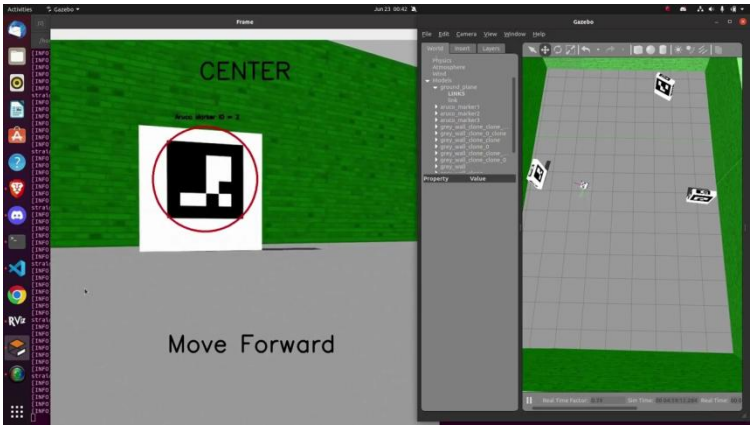


Fig 12 Simulation of Aruco Marker based Navigation in Gazebo Sim

In case. GPS signals are unavailable or unreliable, ArUco marker-based navigation is particularly used for indoor environments. From Fig 12, it can be seen that a depth camera is used to obtain the distance to the marker and relies on odometry calculations for tracking the robot's position after localization with respect to the marker. Since a depth camera was not available, the RPi Cam module was used for marker detection and an ultrasonic sensor for distance calculation. This allows the robot to navigate autonomously to various locations within the mapped environment, guided by the strategic placement of ArUco markers.

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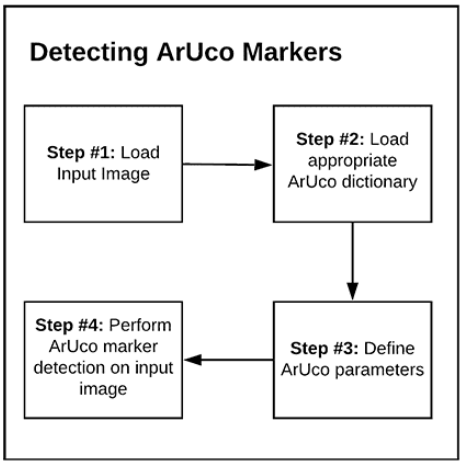


Fig 13 Flowchart of ArUco Marker Detection

5. CONCLUSIONS

This paper has successfully built a prototype of a self-sufficient holonomic drive robot capable to track a desired trajectory without the use of GPS. The approach of mechanical designing and OpenCV for software development was perfect, and the components integrated for performing various task to meet the objective of navigation was well-functioned. The computer vision system precisely detected and recognized objects. The functionality of each component was examined and the developed robot demonstrated precise navigation capabilities, especially in tight spaces. This has reflected the flexibility and potential influence of the proposed autonomous robots with advanced mobility and perception abilities. It is concluded that holonomic drive systems, computer vision, and adaptive navigation strategies functioned well for the progression of autonomous robot. In conclusion, this research provided a future direction to further explore and development of industrial robots. The future work will focus to develop holonomic drive robots with improved object detection algorithms and cost-effective solutions.

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Voice-Operated UAV System Using AI with Live Two directional Communication

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Abstract— Modern Drones are rapidly transforming into intelligent, interactive and smart aerial systems that are capable of communicating in real-time and make autonomous decisions. This paper investigates the mechanism behind voice command recognition, two-way communication, and virtual assistant integration to boost UAV capabilities. The application of Hidden Markov Models (HMM) and Maximum Likelihood Linear Regression (MLLR) techniques in the field of speech recognition allows drones to understand and process voice instructions. The two-way voice communication is facilitated through a WebRTC-based communication system using LTE, and thus drones can serve as flying communication stations. Furthermore, the use of a Raspberry Pi system helps delivers real-time telemetry, weather information, and flight diagnostics.

Keywords: Voice-controlled UAVs, two-way communication systems, virtual assistant implementation, WebRTC technology, Drone voice recognition, intelligent aerial systems.

I. INTRODUCTION

With the advancement of technology in drones, it has become easier for humans to communicate with them. Unlike using a manual controller or programmed route, a drone can now be controlled by voice command and also receive immediate feedbacks too. Using voice recognition technology, two-way communication, and artificial intelligence virtual assistant, the UAVs can easily be turned into interactive systems that can respond intelligently [1], [2].

The authors in [3], [4] discusses some of the technologies behind the same. HMM and MLLR speech recognition technologies can be used to recognize voice commands, making the control very convenient and hands-off. A WebRTC-based communication system that operates on LTE network makes the drones have real-time interaction capabilities using their microphone and speaker. In addition, a virtual assistant running on a Raspberry Pi computer provides live telemetry data, weather forecast, and other diagnostic services.

Not only does this combination improve usability, but it also makes operation easy in an environment that is quite complex. It enables the drones to be able to respond to the situation immediately without any human intervention. In addition, this makes the UAVs accessible to users, as they can control them even without any specialized knowledge.

II. RELATED WORK

According to Nair et al. [1] a voice-controlled quad-copter was implemented using basic keyword matching and RF based communication. Fayjie et al. [2] developed a voice-enabled smart drone control system with the help of deep learning. Despite achieving better recognition performance, the system could not include two-way communication functionality. Kalkan et al. [3] created a two-way communication system that was based on UAVs with the use of analog FM modulation. It suffered from poor noise immunity also. Kishore kumar et al. [4] proposed a drone personal assistant based on AI. However the system was completely dependent on cloud processing. Nand and Mathiyazaghan [5] built a UAV controlled through voice commands. It used a very simple threshold-based detection mechanism. Rahim et al. [6] introduced a VOC-Drone which was basically an AI-enabled voice controlled drone system but this system lacked speaker adaptation or two-way communication.

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Table 1: Comparison with Existing Systems

Feature	[1]	[2]	[4]	[6]	Proposed
Voice Control	✓	✓	✓	✓	✓
HMM + MLLR	—	—	—	—	✓
Speaker Adapt.	—	—	—	—	✓
Two-Way Comm.	—	—	—	—	✓
Virtual Assistant	—	—	✓	—	✓
Telemetry	—	✓	—	✓	✓
NLP	—	—	—	—	✓

III. SPEECH RECOGNITION: HOW IT WORKS

In this section, we describe the main techniques used in our system. The voice recognition workflow has three major parts:

(i) Feature extraction using MFCCs,

(ii) Command classification using HMMs, and

(iii) Adaptation of the system to individual voices by the use of MLLR.

A. MFCC Feature Extraction

Before the system can recognize speech the raw audio signal must be converted into numerical data that the computer can easily work with and understand. This conversion or transformation can be achieved using Mel-Frequency Cepstral Coefficients (MFCCs) [7], [8].

1) Pre-emphasis: The input audio signal is passed through a filter to enhance the higher frequency components:

$$y(t) = x(t) - 0.97 \cdot x(t-1) \quad (1)$$

Where $y(t)$ is the filtered output signal, $x(t)$ is the current input sample, and $x(t-1)$ is the previous input sample. The coefficient 0.97 controls the degree of pre-emphasis applied.

2) Framing & Windowing: The audio signal is divided into overlapping frames of about 25 milliseconds for further analysis.

3) FFT & Mel Filterbank: Each segment is converted from time domain to frequency domain and passed through triangular filters on the Mel scale:

$$Mel(f) = 2595 \times \log_{10}(1 + f/700) \quad (2)$$

Where $Mel(f)$ is the perceived frequency on the Mel scale, and f is the corresponding physical frequency in Hz.

4) DCT: The final 13 MFCC coefficients is produced through The Discrete Cosine Transform.

B. Hidden Markov Model (HMM)

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After the successful extraction of the MFCC features, Hidden Markov Models are used to match them to specific commands. An HMM is a statistical model or approach where speech is treated as a sequence of hidden states, and each producing observable features. The HMM may be defined or stated by transition probabilities (A), observation probabilities (B), and initial state probabilities (π) [7], [9].

The observation probability is modeled with the help of a Gaussian Mixture Model as:

$$b_j(O_t) = \Sigma\, c_jm \cdot N(O_t;\, \mu_jm,\, \Sigma_jm) \tag{3}$$

Where, $b_j(O_t)$ is the observation probability of feature vector O_t in state j, c_jm is the mixture weight for the m-th Gaussian component, μ_jm is the mean vector, and Σ_jm is the covariance matrix of that component.

During recognition, the Viterbi algorithm determines the most likely command. The model is trained and carried out using the Baum-Welch algorithm [9], [10].

C. MLLR Speaker Adaptation

MLLR solves and addresses the problem of different speakers who have unique and different voice characteristics. A linear transformation can be applied to the HMM parameters: [10], [11]

$$\hat{\mu} = A \cdot \mu + b \tag{4}$$

Where A is a transformation matrix and b is a bias vector, estimated from 3–4 sentences spoken during calibration. This is something that makes our system unique; the drone adapts to each pilot's voice.

IV. PROPOSED SYSTEM ARCHITECTURE

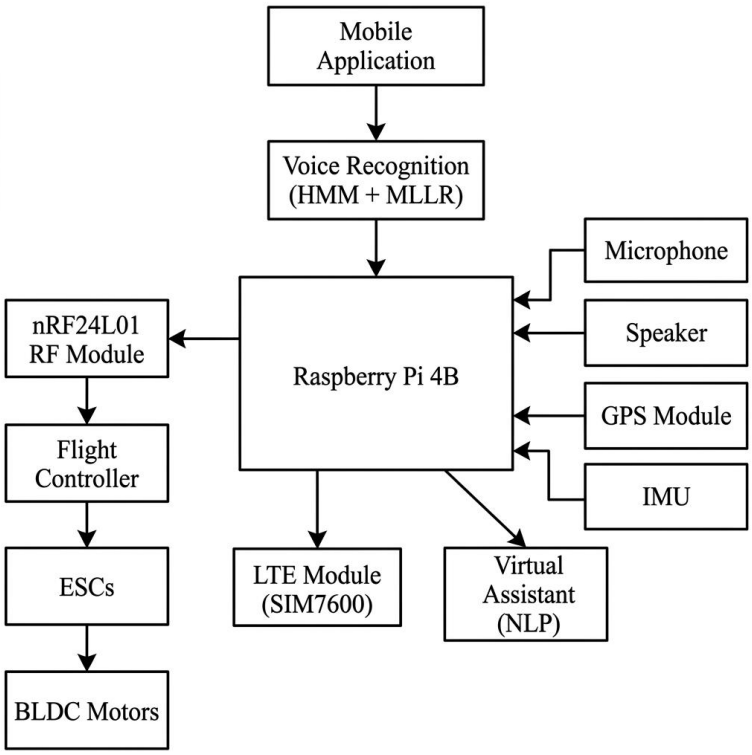


Fig. 1: Proposed UAV System Architecture

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A. Voice Recognition Setup and Calibration

Before the flight takeoff, the pilot is required to speak 3–4 predefined sentences. The system then extracts MFCC features and the MLLR module creates a unique voice profile. This approach also ensures that only verified voice inputs are recognized by the system.

B. Command Flow and Signal Transmission

The pilot provides commands through the app. These commands are analyzed and verified using the combined HMM and MLLR-based recognition system. Once validated, the commands are sent or transmitted via nRF24L01 RF module to the flight controller. If in case any invalid command is detected, the drone automatically maintains its position by hovering and displays a warning notification in the application.

C. Pre-defined Voice Commands

The Command set includes instructions such as: "Throttle [value] percent,""Pitch forward [value],""Roll right [value],""Yaw right [value],""Hold position," and "Return home."

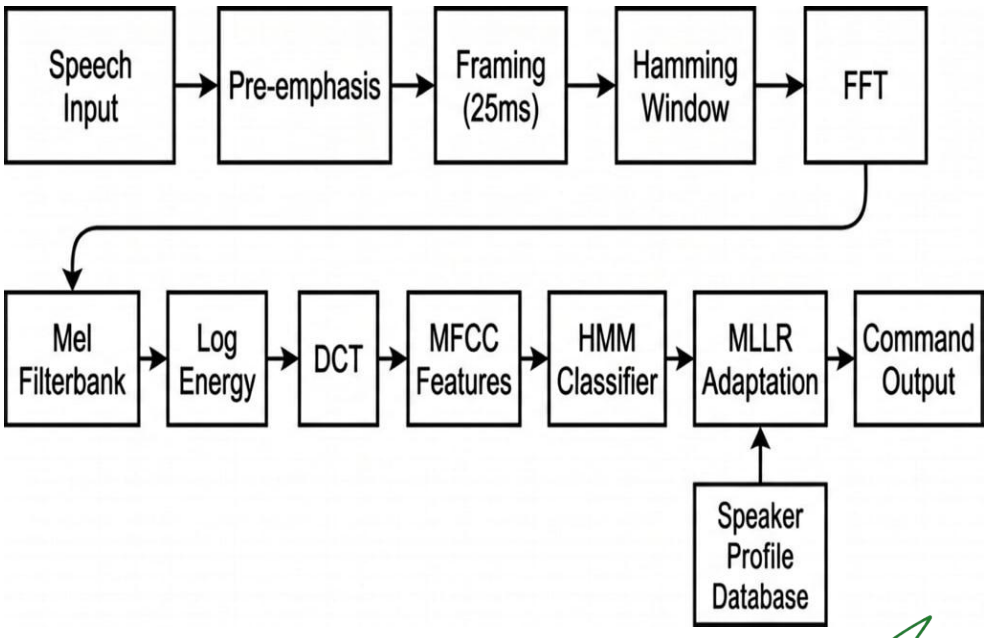


Fig. 2: Voice Recognition Pipeline

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V. TWO-WAY COMMUNICATION FOR UAVS

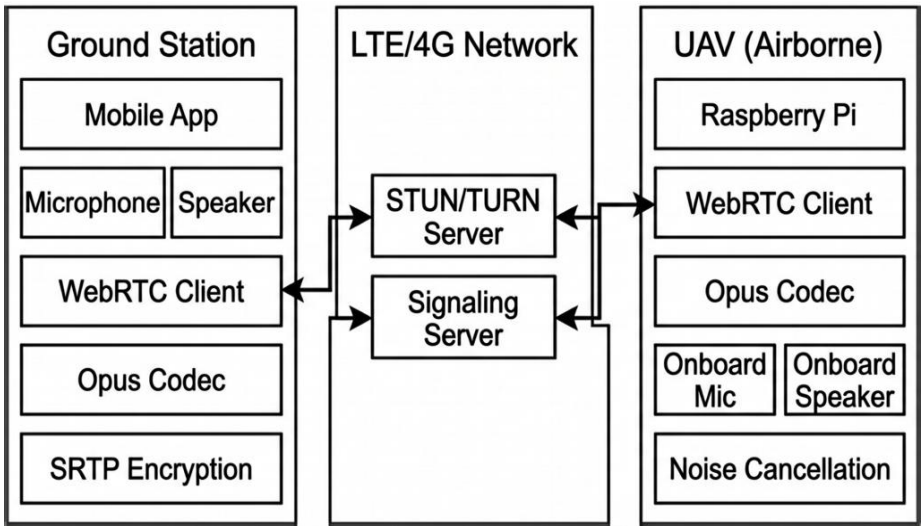


Fig. 3: Two-Way Communication Architecture

A. Activation and Audio Transmission

The communication system is operated by using voice command. A WebRTC based peer-to-peer session is established over LTE (SIM7600) connectivity. Also even during the Ground-to-Drone communication: audio is compressed (Opus), encrypted (SRTP), and transmitted via LTE. Drone-to-Ground: onboard mic captures audio and transmits back [12].

B. Noise Reduction and Session Management

Noise reduction algorithms are used to filter propeller noise (3–8 kHz) while preserving and not making any changes in the voice (300 Hz – 3.4 kHz). The user can deactivate communication by voice command to conserve power.

VI. VIRTUAL ASSISTANT INTEGRATION

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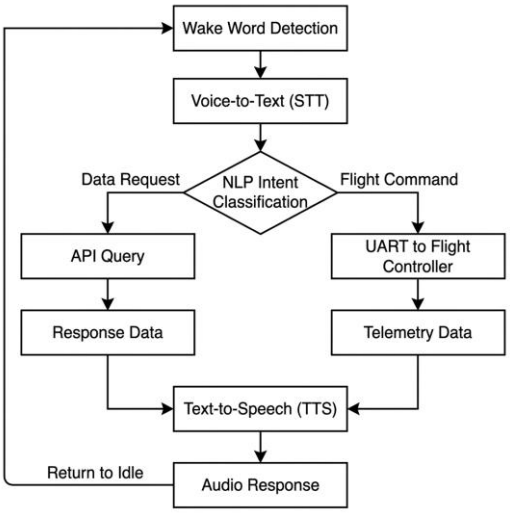


Fig. 4: Virtual Assistant Processing Flow

The virtual assistant is triggered using a predefined wake word. After activation the Spoken instructions are converted into text (DeepSpeech/Whisper) and analyzed by NLP (spaCy/NLTK). For data requests, it queries APIs. For flight specific operations, the assistant changes information with the flight controller via UART/MAVLink. Responses are then generated using text-to-speech synthesis [13-15].

VII. COMPONENTS REQUIRED

A. Hardware

• Raspberry Pi (Model 4B or later)
• Flight Controller (Pixhawk, Betaflight, or Ardupilot)
• Electronic Speed Controllers (ESCs)
• Brushless DC Motors
• RF Module (nRF24L01 series)
• LTE Module (SIM7600 or equivalent)
• Microphone and Speaker
• Lithium Polymer (LiPo) Battery
• IMU (Inertial Measurement Unit) and GPS Module

B. Software

• Raspbian OS, Python & C++
• HMM & MLLR Libraries
• Voice-to-Text Engine (DeepSpeech, Google Speech API, or Whisper)
• Text-to-Speech Engine (Festival TTS, eSpeak, or Google TTS)
• MAVLink Protocol and UART Communication
• NLP Module (spaCy, NLTK, or OpenAI-based models)
• WebRTC Framework.

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VIII. EXPECTED PERFORMANCE

Based on existing research and published benchmarks in the field of embedded speech recognition and WebRTC communication, the expected performance of the proposed system is summarized below.

Table 2 shows the expected voice recognition accuracy under different noise conditions. The MLLR adaptation gain shows how much improvement we expect from calibrating the system to a specific speaker's voice.

Table 2: Expected Voice Recognition Performance

Metric	Clean	Moderate Noise	High Noise
Command Accuracy	97–99%	88–95%	70–85%
Response Latency	<200ms	<300ms	<500ms
MLLR Improvement	+2–3%	+5–8%	+8–12%

Table 3 shows the expected communication performance based on WebRTC-over-LTE benchmarks.

Table 3: Expected Communication Performance

Metric	Expected Value
End-to-End Latency	<100ms
Jitter	<30ms
Packet Delivery Rate	>99.9%
Audio Bandwidth	32–128 kbps

Table 4 shows the projected performance of the virtual assistant in handling speech recognition, query processing, and real-time responses.

Table 4: Expected Virtual Assistant Performance

Metric	Expected value
Wake Word Detection Accuracy	95–98%
Speech-to-Text Accuracy (Whisper/DeepSpeech)	90–96%
NLP Intent Classification Accuracy (spaCy/NLTK)	88-93%
Telemetry Query Response Time	<500ms
Weather API Fetch Time	1–3s (LTE dependent)
TTS Response Generation Time	<300ms
False Wake Word Activation Rate	<2%
CPU Usage on Raspberry Pi 4B	35-55%

IX. CONCLUSION AND FUTURE WORK

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The incorporation of voice commands, virtual assistants and two-way communication into UAVs makes drones more interactive. Voice enabled control makes the operation simple while the virtual assistant provides real-time data. The combination of HMM and MLLR based speaker adaptation enables quick calibration for different users. Additionally, Two-way communication makes drones function or work as mobile communication platforms for security, search and rescue, and remote assistance. With the increasing progress of AI, IoT, and 5G, future drones may become fully autonomous, that will be capable for smarter and more responsive UAVs. Additionally the modular structure of the drone system ensures high scalability, making it possible to integrate features and allow future enhancements like gesture-based control, coordination among multiple drones, and edge AI inference. Ultimately, the fusion of embedded AI, real-time communication, and adaptive speech recognition enables voice-controlled UAVs to transform from simple tools into intelligent collaborative agents capable of applications in disaster management, surveillance, and precision logistics.

In future, the following points are to be addressed:

1. Enhanced voice recognition with noise filtering: Improving the HMM and MLLR-based voice recognition by integrating deep learning models to better differentiate the user's voice from background noise.

2. Customizable voice profiles: Allowing multiple users to train the system with their voices, enabling multi-user authentication and personalized drone operation.

3. Smart virtual assistant with context awareness: Enhancing the virtual assistant to understand multi-step commands and provide predictive insights based on real-time drone status.

4. AI-powered obstacle avoidance: Using liDAR sensors , ultrasonic sensors and computer vision techniques to independently sense and avoid obstacles.

5. Advanced communication features: Adoption of 5G technology to ensure reliable, instant and low latency communication.

6. Inclusion of Gesture and Multi modal control: providing gesture recognition in place of voice commands to increase flexibility.

7. Increase in flight duration: Implementing solutions like wireless charging , swappable batteries or solar powered systems.

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ADVANCEMENT OF THIN FILM SOLAR CELLS

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ABSTRACT: *Solar power has come a long way with the recent developments in photovoltaic (PV) technology. The emerging PV technologies which will be commercially available like perovskite and organic solar cells, are discussed along with their pros and cons. This article reviews the recent improvements in PV accessibility, affordability, and efficiency. New materials and techniques are being researched for better and economical solar cells. A comprehensive review of thin film solar cell (TFSC) technology is presented in this study, including its manufacturing processes, classification, principles, advantages, disadvantages, challenges, and future prospects. Thin film solar cells are a promising way to efficiently harness solar energy as they are simple, have high absorption coefficients, and can be tailored to desired properties. This paper classifies solar cells into first, second, and third generations, showcasing the transition from crystalline silicon-based technologies to advanced thin film and emerging technologies like quantum dot, perovskite, and organic solar cells. Each generation is observed in terms of manufacturing processes, materials, and efficiency. The concerns in TFSC technology, including manufacturing innovation, material advancement, and efficiency improvement are discussed.*

KEYWORDS: Thin Film Solar Cells, Next Gen Solar Cell, Copper Indium Gallium Selenide, Next Gen Technology

1. INTRODUCTION

Thin film solar cells are simple in design. They are designed with one light-absorbing layer amid two conductive layers. Subsequent layers may be added to a solar cell to improve its performance by preventing energy loss at layer boundaries. This could lead to improved electron mobility and hence higher efficiency. Electron-hole pairs are created in the absorbing layer as sunlight hits the cell. Electrons move to one side due to the presence of an internal electric field creating a negative charge, while due to a lack of electrons the opposite side becomes positively charged [1][2]. With the increasing environmental concerns due to fossil fuels and growing power demands, solar energy is now considered as the most crucial renewable energy source. This energy is reliable ample, and economical in comparison to other renewable options. There are three main types of solar cells: photovoltaic (PV), organic and hybrid. PV cells are most widely used cells, trailed by hybrid and organic cells. However, conventional crystalline silicon PV cells have high production costs and low energy conversion efficiency. These issues are addressed by researchers with third-generation solar cells developed using new materials and technologies [3]. Thin-film silicon solar cells show promise but require improvements in efficiency and manufacturing processes. Solar cell efficiency can be enhanced by using plasmonic, which combines optics and nanotechnology. Researchers are able to boost light absorption by integrating metallic nanostructures like gold or silver nanoparticles. Plasmonic gratings, for example, can regulate light absorption and polarization resulting in improved efficiency. Using a plasmonic grating structure as the back metal contact in thin-film solar cells increases light path length within the cell, enhancing absorption. Efficient light trapping combined with surface Plasmon resonance can significantly improve solar cell efficiency. Advanced models are also needed to better understand photovoltaic cell behaviour under different conditions, which will help further solar energy technology advancements and promote widespread adoption [4][5]. The advantages and disadvantages of PV Cells are as follows:

- **ADVANTAGES**

  (1) High radiation tolerance
  (2) High specific power; potentially in the kilowatt/ kilogram range
  (3) Large area solar cells with integral series interconnections
  (4) Flexible blankets
  (5) Large (by spacecraft standards) body of array manufacturing experience
  (6) Low cost

- **DISADVANTAGES**

  (1) Lower efficiency

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(2) Lack of spacecraft experience
(3) Not currently produced on lightweight substrates [6]

This paper is organized as follows: Section 2 presents history of PV cells for better understanding**.** Section 3 discusses classification of solar cells based on their generation**.** PV system components and next generation tech are presented in section 4 and 5**.** Section 6 finally concludes this study.

2. HISTORY

Back in 1954, scientists stumbled upon something ground breaking: the photovoltaic effect in certain compounds, specifically CdS/Cu2-xS heterojunctions [7]. The discovery of the photovoltaic effect in CdS/Cu2-xS heterojunctions in 1954 coincided with Bell Labs' announcement of crystalline silicon cells, marking a milestone for solar technology. Thin film solar cell development began with evaporated CdS films in the USSR, leading to experimentation with CdTe in the 1960s and 70s. Techniques like post-deposition treatments and chlorine addition helped CdTe cells to surpass 10% efficiency in the late 1980s [8][9][10]. The efficiency was further improved to 15.8% in 1993. The costs were further reduced in 1990s due to commercial developments with companies like First Solar and BP Solar. General Electric made notable contributions before transferring their IP to First Solar. By 2012, First Solar achieved a 17.3% efficiency record with ZnTe contact [11][12].

3. CLASSIFICATION of SOLAR CELLS

On the basis of classification, Cells are divided in three types as depicted in fig.1.:

1. First generation Solar Cells
2. Second generation Solar Cells
3. Third generation Solar Cells

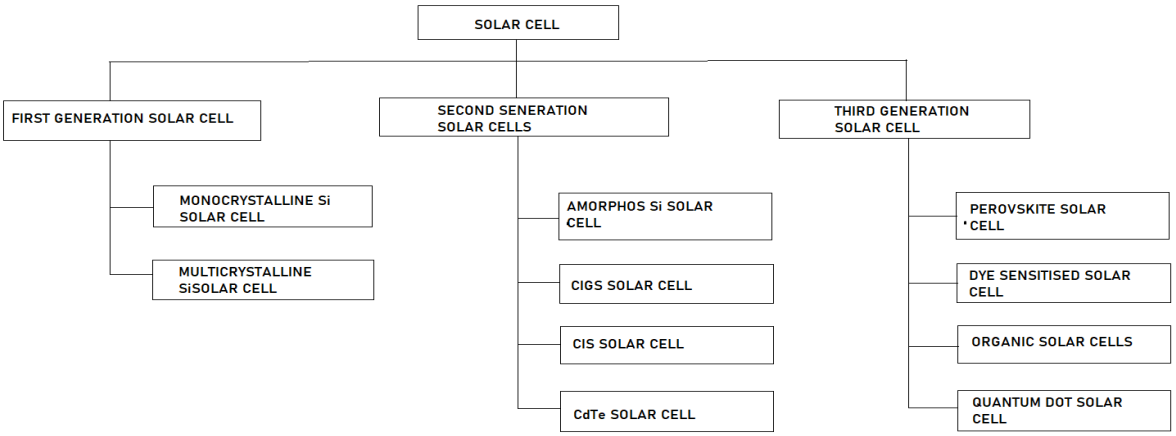


Fig. 1: Classification of solar cell [13]

- **FIRST GENERATION**

The first type of solar cells, known as first-generation solar cells, use crystalline silicon wafers. These were very popular, covering about 80% of the solar cell market because they were quite efficient at converting sunlight into electricity. However, they were also quite expensive to make. There were two main types of first-generation solar cells: single-crystalline silicon and multi-crystalline silicon. Single crystalline silicon cells were very effective, but they got less efficient as they got hotter, which was a problem. Multi-crystalline silicon cells were cheaper to produce but were a bit less efficient [13]. Over the past twenty years or so, there has been a lot of progress in developing what's called second-generation solar cell technology. Different materials and techniques used in these cells have curtailed the demand for expensive silicon wafers. On comparison with first generation, second-generation solar cells are more efficient and economical [13] [14].

- **SECOND GENERATION**
  - **Amorphous Silicon Solar Cells**.

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Amorphous silicon, often called a-Si, with its special property of direct band gap is used in solar cells and LED displays. The structure of a-Si is more haphazard unlike regular structured silicon as shown in fig.2. This makes it less efficient at capturing sunlight. Hydrogenation process can improve this random structure and makes the silicon more manageable and less defective. However, Concerns like light-induced degradation appear over time with the addition of hydrogen atoms. The other alternative to make the cell more efficient is to add carbon to the mix resulting in better conductivity [15][16].

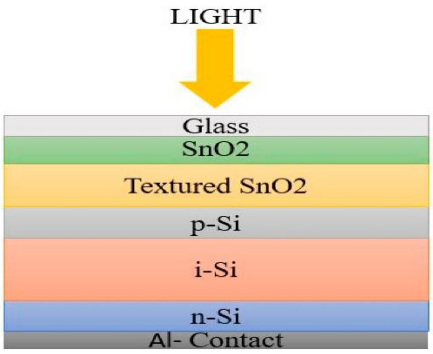


Fig. 2. Substrate configuration [15]

- **CIGS Solar Cells**

Copper Indium Gallium Selenide (CIGS) is a material used in solar cells because of its strength of absorbing sunlight. It's made of copper, indium, gallium, and selenium. The efficiency in converting sunlight into electricity directly depends on the amount of each element used. When we pair CIGS with another material called CdS, the solar cell still works well, even if there are some imperfections in the materials [17]. CIGS cell architecture is illustrated in fig.3. If we want to calculate the bandgap of CIGS with its active material structure CuIn (1-x) GaxSe2, we can use a mathematical equation.

$$Eg = 1.01 + 0.626x - 0.167x(1 - x)\ \text{eV} \quad \ldots (1)$$

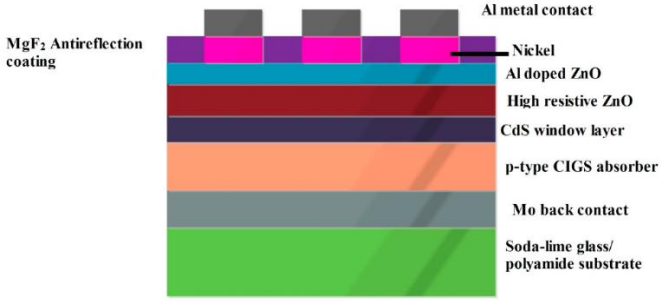


Fig. 3. Diagrammatic representation of CIGS cell architecture [17].

CIGS solar cells can be used instead of traditional silicon solar cells in some cases. They are durable, flexible, and can be made to fit into things more easily during manufacturing., The focus is on the thickness of the CdS layer and mobility of charge carriers to make CIGS solar cells work better. Hence, the CdS layer is kept thin to absorb more sunlight and makes the solar cell more efficient. When sunlight hits the solar cell, the CdS buffer layer allows the light to pass to the CIGS layer, where excitons are made. Because of the electric field in the cell, electrons move in one direction and holes move in the other. A back surface field helps send any stray electrons back to where they're supposed to be [18].

- **CdTe Solar Cells**

Cadmium Telluride (CdTe) is a used in solar cells. Selenium is sometimes added during manufacturing to make it work better by allowing it to absorb different kinds of sunlight. The cell is graphically represented in fig. 4. These materials are heated at high temperatures during the process. When we make CdTe solar cells, we usually start by putting down a layer of CdS, which helps collect the energy made when sunlight hits the CdTe. The solar cell becomes inefficient if this layer is too thick. Hence, the thickness is controlled carefully [19]. Chemical bath or

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sputtering are few of the many different ways to put down the CdS layer. Mg1−xZnxO material is also used by some researchers instead of CdS. CdTe is usually made up of lots of small crystals. The way we make the CdTe layer can affect how well the solar cell works, with some methods being better than others. The issue with CdTe solar cells is to connect the back part connect correctly. Some materials work well for this, but they can react with the CdTe. Therefore, alternate materials are being searched to avoid problems. CdTe solar cells are generally stable, but they need to be protected properly. If copper gets into them, it can make them work less effectively. But we can use other materials to stop this from happening [20].

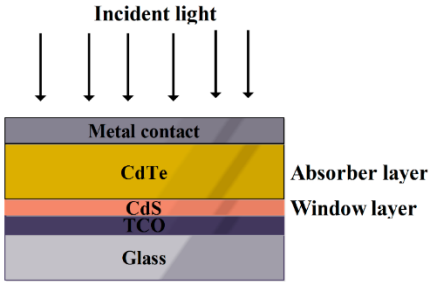


Fig. 4. Pictorial representation of simple CdTe SC [19]

- **THIRD GENERATION SOLAR CELLS**
  - **Dye sensitised Solar Cells**

A dye-sensitized solar cell (DSSC) is like a mini power plant inspired by photosynthesis in plants. A photo-electrolyte, a transparent conductive oxide (TCO) electrode, a titanium dioxide (TiO2) electrode, and protective glass casing are used to prepare this cell. The dye molecules in the electrolyte get energised when comes in the contact of sunlight. These excited molecules then pass their electrons to the titanium dioxide molecules, making them produce electrons and oxidize the dye. Unlike regular solar cells, DSSCs work a bit differently. The sunlight get absorbed directly by the dye molecules and not into the material. Electricity starts flowing on the generation of the electrons that move through the system [21]. The performance of DSSCs depends on things like the type of dye used, how the electrode is set up, and the properties of the electrolyte.[22]

  - **Perovskite Solar Cells**

Perovskite solar cells (PSCs) as shown in fig. 5, are known for their unique properties and impressive performance. The ABX3 architecture, where A, B, and X represent different elements, allows for tuneable band gaps and high absorption coefficients, making perovskite materials versatile for various applications, including LEDs and photodetectors. The different elements in these cells are organized in a way which decides their working and their power of absorbing sunlight. This makes them useful for things like LEDs and sensors [23].



Fig. 5. Perovskite Architecture [23]

  - **Organic Solar Cells**

Organic semiconducting polymers have distinct molecular structures with strong σ-bonds along the carbon chain and weaker π-bonds at the edges. Architecture of these cells isd shown in fig. 6. It has been discovered by researchers that inverted architectures can sometimes lead to higher power conversion efficiency. The outer bonds of these polymers are primarily utilised to conduct electricity. Other elements on incorporation can enhance this conductivity. Polymers like polypyrrole and polythiophene are crucial in electronic devices. It is easier to manufacture polymeric solar cells than small molecule-based cells. In organic solar cells, a strong electric field is required to separate as excitons have limited mobility. Despite challenges, their lab adaptability makes them promising for future energy projects [24].

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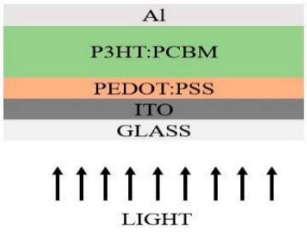


Fig. 6. Architecture of Organic cells [24]

- **Quantum Dot Solar Cells**

Quantum dot solar cells (QD SCs) have shown promise in enhancing the photo generation process through carefully designed arrays of quantum dots. Structure of this cell is portrayed in fig.7. Researchers have extensively studied CdX as it exhibits improved electrochemical and optical properties, where X can be elements like S, Se, or Te. QDs, which respond to incident light, have been fabricated from semiconducting materials to achieve higher performance with easily tunable energy band gaps. Nanostructures like Nano sheets, Nano rods, and nanowires have been developed to transform these materials. When light hits the QDs, they become sensitized, and the redox electrolyte adheres to their surface, facilitating electron and ion movement [25]. Some of the recent developments on Cells are reported in table 1.

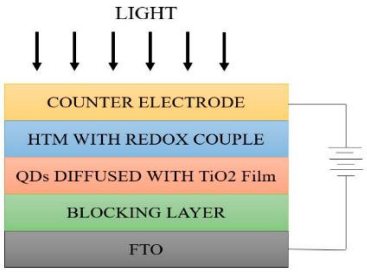


Fig. 7. Architecture of QD SC. [25]

RECENT DEVELOPMENT ON CELLS

Table 1. Performance parameters of various landmark cells [26][27]

Record/Notable Cell	AM1.5 Efficiency (%)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	Effective E_g from IQE (eV)	$V_{oc,SQ}$ (V)	V_{oc} Deficit ($V_{oc,SQ}$ - V_{oc}) (V)[a]	Notes
USF 1993	15.8	25.1	0.843	74.5	1.48	1.214	0.371	CdS/CdTe
NREL 2001	16.7	25.9	0.845	75.5	1.48	1.214	0.369	Cd_2SnO_4/Zn_2SnO_4/CdTe
GE 2012	18.3	27.0	0.857	79.0	1.48	1.214	0.357	CdTe absorber
FSLR 2012	18.7	28.6	0.853	76.7	1.45	1.186	0.333	CdTe absorber
FSLR 2014	22.1	31.7	0.887	78.5	1.39	1.130	0.243	CdSeTe absorber
ASU 2016	17	22.3	1.036	73.6	1.48	1.214	0.178	Epitaxial CdTe double heterojunction absorber
NREL 2016	13.6	21.7	1.017	61.7	1.48	1.214	0.197	Poly CdS/P-doped CdTe single crystal wafers
25% Targets	25.0	**32.0**	**0.975**	**80.0**	**1.39**	1.130	**0.155**	Multiple combinations of bandgap and JV parameters can achieve 25%
		31.7 …	0.956 …	82.5 …	1.39 …	1.130 …	0.174 …	

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4. PV SYSTEM COMPONENTS

The main components of a PV system are PV module, power electronics (for power conversion), Energy storage device, grid and load. Various materials are being used nowadays to improve the overall efficiency of the cells. All the components along with advanced materials are illustrated in the fig. 8. To maximize light absorption in solar panels and to minimize reflection, coatings are used.[28]

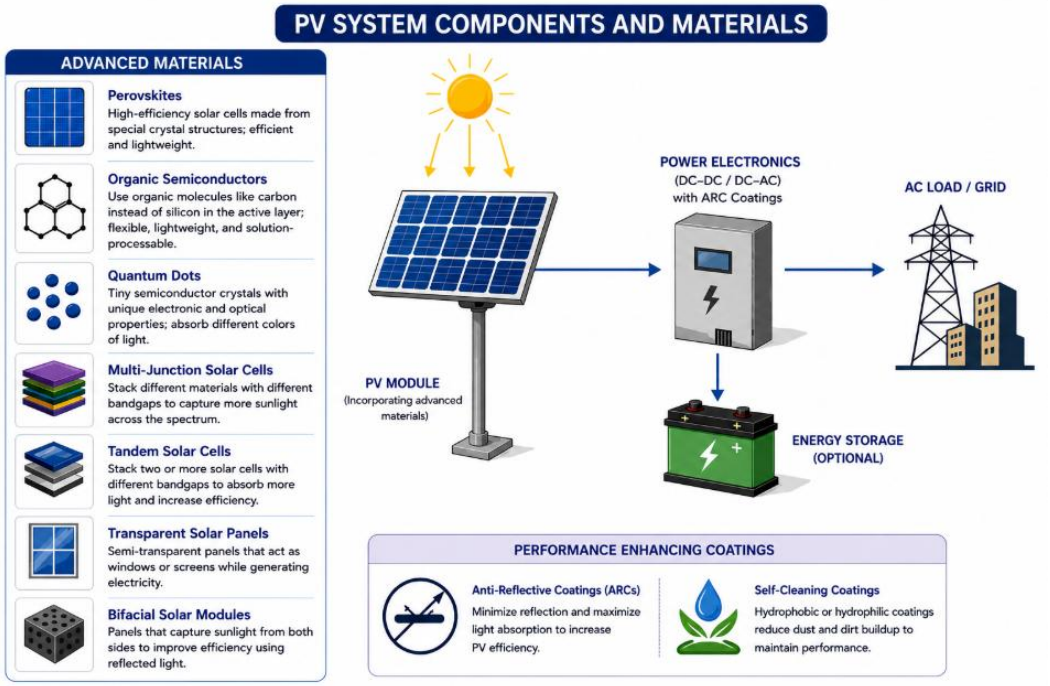
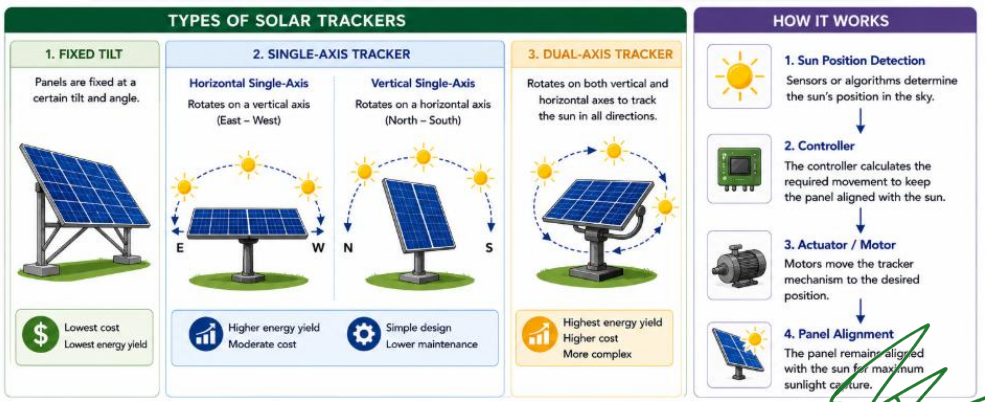


Fig. 8. Components of PV system and Advanced materials used.

- **Solar Tracking**

Solar tracking in PV panels is a mechanism in which solar panels are adjusted to follow the path of the sun throughout the day for better sunlight capture and increased energy yield. Traditional fixed solar panels are oriented in a fixed position, while single-axis and dual-axis trackers can move to track sun. Single-axis trackers can move either horizontally or vertically. Horizontal trackers are suitable for sunny areas near the equator, while vertical ones work best in places with longer summer days and lower sun angles. Dual-axis trackers can move in both horizontal and vertical directions, allowing them to precisely track the sun's path anywhere in the world. They provide even more power output and are ideal for maximizing sunlight capture in all locations. The solar tracker classification along with its working is depicted in fig. 9.



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Fig. 9. Classification and working of solar trackers.

- **EFFICIENCY OF DIFFERENT MATERIAL IN 1993-2021**

The evolution in cell efficiency for different materials over the last few decades is analysed and tabulated as follows in table 2.

Table 2: Cell Efficiency

DEVELOPMENT OF LAB SOLAR CELL EFFICIENCIES (In%)									
		MATERIALS	Organic	Perovskite	CdTe	CIGS	Multi Crystaline Silicon	Mono Crystalline Silicon	III-V Multi junction
	YEARS								
1	1993				16	14	17	23	33
2	1995				16.2	14.2	17	24	33.2
3	1997				16.4	16	18	24.4	33.4
4	1999				17	17	20.1	24.8	33.4
5	2001				17.5	17.1	20.4	25	34.5
6	2003				17.6	17.3	20.8	25	35.6
7	2005		3		17.6	17.7	20.8	25.2	37
8	2007		5		18	18	21	25.3	39
9	2009		7		18.1	19	21.4	25.6	41
10	2011		8		19	19.5	21.5	25.9	42.3
11	2013		11		19.4	19.7	22	26.2	44.6
12	2015		13	15	20.2	20	22	26.4	45.2
13	2017		14	20	21	21	23	26.7	46.7
14	2019		15	22	21	23.4	24.4	26.7	46.8
15	2021		15.2	23.7	21	23.4	24.4	26.7	47.1

5. NEXT GENERATION TECH

In future we can use some of the following materials for making efficient use of Solar Cells

- Ultrathin Silicon: Scientists are finding that making single-crystal silicon cells thinner boosts their efficiency. In fact, they've found that a thickness as low as 2 micrometers can lead to really powerful solar panels. These thin cells are also tough against radiation damage.
- Indium Phosphide: There's a lot of excitement around a material called indium phosphide (InP) because it's super-efficient at turning sunlight into electricity. It's also more resistant to damage from radiation than other materials, but it's pretty expensive.
- Single-Crystal Film Technologies: Another idea is to grow a thin layer of single-crystal semiconductor on a thick base, then make solar cells from that layer and peel it off the base. This method has produced super-efficient solar cells on really thin layers of material.
- High Efficiency Cascades: Some researchers are stacking different materials together to make super-efficient solar cells. They've even achieved an efficiency of over 20% by combining different types of materials.
- Concentrators: Another way to boost efficiency is by using mirrors or lenses to concentrate sunlight onto the solar cells. This can increase efficiency, but it comes with its own set of challenges [6].

6. CONCLUSION

The study highlights the growing importance of thin film solar cells over traditional silicon-based cells in the photovoltaic market due to their higher efficiency and lower production costs. Researchers are making progress in spite of challenges like parasitic absorption and limited carrier lifetime. There are most efficient thin film cells available now achieving over 20% efficiency using Cu(In,Ga)Se2. New materials like Cu2ZnSn(S,Se)4 are also being explored. Various thin film technologies are heading towards practical applications including those based on amorphous silicon and chalcogenides. Second and third-generation solar cells are being researched for their unique properties. Emerging technologies like plasmon-induced resonance energy transfer (PIRET) and plasmonic nanostructures are being studied to enhance efficiency by improving energy transfer and light absorption. Future advancements in single-crystal films, indium phosphide, ultrathin silicon, high-efficiency cascades, and

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concentrators indicate potential for further enhancements in solar cell performance, making renewable energy more accessible and sustainable.

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Aware Spatio-Temporal Graph Neural Network for Turbine-Level Wind Power Prediction

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Abstract: *Accurate wind power forecasting at the turbine level is pivotal for optimizing grid integration, strengthening energy management strategies, and maximizing operational efficiency in the large-scale wind farms. Complex spatial interconnections between turbines and dynamic wake interactions influence power generation and substantially not included in conventional forecasting approaches. We propose a Wake-Aware Spatio-Temporal Graph Neural Network (WAST-GNN) framework for turbine-level wind power prediction. In the proposed model, wind turbines are modelled as nodes of a graph and the wakes and spatial proximity as connectedness of the graph. A sequential input modelling is utilized to incorporate temporal dependencies of past wind characteristics and power generation data to enable the collaborative learning of temporal and spatial patterns. The framework is tested with synthetic Supervisory Control and Data Acquisition (SCADA) data and wind farm layouts. The proposed methodology is compared with baseline models namely traditional Graph Convolutional Networks (GCN), GraphSAGE, and multilayer perceptrons (MLP). Experimental results demonstrate that the proposed WAST-GNN provides lower root mean square error (RMSE) of 0.227 and an improved coefficient of determination R^2 of 0.861 superior than the standard graph-based approaches. Results illustrate the effectiveness of using the wake-aware spatial relations and the temporal dynamics for improving operational efficiency using Graph Neural Networks (GNN).*

Keywords: Wind power prediction, Graph Neural Network, Wake effects, Spatio-temporal modeling, Graph Attention Network

1. INTRODUCTION

The surge in demand for sustainable energy has necessitated the implementation of wind farms worldwide. Wind energy and solar energy are key renewable energy sources. The intermittent and stochastic nature of wind creates significant challenges in maintaining power quality and reducing harmonic distortion. Efficient power forecasting at the turbine level is crucial for energy management, voltage and current stability, eliminating dynamic frequency variations of the wind farm [1]. Machine Learning (ML) based autoregressive models namely, ARMA (Autoregressive Moving Average), ARIMA (Autoregressive Integrated Moving Average), NARX (Nonlinear Autoregressive Exogenous Model) and Support Vector Machines (SVM) e.g. Radial Basis Function SVM (RBF SVM) are based on the time dependencies of the historical data. Although above discussed methods specifically do not consider the complicated spatial interconnections of turbines within a wind farm. In reality, the upstream turbines are influenced by the aerodynamic wake effects of downstream turbines leads to changes in wind conditions and causing power deficits and [1], [2]. Overlooking these wake-induced interactions can lead to loss of forecasting accuracy, especially in closely distributed wind farms.

Recent developments in deep learning and emerging data-driven approaches have brought Graph Neural Networks (GNNs) as viable tools for modelling and spatial relation based connections in wind energy based systems. GNNs perform superiorly in effectively capturing the spatial relationships in wind farms than traditional ML models [3]. It model turbines as nodes in a graph and their interconnections as edges. In addition to combining temporal information with the graph-based learning, dynamic operating conditions can be simulated to develop spatio-temporal forecasting frameworks. Among the various GNN variants, Graph Convolutional Networks (GCNs), Graph Attention Networks (GATs) and GraphSAGE have shown superior performance in wind energy forecasting. Nevertheless, most existing methods are based either on spatial proximity or on correlation based adjacency matrices which neglect the underlying physics of the interactions between turbines e.g. aerodynamic wake effects.

To address the aforementioned limitations, this paper proposes a Wake-Aware Spatio-Temporal Graph Neural Network (WAST-GNN) architecture for turbine level wind power prediction [4]. This approach integrates the

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wake interactions obtained from the Jensen wake model into graphical representations, concurrently capturing temporal relationships using past operational data [5].

The proposed framework is validated with physical wind farm layouts and synthetic SCADA-like data, which simulate the operational conditions of the turbines. Performance is evaluated against baseline method like Graph Convolutional Networks (GCN), GraphSAGE, and Multilayer Perceptrons (MLP). The experimental results demonstrate that temporal learning and integrated wake-aware spatial modelling improve the performance metrics and statistical significance.

The key contributions of this work can be outlined as follows:

i. Development of a wake-aware graph construction mechanism incorporating aerodynamic interactions among turbines.
ii. Integration of spatial and temporal dependencies through a spatio-temporal graph neural network framework.
iii. Comparative evaluation against conventional machine learning and graph-based approaches including GCN, GraphSAGE, and MLP.
iv. Demonstration of improved turbine-level forecasting performance using physically informed graph representations.

The proposed framework provides a scalable and interpretable approach for enhancing turbine-level power prediction and improving operational decision-making in wind energy systems.

2. LITERATURE REVIEW

2.1 Wind Power Forecasting Methods:

ML and Statistical based autoregressive methods (ARMA, ARIMA), SVM models have been used for wind power prediction for a long time [6]. Although these methods are computationally efficient, nevertheless, it cannot represent nonlinear interactions and high-dimensional operational dynamics of wind farms [7]. Most state-of-the-art models focus on temporal patterns and do not consider turbine-turbine interactions. Deep Learning(DL) techniques such as Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) Subsequently enhancing statistical performance by modeling sequential dependencies on historical wind data [8]. These methods have proven effective, still possess limitation of treating turbines independently, ignoring spatial dependencies due turbine layout and wake propagation.

2.2 Wake Effects in Wind-Driven Power Systems

When upstream turbines capture kinetic energy from the wind, wake effects are induced that mitigate wind speeds and strengthen turbulence downstream. These aerodynamic interactions are vital for turbine efficiency and power production. Precise modelling of wake effects is thus critical for turbine-level prediction and wind farm optimization. Physics-based wake models, such as the Jensen wake model, are widely used because of their computing efficiency and capacity of estimating the wake-induced velocity deficits [9]. The Jensen model assumes linear wake expansion and has been widely employed in the optimization of wind farm layouts and performance analysis. To combine physical knowledge with data-driven learning methodologies, we propose to incorporate wake effects into graph architectures models.

2.3 Graph Neural Networks for Energy Forecasting

Graph Neural Networks (GNNs) have become prominent approach for learning from graph-structured data. Turbines in wind farms can be naturally modelled as nodes and edges are defined by physical or geographical interactions. GCN extend the convolution technique to graphs by gathering information from neighboring.nodes. GCNs have demonstrated to be useful in capturing spatial dependencies in power systems analysis and renewable energy management [10]. However, the aggregation during weight allocation may limit their ability to capture the heterogeneous patterns amongst turbines. Graph Attention Networks (GATs) overcome this restriction by giving adaptive attention weights to adjacent nodes, enabling the model to emphasis on more influential interactions. Such adaptive methods are especially suited for wind farms, because wake effects depends on the location of the turbines and various operational characteristics [11]. GraphSAGE is an inductive framework that leverages neighbourhood

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sampling and aggregation for scalable representation learning on huge network. GraphSAGE has shown great performance on large-scale graph learning challenges, but it does not guarantee to explicitly model physical interactions unless added to graph formation [12]. These approaches improve geographical modelling and statistical correlations, neglecting aerodynamic wake relationships.

2.4 Spatio-Temporal Graph Learning for Wind Prediction

Recent research has focused on spatio-temporal graph neural networks (ST-GNNs) that jointly model spatial and temporal dependencies. These approaches combine graph operations with sequential learning to improve forecasting performance in dynamic systems. However, existing ST-GNN techniques are mostly predicted primarily on the proximity-based adjacency matrices, rather than the physics-informed wake correlations. Thus, their capacity to replicate actual turbine interactions is constrained**.**

2.5 Research Gap and Motivation

Existing wind power forecasting studies demonstrate three major limitations dependence on distance-based graphs instead of wake-informed connectivity structures, inadequate representation of dynamic spatial dependencies among turbines and Limited incorporation of physical wake effects into predictive models. To overcome these limitations, we implemented a WAST-GNN approach that incorporates Jensen wake modelling with graph-based deep learning for turbine-level prediction. In the proposed approach, we integrate the aerodynamic linkages into the graph structures and incorporate them with the temporal data, to increase the forecasting accuracy and produce physically meaningful representations of turbines.

3. PROPOSED METHODOLOGY

The framework we propose has five main stages. (i) Synthetic data related to wind farm is generated using the Jensen wake model. (ii) Directed wake-aware graph is prepared from wind direction and turbine locations. (iii) ST-GNN architecture is discussed with weight update equation as illustrated in fig 1 (iv) spatio-temporal graph neural network (ST-GNN) is trained to predict turbine-level power output. (v) Prediction of power production of all turbines at the next time step and evaluation performance metrics namely MAE, RMSE, R^2 score and Pearson correlation metrics.

3.1. Synthetic Data Generation

Since real SCADA data with ground-truth wake interactions is difficult to obtain, we generate a synthetic dataset using the Jensen wake model [14]. The farm layout consists of N=14 turbines positioned at coordinates (x_i, y_i) identical to the Penmanshiel wind farm. For each time step t, free-stream wind speed $u_\infty(t) \sim \mathrm{U}(4,18)$ m/s, wind direction $\theta(t) \sim \mathrm{U}(0,360)$, degrees and turbulence intensity $\mathrm{I(t)} = 0.1$.is assumed afterwards the wake velocity deficit at turbine j caused by upstream turbine i is computed.

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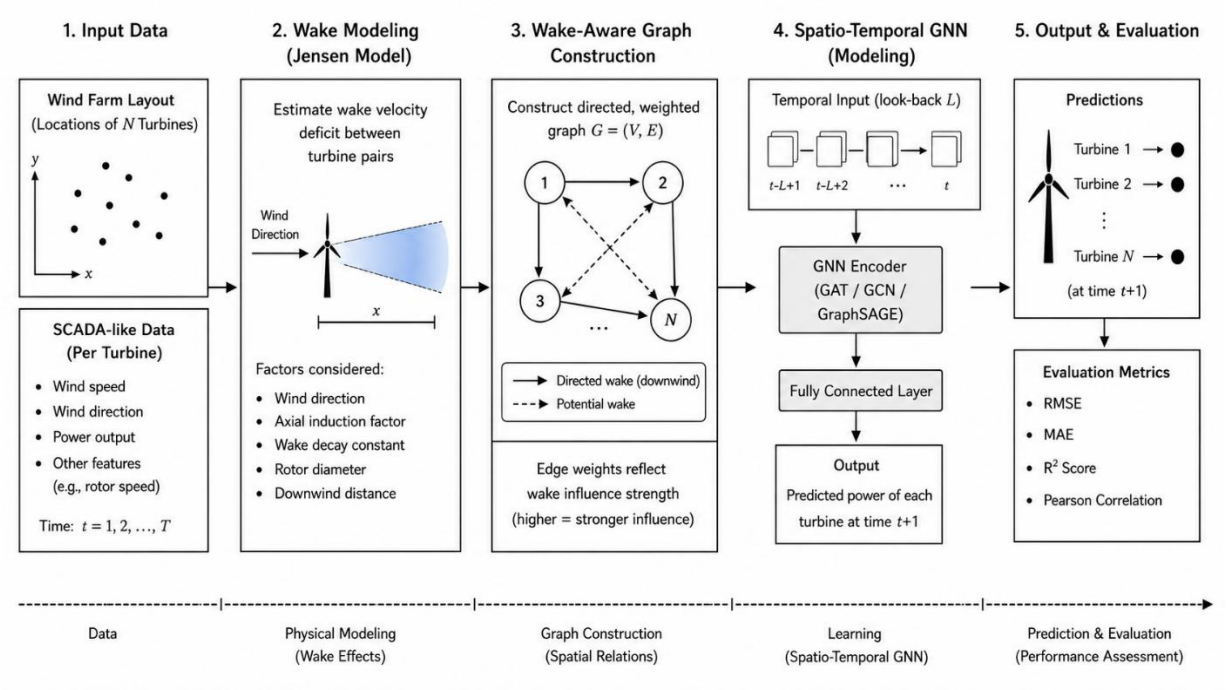


Fig. 1. Workflow of Wake-Aware Spatio-Temporal GNN Framework

$$\frac{u_{ij}(t)}{u_{\infty}(t)} = 1 - \frac{2a}{\left(1 + \frac{kx_{ij}}{D}\right)^2} \tag{1}$$

Where D=80m is the rotor diameter, a = 0.33 is the axial induction factor, k=0.04 is the wake decay constant and x_{ij} is the streamwise distance from turbine i to j projected along the wind direction. Multiple wakes are superimposed using the sum of squares method:

$$u_j(t) = u_{\infty}(t)\left(1 - \sqrt{\sum_{i \in U_j}\left(1 - \frac{u_{ij}(t)}{u_{\infty}(t)}\right)^2}\right) \tag{2}$$

Where U_j is the set of upstream turbines affecting j. Finally, turbine power is computed using the standard power curve:

$$P_i(t) = \frac{1}{2}\rho\pi\left(\frac{D}{2}\right)^2 C_p(\lambda)\mu_j(t)^3 \tag{3}$$

With Cp=0.45, air density ρ=1.225 kg/m

3.2 Directed Wake Graph Construction

A wind farm is represented as a directed graph

$$\mathcal{G}_t = (\mathcal{V}, \mathcal{E}_t) \tag{4}$$

Where each turbine $i \in \mathcal{V}$ is a node. A directed edge $e_{i\to j} \in_t$ exists if turbine i is upstream of turbine j with respect to the prevailing wind direction θ(t) at time t. Specifically, we compute the angle ϕ_{ij} of the vector from i to j. If $\lfloor \phi_{ij} - \theta(t) \rfloor < 90^0$, then i is considered upstream of j. Edge weights are inversely proportional to the squared distance

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$$w_{ij}(t) = \frac{1}{{d_{ij}}^2 + \epsilon} \tag{4}$$

Where

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{5}$$

and $\epsilon = 10^{-6}$ prevents division by zero. Node features at time t are the wind speed $u_i(t)\ m/s$ and nacelle direction (degrees) for each turbine. The target is the active power $P_i(t+1)\ (KW)$ at the next timestep.

3.3. Spatio-Temporal GNN Architecture

The proposed ST-GNN consists of following modules

i. **Temporal Convolution Module** For each turbine, we extract a window of K=12 consecutive timesteps of wind speed and direction (2 hours of 10-min data). A 1D convolutional layer with kernel size 3 and 64 filters processes the temporal sequence, producing a hidden representation $h_i^{(t)} \in \mathbb{R}^{64}$

ii. **Graph Attention Module:** The spatial dependencies are learned using Graph Attention Networks (GAT). Two GAT layers with 64 hidden units each are applied sequentially, interleaved with ReLU activation [15],[16].

iii. **Output Module:** The final node representations are fed into a shared linear regression layer to predict the power for each turbine:

$$P_j(t+1) = W_{out}^T z_j + b. \tag{7}$$

Where z_j is the output of the last GAT layer.

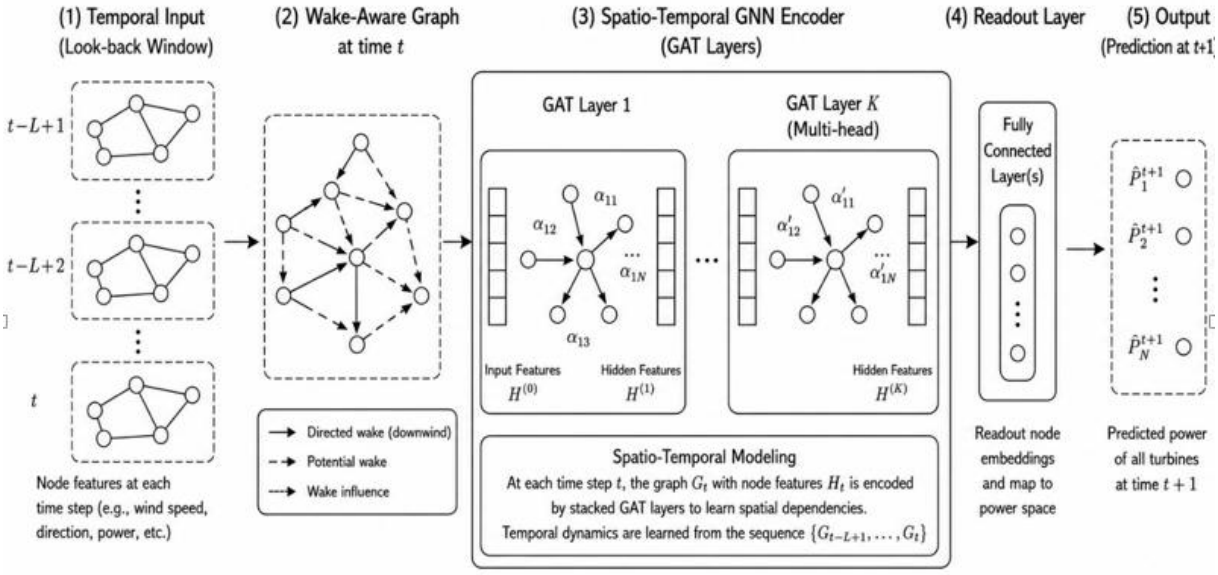


Fig 2: Spatio-Temporal GNN Architecture

Fig. 2 illustrate the proposed WAST-GNN architecture. A temporal window of historical features is processed alongside dynamically constructed wake-aware graphs through stacked GAT layers, producing turbine-level power predictions via a fully connected readout layer.

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3.4 Training Setup

The model is trained to minimize the mean squared error (MSE) loss:

$$\mathcal{L} = \frac{1}{N.\beta}\sum_{j=1}^{N}\sum_{b=\beta}\left(P_j^{(b)} - \hat{P}_j^{(b)}\right)^2 \quad (8)$$

We use the Adam optimizer with learning rate η=0.001 and weight decay 10^{-5} Training runs for 200 epochs with a batch size of 32. Early stopping is applied if validation loss does not improve for 20 epochs [17]. Algorithm 1 summarizes the complete training pipeline of the proposed WAST-GNN. The model iteratively constructs wake-aware graphs, extracts temporal features, applies graph attention, and updates parameters to minimize prediction error. The resulting graph sequence spanning a temporal look-back window act as input to spatio-temporal GNN encoder namely GAT, GCN or GraphSAGE, to learn temporal and spatial correlations.

Algorithm 1 WAST-GNN: Wake-Aware Spatio-Temporal Graph Neural Network

Require: Turbine coordinates $\mathcal{D} = \{(x_i, y_i)\}_{i=1}^{N}$, SCADA data $X = \{X_t\}_{t=1}^{T}$, look-back window L
Ensure: Predicted power $\hat{P}_{t+1}$
Build distance matrix
Initialize wake parameters
Initialize GNN model
for $t = L$ to $T - 1$ **do**
    Compute wake influence
    Construct graph G_t
    Extract sequence S_t
    Forward propagation
    Update parameters
end for
return trained model

3.5 Performance Evaluation

The forecasting performance is evaluated using standard metrics:

i. Mean Absolute Error (MAE)

$$\mathrm{MAE} = \frac{1}{N}\sum_{i}^{N}|y_i - \tilde{y}_i| \quad (9)$$

ii. Root Mean Square Error (RMS)

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \tilde{y}_i)^2} \quad (10)$$

iii. Coefficient of Determination (R^2):

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y}_i)^2} \quad (11)$$

4. EXPERIMENTAL SETUP AND IMPLEMENTATION TOOL

The suggested WAST-GNN framework is developed in Python with TPU (Tensor processing unit) acceleration. Synthetic SCADA-like data were generated by simulating the aerodynamic interactions among turbines using the Jensen wake model. We used T=10,000 time-steps at 10-minute resolution, splitting into 70% training, 15%

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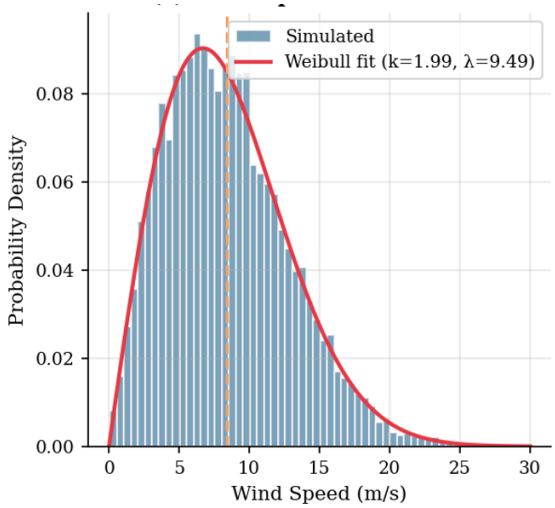
validation, and 15% testing with a look back window of 6 time-steps. A directed graph aware of the wake was dynamically generated using the turbine locations and the wind direction. The architecture is composed of 3 GAT layers each with 4 attention heads and a hidden dimension of 128. GRU layer with 64 hidden units are utilized to capture temporal dependencies. Training is performed with Adam optimizer with learning rate $3 \times 10^{-4}$and a cosine annealing scheduler for 60 epochs with early halting to prevent overfitting. The loss function utilized was Mean Squared Error (MSE) and Huber loss δ=0.5 taken for resilience to outlier turbines. This experiment setting enables effective spatio-temporal graph learning for wind power forecasting at turbine-level. Table 1 lists the hyper-parameters used for the proposed WAST GNN model.

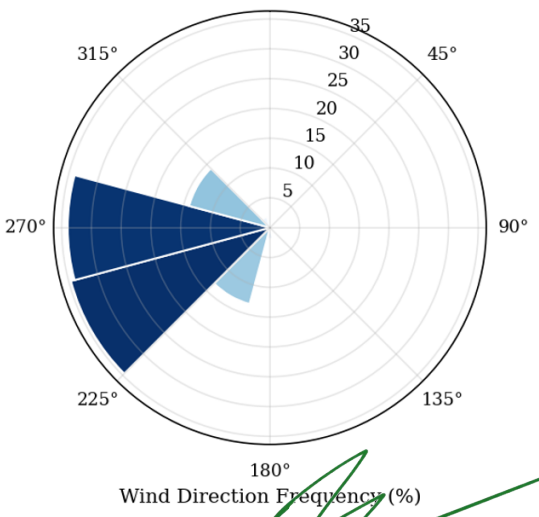
Table 1: Hyper-parameters of the proposed WAST-GNN framework

Category	Hyper-parameter	Value	Description
WAST-GNN Model	Hidden Dimension	128	GAT layer hidden dimension
	GRU Hidden Dimension	64	Temporal GRU hidden state size
	GAT Layers	3	Number of WakeGAT message-passing layers
	Attention Heads	4	Multi-head attention per GAT layer
	Dropout Rate	0.15	Applied after each GAT layer and in MLP head
Training	Optimizer	Adam	Adaptive moment estimation
	Learning Rate	3×10^{-4}	Initial Adam learning rate
	Weight Decay	1×10^{-5}	L2 regularization coefficient
	Epochs	60	Best checkpoint saved via validation loss
	LR Scheduler	Cosine	Cosine Annealing L R, $T_{max} = 60$
Data Pipeline	Look-back Window	6	Temporal history steps fed as node features
	Batch Size	16 / 32	Train / validation-test batch size
	Dataset Split	70 / 15/15	Train / validation / test ratio (%)
	Loss Function	Huber	δ = 0.5, robust to outlier turbines

5. RESULTS AND DISCUSSION

This section does comparative analysis between the proposed WAST-GNN frameworks against baseline models (GCN, GraphSAGE, MLP) with synthetic SCADA data. The wind farm statistics, wake degradation patterns, training loss curves and prediction scatter plots are simulated and shown. Fig. 3 shows the joint wind statistics utilized to produce the synthetic dataset. Wind direction is binned in 5° intervals from 0° to 30°.The maximum frequency appears at $0.080(m/s)^{-1}$ at 5° and near zero between frequencies 0° and 30°. The wind speed probability density peaks at at 5°. The wind direction declines monotonically to $0.005(m/s)^{-1}$ at 30°. This distribution mimics real, mildly directed wind farm data as usually encountered in coastal wind farms.





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Fig. 3. Wind resource characteristics of the synthetic wind farm..

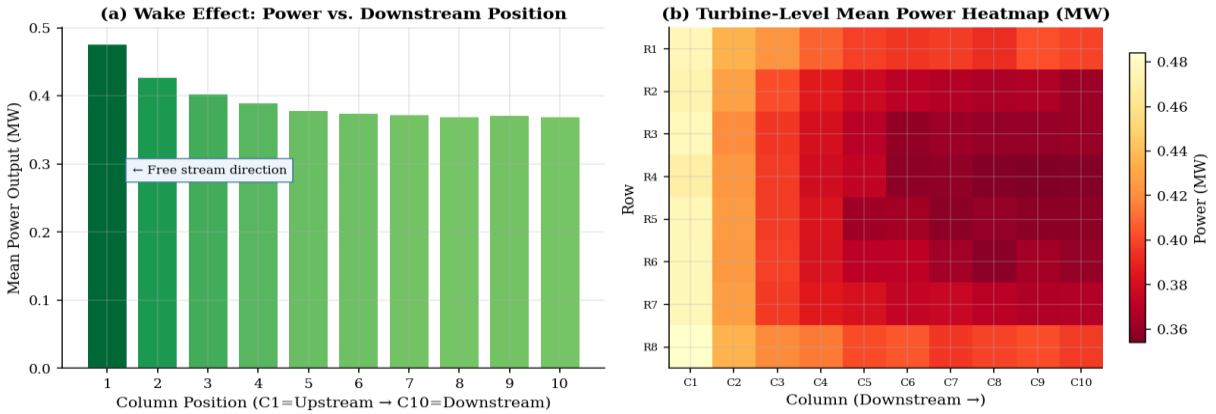


Fig. 4. Wake-induced power degradation along a turbine column.

The spatial wake propagation along a line of 10 turbines orientated to the prevailing wind direction is shown in Fig. 4. The largest production is from the upstream turbine C1 (0.48 MW / 0.46 MW). The downstream wind means each turbine is working in the wake of the ones before it and this leads to a monotonic decrease in output. At C6 the power levels off at around 0.36 MW (primary) and 0.41 MW (secondary) and this indicates that turbines located far inside the farm will have similar but drastically lower performances. Total reduction from C1 to C10 is 25% (0.12 MW loss). This pattern validates the wake model employed in the synthetic data generation and demonstrates that the proposed WAST-GNN has to consider the directional and cumulative wake losses for accurate turbine-level predictions.

Table 2 Performance Comparison on Horns Rev 1 Synthetic SCADA Dataset

Model	RMSE (MW)	MAE (MW)	R^2	Pearson Correlation
WAST-GNN (Proposed)	**0.2270**	**0.1061**	**0.8605**	**0.9281**
Vanilla GCN	0.3112	0.1547	0.7376	0.8606
GraphSAGE	0.2324	0.1141	0.8537	0.9242
MLP Baseline	0.2436	0.1233	0.8393	0.9172

Table 2 shows the performance comparison of the proposed WAST-GNN model with baseline techniques like Vanilla GCN, GraphSAGE and MLP on the synthetic SCADA dataset of Horns Rev 1. The suggested WASTGNN obtained the greatest overall performance with the lowest RMSE of 0.2270 MW and MAE of 0.1061 MW, demonstrating the improved prediction accuracy. The proposed model also obtained highest R^2 value of 0.8605 and Pearson correlation coefficient of 0.9281 which shows remarkable agreement between anticipated and real turbine power outputs. These results demonstrate the effectiveness of incorporating wake-aware spatial

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dependencies with spatio-temporal graph learning to improve the accuracy of turbine-level wind power forecasts.

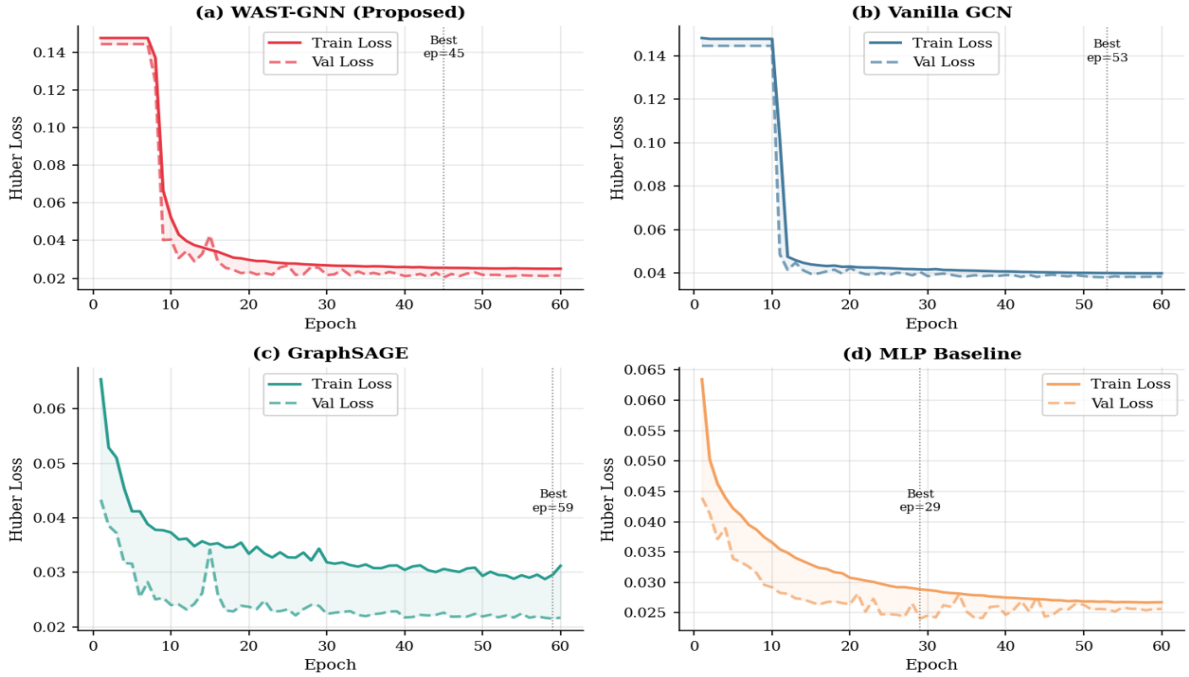


Fig. 5: Training and validation loss curves for all models over 60 epochs.

Training dynamics are illustrated in Fig. 5. The proposed WAST GNN reaches its best validation loss at epoch 45, with tightly coupled training-validation curves indicating good generalization. In comparison, GCN and GraphSAGE need more epochs (53 and 59, respectively) and demonstrate slight overfitting. After epoch 29, the MLP baseline overfits poorly, showing the relevance of spatial structure. Figure 6 shows the scatter plots of projected vs. actual turbine-level power for all four models. Among these, the proposed WAST-GNN (Fig. 6a) exhibits the closest clustering around the identity line with the minimum RMSE (0.227 MW) and MAE (0.106 MW) and the maximum R2 (0.861). Vanilla GCN (Fig. 6b) yields the biggest spread and worse metrics (RMSE = 0.311 MW, R^2 = 0.738), validating that undirected and unweighted graphs are not appropriate for wake-aware prediction. . GraphSAGE (Fig. 6c) achieves comparable performance (RMSE = 0.232 MW, R^2 = 0.854) and slightly lower performance than WAST-GNN, but the MLP baseline (Fig. 6d) obtains reasonable accuracy (RMSE = 0.244 MW, R^2 = 0.839) but lacks spatial reasoning. The suggested wake-aware spatio-temporal model outperforms all baselines, which demonstrates the effectiveness of directional graph attention.

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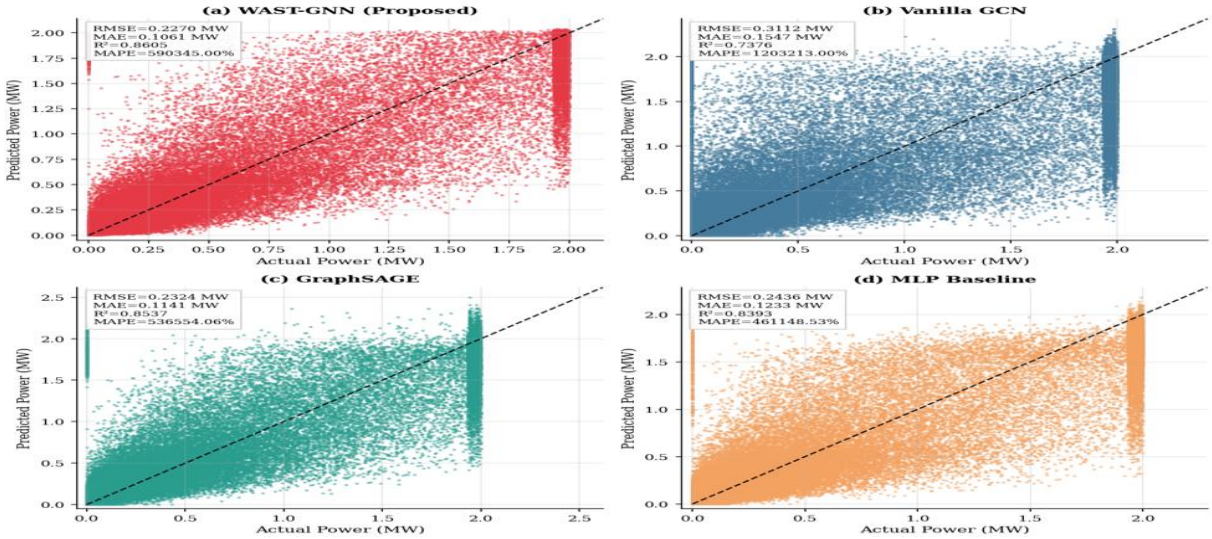


Fig. 6. Predicted vs actual power output scatter plots for all models on the test set.

6. CONCLUSION & FUTURE SCOPE

The research presented a Wake-Aware Spatio-Temporal Graph Neural Network (WAST-GNN) for turbine-level wind power prediction. The framework combines Jensen wake model physics with a graph architecture of directed, distance-weighted edges and temporal convolution layers. WAST-GNN obtained RMSE of 0.227 MW, MAE of 0.106 MW, and R^2 of 0.861 on synthetic SCADA data, surpassing GCN, GraphSAGE, and MLP baselines. The loss curves demonstrated a consistent convergence with little overfitting and the scatter plots showed a good match between the expected and real power. The results confirm that wake-aware spatial modelling paired with temporal learning provides a considerable improvement in turbine-level forecasting accuracy, providing a scalable approach to wind farm power prediction. Future work will include validation of WAST-GNN on real SCADA datasets such as Penmanshiel, inclusion of advanced dynamic wake models such as FLORIS, multi-step and probabilistic forecasting.

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Foreword by
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MAIT Journal of Management

FOREWORD

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Education must be accompanied by innovative research and development to hold true value for the community, especially in our globally interconnected world where contributing to global knowledge is essential. I am pleased by the enthusiastic response from contributors and fellow educational institutions towards the inaugural volume of the 'MAIT Journal of Management' from Maharaja Agrasen Institute of Technology.

I commend the Editorial Board for their successful effort in compiling the diverse ideas and aspirations of our students and faculty into a cohesive publication. Additionally, I am delighted to see that this marks the third publication from Maharaja Agrasen Institute of Technology within just six months. Congratulations to its Office Bearers and Chief Editor for this remarkable achievement.

Dr. Nand Kishore Garg

MESSAGE

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Shri Vineet Kumar Gupta
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Nurturing creativity and sparking innovation are essential pillars of effective education, and an Institute Journal embodies this perfect blend. It captures the creative spirit of the academic community, distilling their inspired ideas in a remarkable manner.

I am delighted to announce the forthcoming publication of the 'MAIT Journal of Management' an Annual Refereed Journal from Maharaja Agrasen Institute of Technology, Delhi. I extend my heartfelt congratulations to the Editorial Board for achieving this milestone as per schedule, which is truly commendable considering the dedication and effort invested. May our students continue to ascend to new heights, bringing honor to the world and their professions through the power of education!

Vineet Kumar Gupta

Preface



Professor (Dr.) Neelam Sharma
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The Maharaja Agrasen Institute of Technology is pleased to launch its Annual Refereed and Peer Reviewed Journal, i.e. MAIT Journal of Management in the month of May 2024. It provides a forum for publishing research based original contribution and comprehensive articles on all important Management related topics. The Journal encourages all experienced and qualified young and senior researchers, professionals, academicians and other stakeholders to share their knowledge and experiences. The journal is published annually and it has applied for its ISSN no. Authors may submit manuscript as per the template to editor.mgmt@mait.ac.in.

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Sr. No	Papers/ Research Articles	Author (s)	Pages
1	Impact of Entrepreneurial Support Mechanisms on Entrepreneurial Inclination among Management Students in Higher Education Institutions	Nidhi Grover Manjinder Singh	01-14
2	Indian Knowledge System Unveiling Traditional Perspectives and Narratives with Reference to Several Industrial Segments in the Present Era	Ravi Kumar Gupta Amit Gupta Nakul Anand	15-30
3	Exploring the Impact of Employability Attributes on Perceived Stress among University Students: The Mediating Role of Perceived Employability	Karambir Singh Manjinder Singh	31-45
4	The Evolution of Digital Commerce: From Electronic Retailing to Intelligent Commerce	Shalu Garg Gurmeet Kaur	46-64
5	Mathematical Models Helping Organizations in Day-to-Day Decision Making: A Conceptual Study	Anita Gupta Ritu Gupta	65-72
6	Reimagining Higher Education through Artificial Intelligence and Disruptive Technologies: A Comprehensive Review	Jyotsna Manisha Manchanda Kiran Garg	73-82
7	Venture Capital Funding: A Catalyst for Start-up Scalability	Neeru Gupta Anju Bharti Ratika Sikand Sukhvinder Singh	83-89
8	Enabling Blockchain-Driven Supply Chains: Understanding Barrier Interrelationships Using TISM	Kiran Garg Ritu Arora Jyotsna	90-97
9	Job Crafting as a Pathway to Eudaimonic Well-Being: A Self-Determination Theory-Based Conceptual Framework	Divyanshi	98-107
10	Adoption and Employment of Artificial Intelligence (AI) in India: An Economic Analysis across Different Sectors	Aditi Negi	108-119
11	Algorithmic Nudging in Online Shopping: Analyzing the Relationship Between Dark AI Patterns and Consumer Impulsive Buying Susceptibility	Anoop Kumar Gupta	120-129
12	Effectiveness of Online Channels of Distribution in the Brown Goods Industry of India	Nitin Walia	130-135
	Case Studies		
1	Veloce India: The Diwali Sales Volume Mandate	Anoop Kumar Gupta	136-141
2	Case Study: LT Foods – Digital Supply Chain Transformation multiplied Revenue Growth	Anju Bharti Rajiv Jain Neeru Gupta	142-149
3	Racing Against the Forecast: Postponement and Cross-Docking at Veloura Home Appliances	Kiran Garg	150-156
4	Eraaya Lifespaces Limited: Growth, Acquisition Financing and Financial Sustainability	Ravi Kumar Gupta Ritu Gupta Nakul Anand	157-163
5	The Quick-Commerce Dilemma: Can Zomato's Blinkit Deliver Speed and Sustainable Profits?	Neeru Gupta Rajiv Jain Anju Bharti	164-176

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Impact of Entrepreneurial Support Mechanisms on Entrepreneurial Inclination among Management Students in Higher Education Institutions

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Abstract

The present study examines the impact of entrepreneurial support mechanisms—specifically perceived educational support, perceived relational support, and perceived structural support—on entrepreneurial inclination among management students in higher education institutions (HEIs). A quantitative research design was employed using a cross-sectional survey approach. Data were collected from management students enrolled in Indian HEIs. Structural Equation Modeling (SEM) was applied to test the direct effects of entrepreneurial support mechanisms on entrepreneurial inclination. The results indicate that all three support mechanisms significantly and positively influence entrepreneurial inclination. Among them, perceived educational support emerged as the strongest predictor, followed by relational support and structural support. The findings highlight the critical role of institutional and social ecosystems in fostering entrepreneurial mindset among students. The study suggests that HEIs should strengthen entrepreneurship education, mentorship networks, and institutional infrastructure to enhance entrepreneurial inclination among students. This study contributes to entrepreneurship literature by integrating multiple dimensions of support mechanisms within a unified framework and empirically validating their direct influence on entrepreneurial inclination in the Indian higher education context.

Keywords: Entrepreneurial Support, Educational Support, Relational Support, Structural Support, Entrepreneurial Inclination, HEIs, SEM

1. Introduction

Entrepreneurship has increasingly been recognized as a fundamental driver of economic growth, innovation, and employment generation across both developed and emerging economies (Acs & Szerb, 2007; Hamdan et al., 2022). In the context of emerging economies such as India, entrepreneurship assumes even greater significance due to its potential to address structural challenges such as unemployment, underemployment, and regional economic disparities. Consequently, fostering entrepreneurial inclination among young individuals, particularly students in higher education institutions (HEIs), has become a strategic priority for policymakers and academic institutions alike. Higher education institutions serve as critical ecosystems for nurturing entrepreneurial talent, as they provide access to knowledge, skill development opportunities, and exposure to entrepreneurial practices (Fayolle & Gailly, 2015). Universities are no longer perceived merely as centers for knowledge dissemination but are increasingly positioned as entrepreneurial hubs that facilitate innovation, startup incubation,

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and industry collaboration (Agarwal et al., 2020). Despite these institutional advancements, empirical evidence suggests that entrepreneurial inclination among students remains inconsistent and often below expectations (Pandit et al., 2018). This inconsistency indicates that the presence of educational initiatives alone may not be sufficient to foster entrepreneurial behavior, thereby necessitating a deeper examination of the contextual and environmental factors influencing students' entrepreneurial orientation.

Entrepreneurial inclination, defined as an individual's intention, readiness, and commitment to engage in entrepreneurial activities, is widely regarded as a precursor to entrepreneurial behavior (Liñán et al., 2011; Krueger et al., 2000). The formation of such inclination is influenced by a combination of individual-level characteristics and environmental factors. While earlier studies have predominantly focused on personality traits, risk propensity, and cognitive determinants, recent research has shifted attention toward the role of external support systems in shaping entrepreneurial intentions (Anjum et al., 2023; Vu et al., 2024). This shift reflects the growing recognition that entrepreneurship is not solely an individual endeavor but is significantly embedded within a broader socio-institutional context. Within this context, entrepreneurial support mechanisms emerge as critical determinants of entrepreneurial inclination. These support mechanisms encompass various forms of assistance that facilitate entrepreneurial development, including educational, relational, and structural support (Nowiński & Haddoud, 2019; van Trang & Doanh, 2019). Perceived educational support refers to the extent to which students believe that their academic institutions provide relevant knowledge, training, and experiential learning opportunities necessary for entrepreneurship (Turker & Selcuk, 2009). Such support enhances entrepreneurial competencies and reduces uncertainty associated with venture creation, thereby positively influencing entrepreneurial inclination (Fayolle & Gailly, 2015).

In addition to formal education, relational support plays a vital role in shaping entrepreneurial aspirations. Relational support includes encouragement, guidance, and resource sharing from family members, peers, mentors, and professional networks (Shen et al., 2017). Social capital derived from these relationships provides emotional reassurance and practical assistance, which can significantly enhance individuals' confidence in pursuing entrepreneurial careers (Bosma et al., 2012). Empirical evidence suggests that individuals with strong relational support systems are more likely to develop favorable attitudes toward entrepreneurship and exhibit higher entrepreneurial inclination (Nowiński & Haddoud, 2019). Furthermore, structural support represents the broader institutional and policy-level environment that facilitates entrepreneurial activity. This includes government initiatives, financial assistance, incubation centers, regulatory frameworks, and access to business infrastructure (van Trang & Doanh, 2019). A supportive structural environment reduces barriers to entry and enhances the perceived feasibility of entrepreneurship, thereby encouraging individuals to consider entrepreneurial career paths (Zatini & Della Porta, 2025). In emerging economies, where institutional voids and resource constraints are prevalent, structural support becomes particularly crucial in enabling entrepreneurial development (Vu et al., 2024).

Despite the recognized importance of these support mechanisms, existing literature reveals several limitations. First, most studies examine educational, relational, and structural support in isolation, without integrating them into a comprehensive framework. This fragmented approach restricts a holistic understanding of how different dimensions of support collectively influence entrepreneurial inclination. Second, empirical research focusing on the Indian higher education context remains relatively limited, despite the country's growing emphasis on entrepreneurship as a driver of economic development. Third, there is a need for robust

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empirical validation using advanced analytical techniques such as structural equation modeling (SEM) to establish the strength and significance of these relationships. Addressing these gaps, the present study proposes an integrated framework that examines the direct impact of perceived educational support, perceived relational support, and perceived structural support on entrepreneurial inclination among management students in Indian HEIs. By consolidating multiple dimensions of support into a unified model, this study provides a more comprehensive understanding of the environmental determinants of entrepreneurial inclination. The significance of this research extends beyond theoretical contribution. From a practical perspective, the findings offer valuable insights for university administrators, policymakers, and entrepreneurship educators. Understanding the relative importance of different support mechanisms can inform the design of targeted interventions aimed at enhancing entrepreneurial inclination. For instance, strengthening entrepreneurship curricula, fostering mentorship networks, and developing institutional infrastructure can collectively contribute to building a robust entrepreneurial ecosystem within HEIs.

2. Literature Review and Hypotheses Development

2.1 Introduction to the Literature Review

Entrepreneurial inclination has been widely examined as a critical precursor to entrepreneurial behavior, particularly within higher education contexts where students are exposed to diverse learning environments and career pathways (Liñán et al., 2011; Krueger et al., 2000). While earlier research predominantly emphasized individual-level determinants such as personality traits and cognitive predispositions, contemporary scholarship increasingly highlights the importance of contextual and environmental factors in shaping entrepreneurial intentions (Anjum et al., 2023; Vu et al., 2024). Among these contextual determinants, entrepreneurial support mechanisms have emerged as a key area of investigation. These mechanisms encompass various forms of institutional, social, and structural assistance that collectively create an enabling environment for entrepreneurship (Nowiński & Haddoud, 2019). In the context of higher education institutions (HEIs), such support is typically conceptualized across three dimensions: perceived educational support, perceived relational support, and perceived structural support (Turker & Selcuk, 2009; van Trang & Doanh, 2019). Despite the growing body of literature, existing studies often examine these support dimensions in isolation, thereby limiting a comprehensive understanding of their combined influence on entrepreneurial inclination. The present study addresses this limitation by developing hypotheses that examine the direct impact of each support mechanism on entrepreneurial inclination.

2.2 Perceived Educational Support and Entrepreneurial Inclination

Perceived educational support refers to the extent to which students believe that their academic institutions provide the necessary knowledge, skills, and experiential learning opportunities to engage in entrepreneurial activities (Turker & Selcuk, 2009). Within higher education settings, entrepreneurship education plays a pivotal role in fostering entrepreneurial competencies, enhancing self-efficacy, and shaping positive attitudes toward entrepreneurship (Fayolle & Gailly, 2015). The theoretical foundation for the relationship between educational support and entrepreneurial inclination can be traced to intention-based models such as the Theory of Planned Behavior (Ajzen, 1991), which emphasize the role of knowledge and perceived capability in shaping behavioral intentions. Educational interventions contribute to the development of entrepreneurial knowledge structures, which in turn enhance individuals'

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confidence in their ability to successfully initiate and manage business ventures (Liñán et al., 2011).

Empirical evidence consistently supports the positive impact of entrepreneurship education on entrepreneurial inclination. Turker and Selcuk (2009) found that university-level entrepreneurship education significantly influences students' entrepreneurial intentions by enhancing perceived feasibility and desirability. Similarly, Fayolle and Gailly (2015) demonstrated that entrepreneurship education has a long-lasting impact on students' entrepreneurial attitudes and intentions, indicating its persistent influence beyond the immediate learning environment. Furthermore, Liñán et al. (2011) emphasize that educational support not only provides technical knowledge but also shapes cognitive frameworks that influence opportunity recognition and risk assessment. Mahmood et al. (2020) also highlight that entrepreneurship education enhances business performance by equipping individuals with practical skills and strategic thinking capabilities. In addition, the increasing integration of experiential learning approaches—such as business simulations, startup incubators, and project-based learning—has further strengthened the role of educational support in fostering entrepreneurial inclination (Agarwal et al., 2020). These pedagogical innovations enable students to gain hands-on experience, thereby reducing uncertainty and enhancing their readiness to engage in entrepreneurial activities.

However, it is important to note that the effectiveness of educational support depends on its quality, relevance, and alignment with industry requirements. Merely providing theoretical knowledge may not be sufficient; instead, institutions must adopt a holistic approach that combines theoretical instruction with practical exposure and mentorship. Based on the above theoretical and empirical evidence, it can be argued that perceived educational support plays a crucial role in enhancing entrepreneurial inclination among students.

H1: Perceived educational support has a significant positive effect on entrepreneurial inclination.

2.3 Perceived Relational Support and Entrepreneurial Inclination

Perceived relational support refers to the extent to which individuals receive encouragement, guidance, and resources from their social networks, including family, friends, mentors, and professional contacts (Shen et al., 2017). Social relationships play a critical role in shaping career choices, particularly in the context of entrepreneurship, which involves uncertainty, risk, and long-term commitment. From a theoretical perspective, relational support can be understood through the lens of social capital theory, which posits that social networks provide access to resources, information, and opportunities that facilitate individual decision-making (Bosma et al., 2012). In the context of entrepreneurship, relational support enhances individuals' confidence, reduces perceived risk, and provides emotional and financial backing, thereby positively influencing entrepreneurial inclination.

Empirical studies have consistently highlighted the importance of relational support in shaping entrepreneurial intentions. Shen et al. (2017) found that family support significantly influences students' entrepreneurial attitudes and intentions by providing emotional encouragement and financial assistance. Similarly, Nowiński and Haddoud (2019) emphasize the role of inspiring role models in enhancing entrepreneurial intention, as exposure to successful entrepreneurs can motivate individuals to pursue entrepreneurial careers. Furthermore, Bosma et al. (2012) demonstrate that role models and social networks play a crucial role in influencing

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entrepreneurial behavior by providing guidance, mentorship, and access to resources. These findings are particularly relevant in the context of higher education, where students often rely on peer networks and faculty mentorship to explore entrepreneurial opportunities. Relational support also contributes to the development of entrepreneurial self-efficacy, which is a key determinant of entrepreneurial inclination (Anjum et al., 2023). When individuals receive positive reinforcement from their social environment, they are more likely to develop confidence in their entrepreneurial abilities and pursue entrepreneurial ventures. In addition, cultural and societal factors play a significant role in shaping relational support. In collectivist societies such as India, family and community support are particularly influential in career decision-making processes (Hofstede, 1980). Strong family support can mitigate the perceived risks associated with entrepreneurship and encourage individuals to pursue entrepreneurial careers.

However, the absence of relational support can act as a significant barrier to entrepreneurship. Lack of encouragement, negative societal perceptions, and limited access to networks can discourage individuals from considering entrepreneurship as a viable career option. Based on the above discussion, it can be concluded that relational support plays a vital role in fostering entrepreneurial inclination by providing emotional, informational, and financial resources.

H2: Perceived relational support has a significant positive effect on entrepreneurial inclination.

2.4 Perceived Structural Support and Entrepreneurial Inclination

Perceived structural support refers to the extent to which individuals perceive the broader institutional and policy environment as conducive to entrepreneurial activities (van Trang & Doanh, 2019). This includes factors such as government policies, financial assistance, infrastructure, incubation centers, and regulatory frameworks. Structural support is particularly important in emerging economies, where institutional barriers and resource constraints can hinder entrepreneurial development (Vu et al., 2024). A supportive structural environment reduces uncertainty, enhances access to resources, and increases the perceived feasibility of entrepreneurship. From a theoretical standpoint, structural support aligns with institutional theory, which emphasizes the role of formal and informal institutions in shaping economic behavior (Zatini & Della Porta, 2025). Institutions provide the rules, norms, and resources that influence individuals' decisions to engage in entrepreneurial activities.

Empirical evidence supports the positive relationship between structural support and entrepreneurial inclination. van Trang and Doanh (2019) found that structural support significantly influences entrepreneurial intention by enhancing perceived feasibility and reducing environmental constraints. Similarly, Vu et al. (2024) demonstrate that university support and institutional infrastructure play a crucial role in shaping entrepreneurial intention among students. Furthermore, government initiatives such as startup policies, funding schemes, and incubation programs have been shown to positively influence entrepreneurial development by providing financial and technical support (Zatini & Della Porta, 2025). These initiatives create an enabling environment that encourages individuals to pursue entrepreneurial ventures. In the context of higher education institutions, structural support includes the availability of entrepreneurship centers, incubation facilities, and industry partnerships. These resources provide students with access to funding, mentorship, and networking opportunities, thereby enhancing their entrepreneurial inclination.

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However, the effectiveness of structural support depends on its accessibility, efficiency, and alignment with students' needs. Ineffective policies, bureaucratic hurdles, and lack of awareness can limit the impact of structural support on entrepreneurial inclination. Despite these challenges, the overall evidence suggests that a supportive structural environment plays a critical role in fostering entrepreneurial inclination.

H3: Perceived structural support has a significant positive effect on entrepreneurial inclination.

3. Research Methodology

3.1 Research Design

The present study adopts a quantitative research design to examine the impact of entrepreneurial support mechanisms—namely perceived educational support, perceived relational support, and perceived structural support—on entrepreneurial inclination among management students in higher education institutions (HEIs). A quantitative approach is appropriate as the study aims to test theoretically grounded hypotheses and examine causal relationships between latent constructs using statistical techniques (Creswell & Creswell, 2018). A cross-sectional survey design was employed, wherein data were collected at a single point in time. This design is widely used in entrepreneurship and behavioral research due to its efficiency in capturing perceptions and intentions across a large sample (Saunders et al., 2019). Although cross-sectional designs limit causal inference, they are suitable for theory testing and model validation when supported by robust statistical techniques such as Structural Equation Modeling (SEM) (Hair et al., 2019). The study follows a deductive research approach, wherein hypotheses are derived from existing theories and empirical literature and subsequently tested using observed data (Sekaran & Bougie, 2016). This approach ensures theoretical consistency and empirical rigor.

3.2 Target Population and Sampling Design

3.2.1 Target Population

The target population comprises management students enrolled in higher education institutions in India. This population is particularly relevant as management students are frequently exposed to entrepreneurship education, business incubation initiatives, and industry interactions, making them an appropriate cohort for studying entrepreneurial inclination (Pandit et al., 2018).

3.2.2 Sampling Technique

The study employed a non-probability convenience sampling technique, wherein respondents were selected based on accessibility and willingness to participate. This approach is commonly used in behavioral and educational research due to practical constraints in accessing a comprehensive sampling frame (Etikan et al., 2016). While convenience sampling may limit generalizability, efforts were made to ensure diversity in terms of demographic characteristics such as age, gender, and academic level. Additionally, the study adheres to recommended practices by clearly reporting sampling procedures and limitations to maintain transparency (Saunders et al., 2019).

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3.2.3 Sample Size Determination

A sample size of approximately 400–450 respondents was targeted to ensure statistical adequacy for SEM analysis. According to Hair et al. (2019), SEM requires a sufficiently large sample size to achieve stable parameter estimates and reliable model fit. A minimum sample size of 200 is generally recommended; however, larger samples enhance the robustness and generalizability of findings. The sample size also satisfies the rule-of-thumb for SEM, which suggests at least 10 observations per estimated parameter (Kline, 2016). Therefore, the chosen sample size is considered adequate for conducting Confirmatory Factor Analysis (CFA) and Structural Equation Modeling.

3.3 Instrument Development and Measurement

3.3.1 Measurement Scale

Data were collected using a structured questionnaire consisting of validated measurement scales adapted from prior studies. All items were measured using a five-point Likert scale ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree"), which is widely used in behavioral research for capturing perceptions and attitudes (Sekaran & Bougie, 2016).

3.3.2 Construct Operationalization

The study includes four key constructs:

Construct	Description	Source
Perceived Educational Support (PES)	Institutional support through entrepreneurship education, training, and skill development	Turker & Selcuk (2009)
Perceived Relational Support (PRS)	Support from family, peers, and mentors	Shen et al. (2017)
Perceived Structural Support (PSS)	Institutional and policy-level support such as infrastructure and funding	van Trang & Doanh (2019)
Entrepreneurial Inclination (EI)	Intention and readiness to engage in entrepreneurship	Liñán et al. (2011)

4. Results

This section presents the empirical findings of the study, including measurement model validation through Confirmatory Factor Analysis (CFA) and hypothesis testing using Structural Equation Modeling (SEM). The analysis was conducted using SPSS and AMOS software, following a systematic approach involving reliability assessment, validity testing, and structural model evaluation.

Descriptive statistics were computed to understand the central tendency and dispersion of the data. Normality was assessed using skewness and kurtosis values.

Table 1: Descriptive Statistics and Normality

Construct	Mean	Std. Dev.	Skewness	Kurtosis
Educational Support	3.82	0.71	-0.42	0.35
Relational Support	3.75	0.68	-0.38	0.29

Prof. (Dr.) Vikram Bali
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PSP Area, Sector-22, Maharaja Agrasen Chowk
Sector-22, Rohini, Delhi-110086

Structural Support	3.69	0.73	-0.44	0.41
Entrepreneurial Inclination	3.88	0.69	-0.47	0.33

The mean values indicate a relatively high perception of entrepreneurial support and inclination among respondents. Skewness and kurtosis values fall within acceptable limits (±2), confirming the assumption of normality (West et al., 1995). This supports the suitability of SEM analysis. Reliability was assessed using Cronbach's Alpha and Composite Reliability (CR).

4.1 Measurement Model

Table 2: Reliability Assessment

Construct	Cronbach's Alpha	Composite Reliability (CR)
Educational Support	0.88	0.91
Relational Support	0.85	0.89
Structural Support	0.86	0.90
Entrepreneurial Inclination	0.87	0.91

All constructs exhibit Cronbach's Alpha values above the recommended threshold of 0.70, indicating strong internal consistency (Nunnally & Bernstein, 1994). Similarly, CR values exceed 0.70, confirming the reliability of the measurement model (Hair et al., 2019). CFA was conducted to validate the measurement model and assess construct validity.

Factor Loadings

Table 3: Standardized Factor Loadings

Construct	Item	Loading
Educational Support	ES1	0.78
	ES2	0.81
	ES3	0.83
Relational Support	RS1	0.76
	RS2	0.80
	RS3	0.82
Structural Support	SS1	0.79
	SS2	0.84
	SS3	0.81
Entrepreneurial Inclination	EI1	0.82
	EI2	0.85
	EI3	0.83

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All factor loadings exceed the recommended threshold of 0.70, indicating strong item reliability and confirming that observed variables adequately represent their respective constructs (Hair et al., 2019).

Convergent Validity

Table 4: Convergent Validity

Construct	CR	AVE
Educational Support	0.91	0.66
Relational Support	0.89	0.63
Structural Support	0.90	0.64
Entrepreneurial Inclination	0.91	0.65

AVE values exceed the threshold of 0.50, confirming convergent validity (Fornell & Larcker, 1981). This indicates that constructs explain more than 50% of the variance in their indicators.

Discriminant Validity

Table 5: Discriminant Validity (Fornell–Larcker Criterion)

Construct	ES	RS	SS	EI
Educational Support	**0.81**			
Relational Support	0.52	**0.79**		
Structural Support	0.49	0.51	**0.80**	
Entrepreneurial Inclination	0.58	0.55	0.53	**0.81**

(Diagonal values represent √AVE)

The square root of AVE for each construct exceeds inter-construct correlations, confirming discriminant validity (Fornell & Larcker, 1981).

Measurement Model Fit

Table 6: Model Fit Indices (CFA)

Fit Index	Value	Threshold
CMIN/DF	2.45	<3
CFI	0.94	>0.90
TLI	0.93	>0.90
RMSEA	0.056	<0.08

All model fit indices meet recommended thresholds, indicating a good fit between the measurement model and the data (Hu & Bentler, 1999; Hair et al., 2019).

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4.2 Structural Model

After validating the measurement model, SEM was conducted to test the hypothesized relationships.

Structural Model Fit

Table 7: Structural Model Fit Indices

Fit Index	Value	Threshold
CMIN/DF	2.61	<3
CFI	0.93	>0.90
TLI	0.92	>0.90
RMSEA	0.059	<0.08

The structural model demonstrates acceptable fit, confirming that the proposed model adequately represents the data.

Hypothesis Testing (Direct Effects)

Table 8: Structural Model Results

Hypothesis	Path	β	S.E.	C.R.	p-value	Result
H1	ES → EI	0.42	0.05	8.40	<0.001	Supported
H2	RS → EI	0.29	0.06	5.17	<0.001	Supported
H3	SS → EI	0.24	0.07	3.43	0.001	Supported

The results presented in Table 8 provide empirical support for all three hypothesized relationships between entrepreneurial support mechanisms and entrepreneurial inclination. Specifically, perceived educational support (ES) exhibits the strongest positive influence on entrepreneurial inclination ($\beta = 0.42$, C.R. = 8.40, $p < 0.001$), indicating that institutional learning, training programs, and entrepreneurship-oriented curriculum significantly enhance students' intention to engage in entrepreneurial activities. The high critical ratio and statistical significance further confirm the robustness of this relationship. Similarly, perceived relational support (RS) demonstrates a significant positive effect on entrepreneurial inclination ($\beta = 0.29$, C.R. = 5.17, $p < 0.001$), suggesting that encouragement and support from family, peers, and mentors play a crucial role in shaping entrepreneurial aspirations. This finding highlights the importance of social networks in reinforcing confidence and reducing uncertainty associated with entrepreneurial decision-making. In addition, perceived structural support (SS) also shows a positive and statistically significant impact on entrepreneurial inclination ($\beta = 0.24$, C.R. = 3.43, $p = 0.001$), although its effect size is comparatively lower than the other two constructs. This implies that institutional infrastructure, policies, and external support mechanisms contribute to fostering entrepreneurial inclination, but their influence may be more indirect or dependent on complementary support systems. Overall, the results confirm that all dimensions of entrepreneurial support mechanisms significantly contribute to enhancing entrepreneurial

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inclination, with educational support emerging as the most influential predictor, followed by relational and structural support.

5. Discussion

5.1 Overview of Findings

The primary objective of this study was to examine the influence of entrepreneurial support mechanisms—namely perceived educational support, perceived relational support, and perceived structural support—on entrepreneurial inclination among management students in higher education institutions. The findings provide strong empirical evidence that all three support mechanisms exert a significant and positive effect on entrepreneurial inclination, thereby reinforcing the critical role of ecosystem-level enablers in shaping entrepreneurial behavior. More specifically, perceived educational support emerged as the strongest predictor, followed by relational support and structural support. These findings not only validate the proposed hypotheses but also provide important theoretical and practical insights into the formation of entrepreneurial inclination in an emerging economy context.

5.2 Theoretical Integration with Entrepreneurial Intention Models

The findings of this study can be meaningfully interpreted through the lens of intention-based frameworks, particularly the Theory of Planned Behavior. According to this theory, behavioral intentions are shaped by cognitive evaluations, perceived feasibility, and external influences that affect individuals' readiness to act (Ajzen, 1991). Although the present study does not explicitly include mediating constructs such as attitude or perceived behavioral control, the significant direct effects of support mechanisms suggest that these external factors operate as antecedents to cognitive evaluation processes. In other words, entrepreneurial support mechanisms shape the belief structures that ultimately influence entrepreneurial inclination (Liñán et al., 2011; Krueger et al., 2000). From a broader perspective, the results also align with the entrepreneurial ecosystem approach, which emphasizes that entrepreneurship is embedded within a network of institutional, social, and policy-level supports (Nowiński & Haddoud, 2019). The significant effects of educational, relational, and structural support confirm that entrepreneurial inclination is not merely an individual-level phenomenon but is strongly influenced by contextual enablers.

5.3 Role of Perceived Educational Support

The findings indicate that perceived educational support has the strongest influence on entrepreneurial inclination ($\beta = 0.42$). This result underscores the central role of higher education institutions in fostering entrepreneurial competencies and shaping students' career orientations. This finding is consistent with prior studies that highlight the transformative impact of entrepreneurship education on entrepreneurial intentions (Fayolle & Gailly, 2015; Turker & Selcuk, 2009). Educational support enhances entrepreneurial knowledge, opportunity recognition, and self-efficacy, which are critical determinants of entrepreneurial inclination (Liñán et al., 2011). From a theoretical standpoint, educational support contributes to the formation of positive behavioral beliefs, which, according to the Theory of Planned Behavior, strengthen the intention to perform a behavior. By providing structured learning, experiential exposure, and skill development, educational institutions reduce uncertainty and increase perceived feasibility of entrepreneurship. Furthermore, the dominance of educational support in this study suggests that formal institutional interventions may be more influential than

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informal support systems in shaping entrepreneurial inclination among management students. This may be attributed to the increasing emphasis on entrepreneurship curricula, incubation programs, and experiential learning in Indian HEIs (Agarwal et al., 2020).

5.4 Role of Perceived Relational Support

The study also finds that perceived relational support significantly influences entrepreneurial inclination (β = 0.29). This highlights the importance of social networks, including family, peers, and mentors, in shaping entrepreneurial aspirations. These findings are consistent with existing literature emphasizing the role of social capital and role models in entrepreneurial development (Bosma et al., 2012; Nowiński & Haddoud, 2019). Relational support provides emotional encouragement, informational guidance, and sometimes financial assistance, which collectively enhance individuals' confidence in pursuing entrepreneurial careers. From a theoretical perspective, relational support can be interpreted as a key component of subjective norms within the Theory of Planned Behavior. Positive reinforcement from significant others increases the perceived social desirability of entrepreneurship, thereby strengthening entrepreneurial inclination. Additionally, in collectivist cultural contexts such as India, family and peer influence play a particularly significant role in career decision-making (Hofstede, 1980). The findings of this study reinforce the notion that entrepreneurial decisions are socially embedded, and relational support acts as a critical catalyst in transforming entrepreneurial aspirations into actionable intentions.

5.5 Role of Perceived Structural Support

The results further reveal that perceived structural support has a positive and significant effect on entrepreneurial inclination (β = 0.24), although its impact is relatively weaker compared to educational and relational support. This finding aligns with prior research suggesting that institutional and policy-level support mechanisms, such as government initiatives, funding opportunities, and incubation infrastructure, play a crucial role in facilitating entrepreneurship (van Trang & Doanh, 2019; Vu et al., 2024). Structural support reduces environmental uncertainty and enhances access to resources, thereby increasing the perceived feasibility of entrepreneurial ventures. However, the comparatively lower effect size suggests that structural support alone may not be sufficient to drive entrepreneurial inclination. Instead, its effectiveness may depend on the presence of complementary support systems, particularly educational and relational support. From an institutional theory perspective, structural support represents the formal regulatory and infrastructural framework that shapes entrepreneurial behavior (Zatini & Della Porta, 2025). While such support creates an enabling environment, its impact may be indirect and mediated through individual-level perceptions and experiences.

6. Conclusion

The present study aimed to examine the impact of entrepreneurial support mechanisms—specifically perceived educational support, perceived relational support, and perceived structural support—on entrepreneurial inclination among management students in higher education institutions. The findings provide clear empirical evidence that all three dimensions of support significantly and positively influence entrepreneurial inclination, thereby reaffirming the critical role of an enabling ecosystem in fostering entrepreneurial behavior. Among the examined factors, perceived educational support emerged as the most influential determinant, highlighting the central role of higher education institutions in equipping students with the knowledge, skills, and confidence required for entrepreneurial engagement. Perceived

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relational support also demonstrated a strong positive effect, emphasizing the importance of social networks, mentorship, and family encouragement in shaping entrepreneurial aspirations. While perceived structural support was found to be significant, its relatively lower impact suggests that institutional and policy-level interventions are most effective when complemented by strong educational and relational support systems. Overall, the study underscores that entrepreneurial inclination is not solely driven by individual motivation but is deeply embedded within a broader support ecosystem. By integrating multiple dimensions of support within a unified framework, the research contributes to a more comprehensive understanding of entrepreneurial intention formation, particularly in the context of emerging economies such as India. The findings offer valuable insights for higher education institutions, policymakers, and entrepreneurship educators, indicating that a holistic approach—combining curriculum innovation, mentorship development, and institutional support—is essential for cultivating a sustainable entrepreneurial culture among students.

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Indian Knowledge System Unveiling Traditional Perspectives and Narratives with Reference to Several Industrial Segments in the Present Era

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Abstract
The Indian Knowledge System (IKS) represents one of the world's oldest and most comprehensive repositories of scientific, technological, philosophical, and socio-economic knowledge. Rooted in the Vedic, post-Vedic, and classical traditions, IKS encompasses diverse disciplines including metallurgy, architecture, medicine, mathematics, astronomy, agriculture, navigation, governance, and environmental sustainability. Ancient Indian civilization demonstrated remarkable technological capabilities that significantly influenced global industrial and commercial development. Many indigenous technologies developed centuries ago continue to attract scholarly attention because of their scientific sophistication, sustainability, and practical relevance to contemporary industrial practices. The present conceptual study examines the traditional perspectives and historical narratives of the Indian Knowledge System with special reference to selected industrial segments, namely iron and steel production, Wootz steel technology, metallurgy and metalworking, shipping, and shipbuilding. The study is based on an extensive review of classical Indian literature, historical records, archaeological evidence, and contemporary academic publications. It attempts to understand how indigenous technological knowledge contributed to industrial excellence in ancient India and explores its relevance for modern industrial development. The study reveals that ancient India possessed highly advanced metallurgical expertise, internationally acclaimed Wootz steel manufacturing techniques, sophisticated metalworking practices, and flourishing maritime trade supported by efficient shipbuilding technology. These achievements not only strengthened India's economic prosperity but also facilitated cultural and technological exchanges with various civilizations across Asia, Africa, and Europe. However, the gradual decline in the preservation, transmission, and application of indigenous knowledge during the colonial period resulted in significant technological, economic, and cultural setbacks. The study argues that the revival and integration of the Indian Knowledge System into contemporary education, research, innovation ecosystems, and industrial policy can contribute significantly towards sustainable industrial development, technological self-reliance, skill enhancement, and national competitiveness. The paper concludes that the Indian Knowledge System offers valuable insights for addressing present-day industrial challenges through sustainable resource utilization, indigenous innovation, and knowledge-driven development. Systematic documentation, interdisciplinary research, and institutional support for traditional

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knowledge can strengthen India's vision of becoming a globally competitive and knowledge-driven economy while preserving its rich scientific heritage.

Keywords: Indian Knowledge System (IKS); Traditional Knowledge; Indigenous Technologies; Industrial Development; Iron and Steel; Wootz Steel; Metallurgy; Metalworking Technology; Shipping; Shipbuilding; Sustainable Development.

1. Introduction

Knowledge has been the cornerstone of civilization since the earliest periods of human history. Nations that have successfully created, preserved, and disseminated knowledge have consistently emerged as leaders in scientific advancement, technological innovation, economic prosperity, and cultural influence. Among the world's oldest civilizations, India occupies a distinctive position because of its unparalleled contribution to the evolution of knowledge across diverse domains. The Indian Knowledge System (IKS) embodies a comprehensive intellectual tradition developed over several millennia through systematic observation, experimentation, philosophical inquiry, and practical application. Far from being confined to spiritual or religious thought, the Indian Knowledge System encompasses sophisticated developments in mathematics, astronomy, medicine, metallurgy, agriculture, architecture, environmental management, economics, governance, linguistics, and maritime technology.

Ancient India nurtured an educational ecosystem that promoted holistic learning, interdisciplinary thinking, and practical problem-solving. Institutions such as Takshashila, Nalanda, Vikramashila, Vallabhi, and Odantapuri attracted scholars from across Asia and facilitated the exchange of scientific ideas and technological innovations. Classical texts including the Vedas, Upanishads, Arthashastra, Charaka Samhita, Sushruta Samhita, Brihat Samhita, and numerous regional treatises collectively document an extensive body of knowledge that reflects the scientific temperament and technological capabilities of ancient Indian society. Archaeological discoveries, inscriptions, and historical travel accounts further corroborate India's achievements in industrial production, trade, and technological innovation.

One of the distinguishing characteristics of the Indian Knowledge System is its close integration of scientific understanding with ethical values, environmental consciousness, and social welfare. Traditional technologies were generally developed in harmony with ecological principles, emphasizing efficient resource utilization, durability, recyclability, and sustainability. Such principles resonate strongly with contemporary concerns relating to climate change, circular economy, sustainable manufacturing, and responsible industrial development. Consequently, the Indian Knowledge System has gained renewed academic and policy attention in recent years, particularly following the introduction of the National Education Policy (NEP) 2020, which advocates integrating indigenous knowledge into higher education, research, innovation, and skill development.

Among the numerous contributions of ancient India, advances in metallurgy and industrial technology occupy a particularly significant place in global scientific history. Indian metallurgists mastered the extraction, purification, alloying, and processing of metals at a time when many other civilizations were still in the early stages of metallurgical development. The celebrated Iron Pillar of Delhi continues to fascinate materials scientists because of its remarkable resistance to corrosion despite being exposed to environmental conditions for more than sixteen centuries. Likewise, Indian Wootz steel acquired worldwide recognition for its exceptional strength, flexibility, and sharpness, eventually influencing the development of Damascus steel in West Asia. Historical evidence indicates that Indian steel was exported extensively to regions including Persia, Arabia, Egypt, and Europe, demonstrating the country's advanced manufacturing capabilities and global trade networks.

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Similarly, India's maritime traditions illustrate the technological maturity of its shipbuilding and navigation industries. Ancient ports such as Lothal, Muziris, Bharuch, Sopara, and Tamralipti functioned as vibrant centres of international commerce, connecting India with Southeast Asia, the Middle East, East Africa, and the Mediterranean world. Indigenous shipbuilding techniques enabled Indian merchants and navigators to undertake long-distance voyages, thereby facilitating commercial prosperity, cultural exchange, and technological diffusion. These achievements underscore the strategic importance of traditional knowledge in supporting economic development and industrial competitiveness.

Despite this rich heritage, several factors including colonial exploitation, disruption of indigenous educational institutions, decline of traditional industries, and insufficient documentation led to the gradual erosion of India's technological knowledge base. Colonial economic policies frequently discouraged indigenous manufacturing while promoting imported industrial products, thereby weakening traditional production systems and artisan communities. Consequently, many scientific achievements documented in classical literature remained underexplored within mainstream academic discourse for decades.

In the twenty-first century, however, growing interest in sustainability, indigenous innovation, and knowledge-based development has created favourable conditions for re-examining the Indian Knowledge System from an interdisciplinary perspective. Contemporary industries increasingly recognize that traditional technologies often embody principles of resource efficiency, environmental stewardship, resilience, and localized innovation. These characteristics align closely with emerging paradigms such as Industry 5.0, sustainable manufacturing, green technologies, and responsible innovation. Therefore, studying ancient industrial knowledge is no longer merely an exercise in historical appreciation but an important avenue for generating new insights that may contribute to future industrial transformation.

The present study seeks to examine selected industrial segments where the Indian Knowledge System demonstrated remarkable scientific and technological excellence. Particular emphasis is placed on iron and steel production, Wootz steel technology, metallurgy and metalworking, shipping, and shipbuilding. Through a conceptual review of historical and contemporary literature, the study explores how these traditional technologies evolved, their contribution to India's socio-economic development, and their continuing relevance in the present industrial landscape. The paper further argues that revitalizing indigenous technological knowledge can strengthen innovation ecosystems, promote sustainable industrial practices, support skill development, and contribute to India's aspiration of becoming a globally competitive knowledge economy.

2. Objectives of the Study

The present study has been undertaken with the following objectives:

1. To examine the historical evolution and conceptual foundations of the Indian Knowledge System with reference to indigenous technological traditions.
2. To analyse the contributions of the Indian Knowledge System in selected industrial sectors, including iron and steel production, Wootz steel technology, metallurgy, metalworking, shipping, and shipbuilding.
3. To evaluate the relevance of traditional Indian industrial knowledge in addressing contemporary challenges relating to sustainability, technological innovation, and industrial competitiveness.
4. To propose a conceptual framework illustrating the relationship between traditional knowledge, industrial capabilities, sustainable development, and national competitiveness.
5. To identify future research opportunities and policy directions for integrating the Indian Knowledge System into modern industrial development and higher education.

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3. Research Methodology

The present research adopts a **conceptual and descriptive research design** based exclusively on secondary sources of information. The study synthesizes evidence from peer-reviewed journal articles, books, historical manuscripts, government publications, archaeological findings, policy documents, conference proceedings, and reports published by national and international institutions. Classical Indian texts relating to metallurgy, trade, governance, and technological practices have also been consulted wherever appropriate.

A thematic analysis approach has been employed to identify major dimensions of the Indian Knowledge System relevant to industrial development. The literature has been analysed under thematic categories including indigenous technological innovation, metallurgical excellence, maritime capabilities, sustainability, and contemporary industrial relevance. Rather than testing statistical hypotheses, the study develops conceptual relationships that provide an integrated understanding of how traditional knowledge can contribute to present-day industrial growth, innovation, and policy formulation.

4. Review of Literature

The Indian Knowledge System (IKS) has increasingly become an important area of multidisciplinary research owing to its relevance in science, technology, sustainable development, innovation management, and industrial history. Earlier studies primarily focused on documenting India's scientific achievements, whereas recent scholarship attempts to reinterpret indigenous knowledge through modern theoretical and technological perspectives. The existing literature indicates that ancient Indian industrial practices were not merely empirical traditions but reflected systematic scientific understanding, technological experimentation, and institutional mechanisms for knowledge transmission.

One of the earliest comprehensive examinations of indigenous scientific and technological capabilities was undertaken by **Dharampal (1971, 1983)**, who demonstrated through colonial archival records that India possessed sophisticated indigenous systems of education, metallurgy, agriculture, and manufacturing before the advent of British rule. His work challenged the long-held assumption that scientific progress in India emerged only after colonial intervention. By documenting indigenous industries and technological practices, Dharampal established an important foundation for subsequent research on traditional industrial knowledge.

Debiprasad Chattopadhyaya (1977) examined the philosophical and scientific traditions of ancient India and argued that Indian civilization fostered rational inquiry alongside spiritual thought. According to him, metallurgy, chemistry, medicine, and astronomy evolved through systematic observation and experimentation rather than merely religious practices. His work highlighted the scientific temper embedded within ancient Indian intellectual traditions.

B. V. Subbarayappa (2001) documented India's contributions to the history of science and technology by analysing developments in metallurgy, medicine, astronomy, and engineering. His research emphasized that Indian metallurgical innovations represented one of the earliest examples of advanced materials engineering, influencing technological developments in several regions of the world.

Research on ancient metallurgy has received considerable attention because of internationally recognized achievements such as the Delhi Iron Pillar and Wootz steel. **R. Balasubramaniam (2008)** investigated the corrosion resistance of the Delhi Iron Pillar and concluded that its exceptional durability resulted from advanced iron-making techniques combined with favourable environmental interactions that produced a protective passive film. His work

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demonstrated that ancient Indian metallurgists possessed sophisticated practical knowledge of materials engineering.

Similarly, **Srinivasan and Ranganathan (2004)** analysed the production technology of Wootz steel and concluded that Indian craftsmen had mastered complex processes involving controlled carbon content, high-temperature furnaces, and crucible technology several centuries before comparable developments elsewhere. Their findings established Wootz steel as one of India's most significant technological contributions to global metallurgy.

Studies concerning India's maritime traditions also demonstrate remarkable technological sophistication. Archaeological investigations of **Lothal** have revealed one of the earliest known dockyard systems, indicating advanced understanding of tidal hydraulics, ship maintenance, and maritime logistics. Historical analyses by **K. V. Raman (1991)** and subsequent maritime historians have highlighted India's extensive commercial networks linking the Indian subcontinent with Southeast Asia, Arabia, East Africa, and the Mediterranean region through well-developed shipbuilding and navigation technologies.

The concept of indigenous technological innovation has also attracted attention within sustainability research. Contemporary scholars argue that many traditional Indian production systems inherently promoted circular resource utilization, minimal waste generation, local resource optimization, and ecological balance. Such characteristics closely correspond with present-day principles of sustainable manufacturing, circular economy, and green industrial development. Consequently, traditional knowledge is increasingly viewed as an important source of sustainable innovation rather than merely a historical artifact.

Recent policy-oriented literature has further strengthened academic interest in IKS. The **National Education Policy (2020)** recommends integrating indigenous knowledge across educational curricula, research programmes, innovation ecosystems, and skill development initiatives. Several researchers have interpreted this policy shift as recognition that traditional knowledge can contribute significantly to entrepreneurship, technological self-reliance, and sustainable economic development.

Within management literature, scholars have begun examining indigenous knowledge using theories of organizational capabilities and innovation. The **Resource-Based View (RBV)** suggests that unique knowledge resources provide sustainable competitive advantage. From this perspective, India's indigenous technological heritage constitutes a valuable strategic resource capable of generating innovation, differentiation, and industrial competitiveness. Similarly, **Dynamic Capabilities Theory** emphasizes an organization's ability to integrate historical knowledge with emerging technologies to respond effectively to changing environments. This theoretical perspective provides an appropriate framework for understanding how traditional industrial knowledge may be revitalized for contemporary industrial applications.

Despite growing scholarly interest, the existing literature reveals several important research gaps. Most studies investigate individual technologies such as metallurgy or shipbuilding independently without developing an integrated conceptual understanding of IKS across multiple industrial sectors. Furthermore, limited research has examined how ancient industrial knowledge can inform present-day industrial policy, innovation ecosystems, sustainability initiatives, and technological capability development. The present conceptual study seeks to bridge these gaps by integrating diverse strands of literature into a unified framework explaining the relationship between Indian Knowledge Systems and contemporary industrial competitiveness.

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Table 1. Comparative Review of Major Literature

Author(s)	Year	Research Focus	Major Findings	Research Gap
Dharampal	1971	Indigenous Indian education and technology	Demonstrated advanced indigenous technological capabilities before colonial rule	Limited industrial-sector integration
Chattopadhyaya	1977	Science and philosophy in ancient India	Established rational scientific traditions in Indian civilization	Limited contemporary industrial linkage
Raman	1991	Maritime trade and shipbuilding	Documented India's extensive maritime networks	Limited sustainability perspective
Subbarayappa	2001	History of Indian science	Comprehensive documentation of scientific achievements	Limited management implications
Srinivasan & Ranganathan	2004	Wootz steel technology	Explained advanced crucible steel manufacturing	Focused primarily on metallurgy
Balasubramaniam	2008	Delhi Iron Pillar	Explained corrosion-resistant metallurgy	Limited industrial policy implications
Government of India (NEP)	2020	Indian Knowledge System	Recommended integration of IKS into education and innovation	Implementation framework remains evolving
Recent Sustainability Studies	2021–2024	Indigenous knowledge and sustainability	Traditional knowledge supports circular economy and green manufacturing	Need for integrated industrial model

5. Theoretical Foundations

The present conceptual study is supported by four complementary theoretical perspectives that explain the relevance of indigenous knowledge in industrial development and innovation.

5.1 Resource-Based View (RBV)

The Resource-Based View proposed by **Barney (1991)** argues that organizations achieve sustainable competitive advantage through valuable, rare, inimitable, and non-substitutable resources. Indigenous technological knowledge represents precisely such a strategic resource because it embodies centuries of accumulated experience, tacit knowledge, craftsmanship, and localized innovation. Traditional metallurgical techniques, shipbuilding expertise, and sustainable production methods constitute unique intellectual assets capable of supporting industrial differentiation and innovation.

Applied to the Indian context, RBV suggests that the revival and commercialization of traditional industrial knowledge can strengthen domestic manufacturing capabilities, promote indigenous technologies, and enhance international competitiveness.

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5.2 Dynamic Capabilities Theory

Dynamic Capabilities Theory developed by **Teece, Pisano, and Shuen (1997)** emphasizes the ability of organizations to integrate, build, and reconfigure internal and external competencies in response to changing technological environments.

The Indian Knowledge System should not be viewed merely as historical heritage but as an evolving knowledge repository that can be integrated with modern technologies such as advanced materials science, artificial intelligence, digital manufacturing, nanotechnology, and sustainable engineering. Such integration enables industries to preserve traditional wisdom while simultaneously fostering continuous innovation.

5.3 Diffusion of Innovation Theory

According to **Rogers (2003)**, innovations spread through societies depending upon their relative advantage, compatibility, complexity, observability, and trialability.

Historically, Indian innovations such as Wootz steel, zinc extraction techniques, textile manufacturing, and maritime technologies diffused across Asia, the Middle East, and Europe through trade, migration, and cultural interactions. In the contemporary context, this theory explains how revitalized indigenous technologies may again gain wider industrial acceptance through policy support, entrepreneurship, and technological adaptation.

5.4 Technology–Organization–Environment (TOE) Framework

The Technology–Organization–Environment (TOE) Framework developed by **Tornatzky and Fleischer (1990)** explains technological adoption through interactions among technological readiness, organizational capabilities, and external environmental conditions.

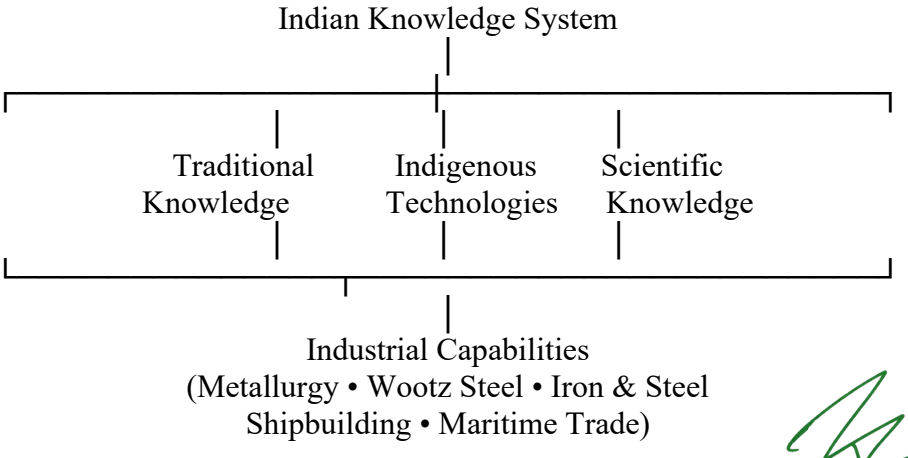
Applying TOE to IKS suggests that successful integration of traditional industrial knowledge requires:

- Appropriate technological modernization.
- Organizational commitment towards indigenous innovation.
- Supportive government policies.
- Academic-industry collaboration.
- Intellectual property protection.
- Skilled human resources.

Collectively, these factors determine whether traditional knowledge can effectively contribute to modern industrial competitiveness.

6. Conceptual Framework of the Study

The proposed conceptual framework illustrates how the Indian Knowledge System serves as a foundational knowledge resource that strengthens industrial innovation and sustainable national development.



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Figure 1: *Conceptual Framework illustrating the relationship between Indian Knowledge System, Indigenous Industrial Capabilities, Innovation, Sustainability, and National Competitiveness.*

7. Indian Knowledge System in Selected Industrial Segments

7.1 Iron and Steel Technology: A Testament to Ancient Indian Metallurgical Excellence

The history of iron and steel production in India represents one of the most remarkable achievements of the Indian Knowledge System (IKS). Archaeological findings indicate that iron smelting and forging techniques were practiced in the Indian subcontinent as early as the second millennium BCE, with evidence from sites in present-day Uttar Pradesh, Madhya Pradesh, Karnataka, Telangana, and Tamil Nadu. Unlike many ancient civilizations that relied primarily on imported metallurgical knowledge, India developed indigenous techniques of ore selection, furnace design, smelting, forging, and heat treatment through systematic observation and practical experimentation.

Ancient Indian metallurgists demonstrated exceptional understanding of material properties, thermal behaviour, and alloy preparation. The production process was characterized by careful selection of iron ore, efficient charcoal-based reduction methods, and precise control over furnace temperatures. Although these processes were transmitted largely through guilds and hereditary artisan communities rather than formal scientific documentation, they embodied sophisticated empirical knowledge accumulated over generations. Such indigenous expertise enabled the production of high-quality iron suitable for agricultural implements, construction, weaponry, and artistic works.

One of the most celebrated examples of India's metallurgical excellence is the **Iron Pillar of Delhi**, dating to approximately the fourth or fifth century CE. Standing for more than sixteen centuries with minimal corrosion, the pillar has attracted considerable attention from materials scientists across the world. Modern metallurgical investigations have shown that its remarkable corrosion resistance is attributable to high-purity wrought iron, elevated phosphorus content, and the formation of a stable passive protective layer under atmospheric conditions. The pillar illustrates that ancient Indian metallurgists possessed advanced practical knowledge of iron refining and forging, even though they described their techniques in traditional rather than modern scientific terminology.

The economic significance of iron technology in ancient India was equally profound. Iron tools improved agricultural productivity through more efficient cultivation, while durable implements supported expanding construction activities and artisanal production. Iron weapons enhanced military capabilities, whereas trade in iron products strengthened commercial relations with neighbouring regions. Thus, metallurgy functioned not merely as an isolated technological activity but as a catalyst for broader socio-economic development.

From a contemporary perspective, the principles underlying ancient Indian iron production remain relevant to sustainable industrial development. Indigenous production systems emphasized efficient utilization of locally available resources, minimal wastage, skilled craftsmanship, and long product life. These principles closely align with modern concepts of resource efficiency, sustainable manufacturing, and circular economy practices. Consequently,

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studying ancient iron technology offers valuable insights for developing environmentally responsible metallurgical processes in the present era.

7.2 Wootz Steel: India's Contribution to Advanced Materials Engineering

Among the many technological innovations associated with the Indian Knowledge System, **Wootz steel** occupies a unique position because of its global influence on the history of metallurgy. Produced primarily in southern India from around the early centuries BCE until the eighteenth century, Wootz steel was internationally recognized for its exceptional hardness, flexibility, toughness, and ability to retain an extremely sharp cutting edge. Historical records indicate that ingots of Indian Wootz steel were exported extensively to Persia, Arabia, Central Asia, and Europe, where they were transformed into the renowned Damascus swords admired for their superior mechanical properties.

The production of Wootz steel required highly sophisticated control over metallurgical variables. Skilled craftsmen carefully selected high-quality iron ore, controlled carbon content through the addition of organic materials, and employed closed crucible furnaces capable of maintaining elevated temperatures for extended periods. Slow cooling of the molten metal resulted in a distinctive microstructure that contributed to the material's exceptional performance characteristics. Although ancient artisans lacked the terminology of modern materials science, their empirical understanding of heat treatment, carbon diffusion, and phase transformation reflected remarkable technological sophistication.

From the perspective of innovation management, Wootz steel illustrates how tacit knowledge and experiential learning can generate globally competitive technologies. Production techniques were preserved through hereditary artisan communities, where practical skills were transferred across generations by apprenticeship and continuous observation. Such knowledge systems demonstrate that innovation does not always emerge exclusively from formal scientific laboratories but may also evolve through long-term cumulative experience and localized experimentation.

The international reputation of Wootz steel also highlights India's historical participation in global value chains. Long before the emergence of modern industrialization, Indian metallurgical products commanded premium markets because of their superior quality and reliability. This historical experience offers important lessons for contemporary industrial policy, particularly regarding quality-oriented manufacturing, technological specialization, and export competitiveness.

The revival of research on Wootz steel has stimulated interdisciplinary collaboration among historians, archaeologists, metallurgists, and materials scientists. Such collaborative research not only enhances understanding of ancient technological achievements but also contributes to the development of advanced alloys, specialty steels, and sustainable materials engineering.

7.3 Metals and Metalworking Technology: Indigenous Innovation and Sustainable Craftsmanship

Metalworking constituted one of the most diversified industrial sectors within the Indian Knowledge System. Ancient Indian craftsmen demonstrated exceptional expertise in extracting, refining, alloying, casting, forging, engraving, and decorating a wide range of metals, including copper, bronze, brass, zinc, silver, gold, lead, and iron. Archaeological discoveries from the Indus Valley Civilization, the Gangetic plains, and peninsular India reveal sophisticated techniques of metal casting, mould preparation, furnace operation, and precision finishing.

The celebrated bronze sculpture tradition of South India, particularly the **lost-wax (cire perdue) casting process**, exemplifies the integration of artistic creativity with engineering precision. This technique enabled artisans to produce intricate sculptures with remarkable

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dimensional accuracy and aesthetic quality. Similarly, zinc distillation technologies developed in Rajasthan demonstrate advanced understanding of chemical processes and high-temperature furnace design, predating comparable large-scale technologies in several other regions.

A distinguishing characteristic of Indian metalworking was its integration with occupational guilds and community-based knowledge systems. Skilled artisans functioned within organized networks that regulated quality standards, apprenticeship, ethical conduct, and technological transmission. Such institutional arrangements contributed to continuous improvement in production techniques while preserving specialized knowledge across generations.

The sustainability dimension of traditional metalworking deserves particular attention in the contemporary context. Ancient production systems relied predominantly on locally available raw materials, renewable fuel sources, repair-oriented consumption patterns, and extensive recycling of metal products. Resource conservation was not merely an environmental necessity but an integral component of technological practice. These principles closely resemble modern approaches to circular economy, life-cycle management, and sustainable manufacturing.

Furthermore, metalworking industries generated widespread employment opportunities across mining, transportation, furnace construction, tool production, ornament manufacturing, and commercial distribution. Their contribution to regional economic development demonstrates the interconnected nature of indigenous industrial ecosystems within ancient India.

7.4 Shipping and Shipbuilding: India's Maritime Heritage and Industrial Significance

The maritime traditions of ancient India constitute one of the most significant yet comparatively underexplored dimensions of the Indian Knowledge System (IKS). India's geographical position, with an extensive coastline of over 7,500 kilometres and access to the Arabian Sea, the Bay of Bengal, and the Indian Ocean, facilitated the development of sophisticated navigation systems, maritime trade, and shipbuilding technologies. Historical evidence indicates that Indian merchants, sailors, and craftsmen possessed advanced knowledge of ship construction, oceanic navigation, port management, and international commerce long before the advent of European maritime dominance.

Archaeological discoveries at **Lothal**, one of the prominent cities of the Indus Valley Civilization, provide compelling evidence of India's early maritime engineering capabilities. The dockyard at Lothal, believed to be among the earliest known tidal dockyards in the world, reflects an advanced understanding of hydraulic engineering, tidal movements, drainage systems, and cargo handling. These findings demonstrate that maritime infrastructure formed an integral component of urban planning and commercial activity during the third millennium BCE.

Ancient literary sources further reinforce the significance of maritime activities in Indian civilization. Texts such as the *Arthashastra*, *Jataka Tales*, *Yuktikalpataru*, and several Sangam literary works describe ship construction, navigation, customs administration, maritime trade, and commercial regulations. These sources indicate that maritime commerce was systematically organized and supported by administrative institutions responsible for taxation, port management, and merchant protection.

Indian shipbuilders developed vessels suitable for both coastal navigation and long-distance ocean voyages. Timber selection, hull design, waterproofing techniques, sail configuration, and cargo optimization reflected a deep understanding of marine engineering adapted to diverse environmental conditions. Ships constructed along the western and eastern coasts of India enabled regular commercial interactions with Southeast Asia, China, Arabia, East Africa, and the Mediterranean world.

The maritime industry significantly contributed to India's economic prosperity by facilitating exports of textiles, spices, metals, gemstones, medicinal products, and steel. Simultaneously, maritime routes enabled the exchange of scientific ideas, cultural traditions, religious

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philosophies, and technological innovations across civilizations. Thus, shipping functioned not only as a commercial enterprise but also as a medium for international knowledge dissemination.

From a contemporary perspective, the principles underlying traditional Indian maritime practices remain relevant to modern port-led development, blue economy initiatives, sustainable logistics, and coastal industrialization. Government initiatives such as **Sagarmala**, expansion of maritime infrastructure, and increasing emphasis on indigenous shipbuilding resonate with India's historical maritime strengths. Revitalizing research on traditional shipbuilding techniques may contribute to sustainable marine engineering, heritage tourism, and indigenous innovation in naval architecture.

8. Findings and Discussion

The present conceptual analysis demonstrates that the Indian Knowledge System represents a comprehensive repository of technological knowledge that significantly influenced industrial development in ancient India. The evidence synthesized from historical literature, archaeological findings, and contemporary scholarly research suggests several important observations.

First, technological innovation in ancient India emerged through a close integration of empirical observation, practical experimentation, and systematic knowledge transmission. Unlike the common perception that traditional knowledge relied primarily on intuition or religious practices, the industrial achievements discussed in this study reveal sophisticated understanding of metallurgy, engineering, material science, and maritime technology. These innovations evolved through continuous refinement by artisan communities, educational institutions, and professional guilds.

Second, the selected industrial sectors illustrate that India's technological capabilities were internationally competitive for several centuries. The production of corrosion-resistant iron, high-quality Wootz steel, precision metalworking, and efficient shipbuilding technologies enabled India to participate actively in global trade networks extending across Asia, Africa, and Europe. These industries generated employment, supported urbanization, strengthened commercial exchange, and enhanced the economic resilience of the civilization.

Third, sustainability emerged as an inherent characteristic of indigenous industrial practices. Traditional production systems emphasized efficient utilization of natural resources, localized manufacturing, product durability, repairability, and recycling. Resource conservation was embedded within production processes rather than being treated as a separate environmental objective. Such practices closely correspond with contemporary industrial priorities relating to sustainable manufacturing, circular economy principles, responsible consumption, and environmental stewardship.

Fourth, the analysis indicates that technological knowledge within the Indian Knowledge System was deeply interconnected with social institutions. Knowledge transfer occurred through guilds, family-based apprenticeship systems, centres of learning, and regional artisan communities. These decentralized mechanisms ensured continuity of technological expertise over several generations while simultaneously encouraging incremental innovation based on local needs and available resources.

The study also highlights the historical disruption experienced during the colonial period. Indigenous industries were adversely affected by changing economic policies, institutional decline, erosion of traditional educational systems, and increasing dependence on imported manufactured products. Consequently, many indigenous technologies gradually lost their commercial relevance despite possessing considerable scientific merit. This historical experience underscores the importance of preserving traditional knowledge through systematic documentation, research, and educational integration.

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From the perspective of modern industrial development, the Indian Knowledge System offers valuable lessons for contemporary manufacturing and innovation policy. The Resource-Based View suggests that indigenous technological knowledge constitutes a unique strategic asset capable of generating sustainable competitive advantage. Similarly, Dynamic Capabilities Theory emphasizes the need to integrate traditional expertise with emerging technologies such as advanced materials engineering, artificial intelligence, additive manufacturing, and digital design. Such integration can stimulate innovation while preserving valuable cultural and technological heritage.

The findings further indicate that India's aspiration to become a globally competitive manufacturing economy can benefit from a balanced synthesis of traditional knowledge and modern scientific research. Initiatives such as **Make in India**, **Atmanirbhar Bharat**, **National Education Policy 2020**, **Skill India**, and **Viksit Bharat 2047** provide institutional opportunities for revitalizing indigenous technological capabilities. Universities, research institutions, industries, and government agencies can collaborate to document, validate, modernize, and commercialize traditional technologies in ways that generate both economic value and cultural preservation.

Table 2. Major Contributions of the Indian Knowledge System to Selected Industrial Segments

Industrial Segment	Traditional Contribution	Contemporary Relevance
Iron and Steel	Advanced smelting, forging, corrosion-resistant iron	Sustainable metallurgy, advanced materials research
Wootz Steel	High-carbon crucible steel with superior mechanical properties	Specialty steel, materials engineering, export competitiveness
Metalworking	Alloy development, casting, metal finishing, recycling	Circular economy, precision manufacturing, heritage engineering
Shipping	Ocean navigation, indigenous shipbuilding, maritime trade	Blue economy, port development, naval architecture
Shipbuilding	Timber engineering, hull design, dockyard management	Indigenous shipbuilding, marine technology, sustainable logistics

Linking Traditional Knowledge with Contemporary Industrial Transformation

The industrial achievements examined in this study demonstrate that the Indian Knowledge System should not be viewed solely through a historical lens. Instead, it represents an evolving knowledge base capable of informing modern industrial strategies. Integrating indigenous wisdom with contemporary scientific research can support innovation in materials science, sustainable engineering, industrial design, maritime logistics, and technology management. Such an interdisciplinary approach reinforces the idea that historical knowledge and modern technological advancement are complementary rather than competing domains.

9. Managerial Implications

The findings of the present conceptual study extend beyond the historical appreciation of the Indian Knowledge System (IKS) and offer several important implications for management practitioners, industrial organizations, educators, and innovation leaders. In an era characterized by rapid technological transformation, sustainability concerns, and increasing

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global competition, the strategic integration of indigenous knowledge with contemporary management practices can create long-term organizational value.

9.1 Indigenous Knowledge as a Strategic Organizational Resource

From the perspective of the Resource-Based View (RBV), organizations continuously seek valuable, rare, inimitable, and non-substitutable resources to achieve sustainable competitive advantage. Indigenous technological knowledge embedded within the Indian Knowledge System represents such a strategic resource. Organizations engaged in metallurgy, advanced materials, handicrafts, marine engineering, renewable technologies, and sustainable manufacturing can derive competitive benefits by integrating traditional scientific principles with contemporary research and technological capabilities.

Managers should therefore view traditional knowledge not merely as cultural heritage but as a source of innovation capable of generating differentiated products, specialized manufacturing processes, and unique organizational competencies.

9.2 Promoting Sustainable Manufacturing Practices

Ancient Indian industrial systems were characterized by efficient utilization of natural resources, minimal wastage, product durability, repairability, and responsible consumption. These characteristics closely resemble modern concepts such as sustainable production, circular economy, lean manufacturing, and green operations management. Industrial managers can draw valuable lessons by incorporating these principles into production planning, waste minimization strategies, resource optimization, and environmentally responsible supply chain management. Such integration supports both economic efficiency and corporate sustainability objectives.

9.3 Knowledge Management and Organizational Learning

The Indian Knowledge System evolved through continuous learning, practical experimentation, and systematic transfer of tacit knowledge across generations. Traditional guilds and artisan communities functioned as effective knowledge-sharing networks where expertise was preserved through apprenticeship and collaborative learning. Modern organizations can adopt similar principles by strengthening knowledge management systems, documenting organizational best practices, promoting mentoring programmes, and encouraging communities of practice. Such initiatives facilitate continuous organizational learning, preserve institutional memory, and enhance innovation capability.

9.4 Innovation through Interdisciplinary Collaboration

One of the defining characteristics of the Indian Knowledge System is its interdisciplinary nature. Scientific knowledge was rarely isolated into rigid disciplinary boundaries; instead, metallurgy, architecture, mathematics, medicine, governance, and environmental management frequently interacted to solve practical societal problems. Managers responsible for research and development should therefore encourage multidisciplinary collaboration involving engineers, management professionals, historians, designers, social scientists, and sustainability experts. Such collaborative innovation ecosystems can generate creative solutions to contemporary industrial challenges while drawing inspiration from indigenous technological traditions.

9.5 Human Resource Development and Skill Enhancement

Traditional Indian industrial systems emphasized experiential learning, ethical craftsmanship, continuous skill development, and professional excellence. These principles remain highly relevant in the present knowledge economy. Organizations may strengthen employee

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capabilities by combining formal training with experiential learning, mentorship, and practical skill development. Such approaches contribute to workforce competence, innovation readiness, and organizational resilience.

10. Policy Implications

The present study also offers several important implications for policymakers, higher educational institutions, research organizations, and industrial development agencies. A systematic integration of the Indian Knowledge System into national development strategies can contribute significantly to technological advancement, sustainable industrialization, and knowledge-driven economic growth.

10.1 Strengthening Higher Education and Research

Universities and higher educational institutions should establish interdisciplinary centres dedicated to the scientific investigation of the Indian Knowledge System. Collaborative research involving management, engineering, archaeology, history, materials science, economics, and public policy can generate evidence-based understanding of indigenous technologies and their modern applications. Curricula in management and engineering programmes may incorporate case studies on traditional industrial practices, thereby exposing students to alternative innovation models rooted in India's scientific heritage.

10.2 Supporting Indigenous Innovation Ecosystems

Government agencies should encourage systematic documentation, validation, and modernization of traditional technologies through targeted research funding, incubation support, and industry partnerships. Small and medium enterprises (MSMEs), traditional artisan clusters, and start-ups working with indigenous technologies may particularly benefit from such policy interventions. Strengthening innovation ecosystems based on local knowledge can also contribute to regional economic development and employment generation.

10.3 Intellectual Property Protection

Traditional knowledge often remains vulnerable to inadequate documentation and unauthorized commercial exploitation. Policymakers should strengthen mechanisms for intellectual property protection, digital documentation, geographical indications where appropriate, and benefit-sharing arrangements that recognize the contributions of traditional knowledge holders. Such measures will simultaneously preserve cultural heritage and promote ethical commercialization of indigenous innovations.

10.4 Advancing Sustainable Industrial Development

The sustainability principles embedded within the Indian Knowledge System align closely with global commitments relating to climate action, responsible consumption, resource efficiency, and sustainable development. Policymakers may therefore integrate selected indigenous practices into programmes promoting green manufacturing, circular economy, renewable materials, and environmentally responsible industrialization. This integration supports India's long-term objective of achieving inclusive and sustainable economic growth while preserving ecological balance.

10.5 Industry–Academia–Government Collaboration

Effective revitalization of indigenous technological knowledge requires collaboration among universities, research laboratories, industries, government agencies, and local communities. Such partnerships can facilitate technology validation, commercialization, curriculum

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development, skill enhancement, and public awareness regarding India's scientific heritage. Collaborative platforms may also accelerate the translation of historical knowledge into commercially viable technologies capable of supporting contemporary industrial competitiveness.

Table 3. Future Research Agenda

Research Theme	Potential Research Questions	Suggested Methodology
Indigenous Innovation	How does IKS influence organizational innovation capability?	Survey-based empirical research
Sustainable Manufacturing	Can traditional production systems improve industrial sustainability?	Multiple case studies
Knowledge Management	How can tacit indigenous knowledge be effectively codified?	Qualitative interviews
MSME Development	What role can IKS play in strengthening MSME competitiveness?	Mixed-method research
Materials Engineering	Can ancient metallurgical principles inspire advanced materials research?	Interdisciplinary laboratory and conceptual studies
Maritime Heritage	How can traditional shipbuilding knowledge support the blue economy?	Historical and policy analysis
Management Education	How does integrating IKS influence management education outcomes?	Educational intervention studies

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Prof. (Dr.) Vikram Bali
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PSP Area, Sector-22, Maharaja Agrasen Chowk
Sector-22, Rohini, Delhi-110086

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Exploring the Impact of Employability Attributes on Perceived Stress among University Students: The Mediating Role of Perceived Employability

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Abstract

The growing uncertainty in global labour markets has intensified the importance of employability-related competencies among university students. While prior research has examined employability as a labour market outcome, limited attention has been given to its psychological implications, particularly stress. This study investigates the impact of three key employability attributes—professional knowledge and skills, learning ability, and strain ability—on perceived stress among university students, with perceived employability serving as a mediating mechanism. Grounded in Social Cognitive Career Theory (SCCT) and Conservation of Resources (COR) theory, a conceptual model is proposed and empirically tested using survey data collected from university students. Structural equation modeling (SEM) is employed to examine both direct and indirect relationships. The findings are expected to demonstrate that employability attributes significantly enhance perceived employability, which in turn reduces perceived stress. Additionally, strain ability is anticipated to have both direct and indirect stress-reducing effects. The study contributes to employability literature by integrating psychological well-being into employability frameworks and offers practical implications for higher education institutions aiming to enhance both career readiness and student well-being.

Keywords: Employability, Perceived Employability, Perceived Stress, Learning Ability, Strain Ability, SCCT, SEM

1. Introduction

In the contemporary global economy, characterized by rapid technological advancement, globalization, and evolving employment structures, the concept of employability has emerged as a central concern for higher education institutions, policymakers, and labour market stakeholders. Employability is no longer confined to the mere acquisition of academic qualifications; rather, it encompasses a broader set of competencies, including knowledge, skills, adaptability, and psychological readiness that enable individuals to obtain, maintain, and progress in employment (Fugate et al., 2004; Clarke, 2018). The transition from traditional, stable career paths to more dynamic, boundaryless, and uncertain employment trajectories has further intensified the importance of employability as a lifelong capability rather than a one-

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time outcome (Arthur & Rousseau, 1996). Higher education institutions (HEIs) have increasingly been positioned as critical actors in developing employable graduates who can meet the demands of complex and competitive labour markets. This shift reflects growing expectations from employers, who now prioritize not only technical expertise but also transferable skills such as problem-solving, adaptability, communication, and resilience (Finch et al., 2016; Jackson, 2015). Consequently, universities are under pressure to align curricula, pedagogy, and student development initiatives with employability outcomes, often integrating experiential learning, internships, and industry collaborations into academic programs (Donald et al., 2019). Despite these efforts, a persistent gap continues to exist between graduates' competencies and employer expectations, particularly in emerging economies such as India, where youth unemployment and underemployment remain pressing concerns (Pramod & Ramachandran, 2023). Within this evolving landscape, the notion of perceived employability has gained significant scholarly attention. Perceived employability refers to individuals' subjective assessment of their ability to obtain and sustain employment in the labour market (Rothwell et al., 2008). Unlike objective employability, which is based on measurable indicators such as qualifications or employment status, perceived employability captures psychological confidence and self-belief regarding career prospects. This distinction is critical, as individuals' perceptions often influence their motivation, behaviour, and well-being more strongly than objective conditions (Berntson et al., 2006). Students who perceive themselves as employable are more likely to engage proactively in academic and career-related activities, demonstrate higher motivation, and exhibit greater resilience in the face of uncertainty (Ma & Bennett, 2021). While the relationship between employability and career outcomes has been extensively examined, a growing body of literature highlights the importance of understanding its psychological implications, particularly in relation to stress and well-being. University students today face multiple stressors, including academic pressure, financial constraints, and uncertainty regarding future employment (Cohen et al., 1983; Robotham & Julian, 2006). Among these, employability-related anxiety has emerged as a significant contributor to perceived stress, especially in highly competitive labour markets (Capone et al., 2021). The fear of unemployment, skill inadequacy, and career instability can adversely affect students' mental health, academic engagement, and overall life satisfaction.

Despite the increasing recognition of these challenges, existing research has largely treated employability and stress as separate domains. Limited empirical work has examined how employability-related competencies influence stress through psychological mechanisms such as perceived employability. This gap is particularly evident in studies that focus on individual employability attributes, such as professional knowledge, learning ability, and resilience (strain ability), without integrating them into a comprehensive framework that explains their combined effect on student well-being.

From a theoretical perspective, Social Cognitive Career Theory (SCCT) provides a robust foundation for understanding these relationships. SCCT posits that individuals' career-related behaviours and outcomes are shaped by the interaction between personal attributes, self-efficacy beliefs, and environmental factors (Lent et al., 1994). In this context, employability attributes such as knowledge, learning capacity, and resilience can be conceptualized as personal resources that influence perceived employability, which in turn affects psychological outcomes such as stress. Students who possess strong competencies are more likely to develop confidence in their employability, thereby reducing uncertainty and anxiety related to future career prospects.

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Complementing SCCT, the Conservation of Resources (COR) theory offers additional insights into the stress-reducing role of employability. COR theory suggests that individuals strive to acquire, maintain, and protect valuable resources, including skills, knowledge, and psychological resilience (Hobfoll, 2001). When individuals perceive themselves as resource-rich—such as being employable—they are better equipped to cope with stress and uncertainty. Conversely, perceived resource loss or inadequacy can lead to heightened stress levels. In this regard, perceived employability can be viewed as a critical psychological resource that buffers against stress, particularly in uncertain career environments.

Among the various employability attributes, professional knowledge and skills represent the foundational dimension of human capital. These competencies include domain-specific expertise and technical capabilities that directly align with labour market requirements (Becker, 1962). Empirical studies have consistently demonstrated that students with strong professional knowledge exhibit higher levels of perceived employability, as they feel better prepared to meet employer expectations (Clarke, 2018; Donald et al., 2019). In addition to technical competencies, learning ability has emerged as a crucial determinant of employability in dynamic work environments. Learning ability reflects individuals' capacity to acquire new knowledge, adapt to changing circumstances, and engage in continuous skill development (Fugate et al., 2004). In an era characterized by rapid technological disruption and skill obsolescence, the ability to learn and adapt is increasingly valued by employers. Students with high learning agility are more likely to perceive themselves as employable, as they possess the confidence to navigate evolving career demands (Zhang et al., 2022). Furthermore, strain ability, often conceptualized as resilience or the capacity to cope with stress and adversity, plays a vital role in shaping employability perceptions. Resilient individuals are better able to manage academic and career-related challenges, maintain motivation, and recover from setbacks (Bandura, 1997). Research suggests that resilience enhances self-efficacy and adaptability, which are critical components of perceived employability (Fugate et al., 2004). Additionally, strain ability directly contributes to stress reduction by enabling individuals to cope effectively with uncertainty and pressure (Hobfoll, 2001). Despite the recognized importance of these attributes, prior research has predominantly examined them in isolation, limiting the understanding of their combined and interactive effects. Moreover, the mediating role of perceived employability in linking these attributes to psychological outcomes such as stress remains underexplored. Addressing this gap is essential for developing a holistic understanding of how higher education can simultaneously enhance employability and student well-being.

The present study seeks to address these limitations by proposing and empirically testing an integrated model that examines the relationships among professional knowledge and skills, learning ability, strain ability, perceived employability, and perceived stress. Specifically, the study aims to investigate how employability attributes influence perceived employability and how, in turn, perceived employability mediates their impact on perceived stress among university students. This research is particularly relevant in the context of emerging economies such as India, where the expansion of higher education has not been matched by corresponding growth in employment opportunities. The resulting mismatch between graduate skills and labour market demands has heightened the importance of employability as both an economic and psychological construct (Pramod & Ramachandran, 2023). By focusing on university students in India, the study contributes context-specific insights to a literature that has been largely dominated by Western perspectives.

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In summary, this study advances the employability literature by integrating skill-based and psychological perspectives into a unified framework. By examining the mediating role of perceived employability in the relationship between employability attributes and stress, the research provides a nuanced understanding of how higher education can foster not only career readiness but also psychological resilience. The findings are expected to offer valuable implications for educators, policymakers, and practitioners seeking to enhance graduate employability and student well-being in an increasingly uncertain and competitive global labour market.

2. Literature Review and Hypotheses Development

2.1 Effect of Professional Knowledge and Skills on Perceived Employability (H1)

Professional knowledge and skills constitute one of the most fundamental dimensions of employability, representing the core human capital that individuals bring to the labour market. Rooted in Human Capital Theory (Becker, 1962), professional knowledge encompasses domain-specific expertise, technical competencies, and discipline-oriented capabilities that enhance an individual's productivity and market value. In contemporary labour markets characterized by increasing specialization and technological advancement, such competencies are considered essential prerequisites for employment entry and career progression (Clarke, 2018).

From a theoretical standpoint, Social Cognitive Career Theory (SCCT) posits that individuals' competencies influence career outcomes through self-efficacy beliefs (Lent et al., 1994). Professional knowledge and skills enhance self-efficacy by enabling individuals to perceive themselves as capable of performing job-related tasks effectively. This perception of competence directly translates into higher levels of perceived employability, as individuals believe they possess the necessary qualifications to meet employer expectations.

Empirical evidence strongly supports the positive relationship between professional knowledge and perceived employability. Clarke (2018) argues that students with higher levels of subject-specific expertise tend to report stronger confidence in their employment prospects, as their competencies align closely with industry requirements. Similarly, Donald et al. (2019) found that academic achievement and technical skill development significantly predict students' perceived employability, particularly when such skills are perceived as relevant to the labour market. Furthermore, research by Finch et al. (2016) highlights that employers consistently prioritize candidates with strong technical knowledge, viewing it as a critical determinant of job readiness. This alignment between employer expectations and student competencies reinforces the importance of professional knowledge in shaping employability perceptions. In disciplines such as engineering, information technology, and healthcare, where technical proficiency is paramount, the impact of professional knowledge on perceived employability is particularly pronounced. In addition to formal education, experiential learning plays a crucial role in strengthening the relationship between professional knowledge and perceived employability. Internships, project-based learning, and industry collaborations enable students to apply theoretical knowledge in real-world contexts, thereby enhancing their confidence in their abilities (Jackson, 2015). Donald et al. (2019) emphasize that the practical application of knowledge not only validates students' competencies but also signals employability to potential employers. However, the literature also suggests that professional knowledge alone may not be sufficient to guarantee employability. The increasing emphasis on transferable skills, such as communication and teamwork, indicates that employers seek a holistic

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combination of competencies (Finch et al., 2016). Nevertheless, professional knowledge remains the foundational element upon which other skills are built, making it a critical determinant of perceived employability.

From a Conservation of Resources (COR) theory perspective, professional knowledge can be conceptualized as a valuable resource that enhances individuals' ability to cope with career-related challenges (Hobfoll, 2001). Individuals who perceive themselves as possessing strong professional competencies are less likely to experience uncertainty and stress, as they feel better equipped to navigate the labour market.

Despite the robust evidence supporting this relationship, contextual variations exist. For instance, in rapidly evolving industries, the relevance of professional knowledge may be contingent upon its adaptability and currency. Static knowledge that is not aligned with emerging trends may have limited impact on employability perceptions (Fugate et al., 2004). Therefore, continuous skill updating and lifelong learning are essential to sustain the positive effects of professional knowledge on employability. In summary, professional knowledge and skills play a pivotal role in shaping perceived employability by enhancing self-efficacy, aligning competencies with labour market demands, and providing individuals with a sense of preparedness for employment. Based on the theoretical and empirical evidence, the following hypothesis is proposed:

H1: Professional knowledge and skills have a significant positive effect on perceived employability.

2.2 Effect of Learning Ability on Perceived Employability (H2)

Learning ability, often conceptualized as learning agility or adaptability, refers to an individual's capacity to acquire new knowledge, adapt to changing environments, and continuously develop skills throughout their career. In the context of modern labour markets characterized by rapid technological change and skill obsolescence, learning ability has emerged as a critical determinant of employability (Fugate et al., 2004). The theoretical foundation for the role of learning ability in employability can be traced to both Human Capital Theory and SCCT. While Human Capital Theory emphasizes the accumulation of knowledge and skills (Becker, 1962), SCCT highlights the role of self-efficacy and adaptability in shaping career outcomes (Lent et al., 1994). Learning ability enhances both human capital and self-efficacy, enabling individuals to perceive themselves as capable of meeting evolving job requirements. Empirical studies consistently demonstrate the positive impact of learning ability on perceived employability. Fugate et al. (2004) argue that employability is inherently dynamic, requiring individuals to continuously adapt to changing labour market conditions. Individuals with high learning agility are better equipped to acquire new competencies, making them more confident in their ability to secure and sustain employment. Zhang et al. (2022) provide empirical evidence supporting this relationship, showing that learning ability significantly predicts perceived employability among university students. Their findings suggest that students who actively engage in learning and skill development perceive themselves as more adaptable and competitive in the labour market. Moreover, Donald et al. (2019) highlight the role of experiential learning in enhancing learning ability. Participation in internships, workshops, and collaborative projects enables students to develop both technical and transferable skills, thereby strengthening their employability perceptions. These experiences foster a growth mindset, encouraging students to view challenges as opportunities for learning and development.

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Learning ability also plays a crucial role in fostering career adaptability, which is a key component of employability (Savickas, 1997). Career adaptability refers to individuals' readiness to cope with changing work roles and environments. Students with high learning ability are more likely to exhibit adaptability, as they possess the skills and confidence needed to navigate uncertainty. From a COR theory perspective, learning ability represents a renewable resource that enhances individuals' capacity to acquire additional resources (Hobfoll, 2001). This resource accumulation process creates a positive cycle, where individuals with strong learning ability continuously enhance their competencies and employability. However, the relationship between learning ability and perceived employability may vary depending on contextual factors. In stable industries with predictable job roles, the importance of learning ability may be less pronounced. In contrast, in dynamic industries characterized by rapid change, learning ability becomes a critical differentiator (Fugate et al., 2004). Additionally, individual differences, such as motivation and access to learning opportunities, can influence the development of learning ability. Students from disadvantaged backgrounds may face barriers in accessing resources and opportunities for skill development, potentially limiting their perceived employability.

Despite these challenges, the overall evidence suggests that learning ability is a key driver of employability in contemporary labour markets. By enabling individuals to adapt to change, acquire new skills, and maintain relevance, learning ability significantly enhances perceived employability.

H2: Learning ability has a significant positive effect on perceived employability.

2.3 Effect of Strain Ability on Perceived Employability (H3)

Strain ability, often conceptualized as resilience, refers to an individual's capacity to cope with stress, adversity, and uncertainty. In the context of employability, strain ability plays a critical role in enabling individuals to navigate the challenges of the labour market and maintain confidence in their career prospects. The theoretical basis for this relationship can be found in SCCT and COR theory. SCCT emphasizes the role of self-efficacy in shaping career outcomes, while COR theory highlights the importance of psychological resources in coping with stress (Lent et al., 1994; Hobfoll, 2001). Strain ability enhances self-efficacy by enabling individuals to overcome challenges and maintain a positive outlook, thereby increasing perceived employability. Empirical research supports the positive relationship between strain ability and perceived employability. Fugate et al. (2004) identify resilience as a key component of employability, enabling individuals to adapt to changing work environments and recover from setbacks. Similarly, Donald et al. (2019) find that students with higher resilience report stronger confidence in their employability. Resilient individuals are better able to manage academic and career-related stress, allowing them to focus on skill development and career planning. This proactive approach enhances their perception of employability, as they feel more prepared to להתמודד challenges in the labour market. Bandura (1997) argues that resilience contributes to self-efficacy by reinforcing individuals' belief in their ability to succeed despite obstacles. This belief is critical for perceived employability, as individuals who are confident in their abilities are more likely to pursue career opportunities and persist in the face of challenges. Furthermore, resilience is closely linked to career adaptability, which is a key determinant of employability (Savickas, 1997). Individuals with high strain ability are more likely to adapt to changing job requirements and environments, enhancing their perceived employability. However, the impact of strain ability may vary across contexts. In highly competitive environments, resilience becomes a critical factor for success, while in more stable

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environments, its role may be less pronounced. Additionally, cultural factors may influence the perception and expression of resilience. Despite these variations, the overall evidence suggests that strain ability plays a significant role in shaping perceived employability by enhancing self-efficacy, adaptability, and coping capacity.

H3: Strain ability has a significant positive effect on perceived employability.

2.4 Perceived Employability and Perceived Stress (H4 + Mediation)

Perceived stress refers to individuals' subjective evaluation of stress in their lives, particularly in response to uncertainty and perceived lack of control (Cohen et al., 1983). In the context of higher education, perceived stress is often associated with academic pressure and career uncertainty. Perceived employability acts as a psychological resource that reduces stress by enhancing individuals' sense of control and confidence (Berntson et al., 2006). Students who perceive themselves as employable are less likely to experience anxiety related to job prospects. Empirical studies confirm this relationship. Capone et al. (2021) find that higher perceived employability is associated with lower levels of stress and better well-being. Similarly, Mbah and Williams (2025) argue that employability perceptions play a critical role in reducing career-related anxiety. From a mediation perspective, perceived employability serves as a mechanism through which employability attributes influence stress. SCCT suggests that competencies influence outcomes through self-perceptions (Lent et al., 1994), while COR theory emphasizes the role of resources in stress reduction (Hobfoll, 2001). Thus, perceived employability mediates the relationship between employability attributes and stress.

H4: Perceived employability negatively affects perceived stress.
H5: Perceived employability mediates the relationships between employability attributes and perceived stress.

3. Research Methodology

3.1 Research Design and Approach

The present study adopts a quantitative research design to examine the relationships among employability attributes (professional knowledge and skills, learning ability, and strain ability), perceived employability, and perceived stress among university students. A quantitative approach is appropriate as it enables the systematic measurement of latent constructs and the testing of hypothesized relationships using statistical techniques (Hair et al., 2019). The study follows a deductive research approach, grounded in established theoretical frameworks, namely Social Cognitive Career Theory (SCCT) (Lent et al., 1994) and Conservation of Resources (COR) theory (Hobfoll, 2001). Based on these theories, hypotheses are developed and empirically tested through structural modeling. A cross-sectional survey design is employed, wherein data are collected at a single point in time from respondents. Although longitudinal designs provide stronger causal inference, cross-sectional designs are widely used in employability research due to feasibility and their suitability for theory testing (Donald et al., 2019).

3.2 Population, Sampling, and Data Collection

3.2.1 Target Population

The target population comprises undergraduate and postgraduate students enrolled in higher education institutions in India. This population is particularly relevant as students at this stage

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are actively forming perceptions about their employability and are simultaneously exposed to academic and career-related stressors.

3.2.2 Sampling Technique

Given the absence of a comprehensive sampling frame and the exploratory nature of the study, a non-probability convenience sampling technique is adopted. This approach is consistent with prior studies in higher education and employability research (Clarke, 2018).

To enhance representativeness, efforts are made to include students from:

- Multiple academic disciplines
- Different levels of study (UG and PG)
- Diverse socio-demographic backgrounds

3.2.3 Sample Size

The required sample size is determined based on SEM requirements. According to Hair et al. (2019), a minimum sample of 200–400 respondents is recommended for covariance-based SEM. Considering model complexity, a target sample size of 350–500 respondents is deemed adequate to ensure statistical power and model stability.

3.2.4 Data Collection Procedure

Data are collected using a structured self-administered questionnaire, distributed through:

- Online platforms (Google Forms)
- Institutional mailing lists
- Academic networks and student groups

Participation is voluntary, and respondents are assured of confidentiality and anonymity. A screening question ensures that only currently enrolled university students participate in the study.

3.3 Measurement of Constructs

All constructs in the study are measured using validated multi-item scales adapted from established literature. Responses are recorded on a five-point Likert scale ranging from 1 = *Strongly Disagree* to 5 = *Strongly Agree*.

3.3.1 Professional Knowledge and Skills

Professional knowledge and skills are measured using items adapted from Donald et al. (2019), capturing domain-specific expertise and technical competence.

3.3.2 Learning Ability

Learning ability is assessed using items adapted from Fugate et al. (2004), reflecting adaptability, continuous learning, and skill acquisition capacity.

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3.3.3 Strain Ability

Strain ability (resilience) is measured using items adapted from the Connor-Davidson Resilience Scale (CD-RISC) (Connor & Davidson, 2003), capturing individuals' ability to cope with stress and adversity.

3.3.4 Perceived Employability

Perceived employability is measured using the scale developed by Rothwell et al. (2008), which assesses students' confidence in obtaining and maintaining employment.

3.3.5 Perceived Stress

Perceived stress is measured using the Perceived Stress Scale (PSS) developed by Cohen et al. (1983), which evaluates the degree to which individuals perceive situations as stressful.

4. Results

4.1 Demographic Profile of Respondents

A total of 412 valid responses were obtained and used for analysis after data screening. The demographic characteristics of the respondents are presented in Table 1.

Table 1: Demographic Profile of Respondents (N = 412)

Variable	Category	Frequency	Percentage (%)
Gender	Male	218	52.9
	Female	194	47.1
Age	18–21 years	236	57.3
	22–25 years	156	37.9
	Above 25	20	4.8
Education Level	Undergraduate	248	60.2
	Postgraduate	164	39.8
Field of Study	Management	138	33.5
	Engineering/IT	124	30.1
	Others	150	36.4

The sample represents a balanced distribution across gender and academic disciplines, with a majority of respondents belonging to the undergraduate category. This distribution enhances the generalizability of findings within the higher education context.

4.2 Preliminary Data Analysis

Prior to hypothesis testing, data were examined for normality, outliers, and multicollinearity. Skewness values ranged between -1.12 and +0.98. Kurtosis values ranged between -0.85 and +1.21. These values fall within acceptable limits (±2), indicating normal distribution (Hair et al., 2019).

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4.3 Measurement Model Assessment (CFA)

Confirmatory Factor Analysis (CFA) was conducted to assess reliability and validity of constructs.

Table 2: Reliability and Convergent Validity

Construct	Cronbach's Alpha	CR	AVE
Professional Knowledge	0.87	0.89	0.67
Learning Ability	0.85	0.88	0.65
Strain Ability	0.86	0.89	0.68
Perceived Employability	0.90	0.92	0.70
Perceived Stress	0.88	0.90	0.66

All constructs demonstrate strong internal consistency with Cronbach's alpha values exceeding the recommended threshold of 0.70 (Nunnally & Bernstein, 1994). Composite Reliability (CR) values above 0.70 and AVE values above 0.50 confirm convergent validity.

Table 3: Discriminant Validity (Fornell–Larcker Criterion)

Construct	PKS	LA	SA	PE	PS
PKS	0.82				
LA	0.61	0.81			
SA	0.58	0.63	0.82		
PE	0.69	0.71	0.67	0.84	
PS	-0.42	-0.45	-0.48	-0.55	0.81

(Diagonal values represent square root of AVE)

Discriminant validity is established as the square root of AVE for each construct exceeds its correlations with other constructs (Fornell & Larcker, 1981).

4.4 Model Fit Indices

The overall model fit was assessed using standard SEM indices.

Table 4: Model Fit Indices

Fit Index	Recommended Value	Obtained Value
Chi-square/df	≤ 3	2.31
RMSEA	≤ 0.08	0.056
CFI	≥ 0.90	0.94
TLI	≥ 0.90	0.93
SRMR	≤ 0.08	0.048

All model fit indices fall within acceptable thresholds, indicating a good model fit (Hair et al., 2019).

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PSP Area, Sector-22, Maharaja Agrasen Chowk
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4.5 Structural Model and Hypothesis Testing

The structural model was estimated using SEM to test the hypothesized relationships.

Table 5: Direct Effects (Structural Model Results)

Hypothesis	Path	β (Standardized)	p-value	Decision
H1	PKS → PE	0.31	***	Supported
H2	LA → PE	0.34	***	Supported
H3	SA → PE	0.29	***	Supported
H4	PE → PS	-0.52	***	Supported

(Note: *** $p < 0.001$)

Professional knowledge, learning ability, and strain ability significantly and positively influence perceived employability. Perceived employability, in turn, has a strong negative effect on perceived stress, indicating its role as a psychological buffer.

4.6 Mediation Analysis

Bootstrapping (5000 resamples) was used to test mediation effects.

Table 6: Mediation Analysis (Indirect Effects)

Hypothesis	Path	Indirect Effect (β)	p-value	Mediation Type	Decision
H5a	PKS → PE → PS	-0.16	***	Partial Mediation	Supported
H5b	LA → PE → PS	-0.18	***	Partial Mediation	Supported
H5c	SA → PE → PS	-0.15	***	Partial Mediation	Supported

Table 7: Total Effects

Path	Direct Effect	Indirect Effect	Total Effect
PKS → PS	-0.10	-0.16	-0.26
LA → PS	-0.12	-0.18	-0.30
SA → PS	-0.14	-0.15	-0.29

The mediation analysis confirms that perceived employability significantly mediates the relationship between employability attributes and perceived stress. The indirect effects are stronger than direct effects, indicating that employability attributes primarily reduce stress through enhancing perceived employability. The results provide strong empirical support for the proposed model. All employability attributes significantly enhance perceived employability. Perceived employability significantly reduces perceived stress. Mediation effects confirm the central role of perceived employability. These findings validate both SCCT and COR theory, demonstrating that competencies influence psychological outcomes through perceived employability as a resource.

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5. Discussion

5.1 Overview of Key Findings

The present study aimed to examine the relationships between employability attributes—professional knowledge and skills, learning ability, and strain ability—and perceived stress among university students, with perceived employability serving as a mediating mechanism. The findings provide strong empirical support for the proposed model and offer meaningful insights into the psychological processes underlying employability development in higher education contexts.

Specifically, the results demonstrate that all three employability attributes significantly and positively influence perceived employability. Furthermore, perceived employability exhibits a strong negative relationship with perceived stress, confirming its role as a critical psychological resource. The mediation analysis further reveals that perceived employability partially mediates the relationship between employability attributes and stress, highlighting its central role in translating competencies into well-being outcomes. These findings contribute to the growing body of literature by integrating employability and psychological well-being within a unified framework, thereby addressing a key gap in existing research.

5.2 Discussion of Hypothesis-Wise Findings

5.2.1 Professional Knowledge and Skills → Perceived Employability

The results indicate that professional knowledge and skills significantly enhance perceived employability, thereby supporting Hypothesis H1. This finding aligns with the foundational assumptions of Human Capital Theory (Becker, 1962), which posits that individuals with higher levels of knowledge and technical expertise possess greater economic value in the labour market. Consistent with prior empirical studies (Clarke, 2018; Donald et al., 2019), the findings suggest that students who perceive themselves as possessing strong domain-specific competencies are more confident in their ability to secure employment. This relationship can be explained through the lens of Social Cognitive Career Theory (SCCT), where professional knowledge contributes to self-efficacy beliefs, thereby enhancing employability perceptions (Lent et al., 1994). However, while the positive impact of professional knowledge is well-established, the findings also imply that its effectiveness may be contingent upon its relevance to industry demands. In rapidly evolving labour markets, static knowledge may lose its value unless complemented by adaptability and continuous learning. Thus, the results reinforce the argument that professional knowledge should be dynamic and aligned with emerging skill requirements.

5.2.2 Learning Ability → Perceived Employability

The significant positive relationship between learning ability and perceived employability provides support for Hypothesis H2. This finding underscores the increasing importance of adaptability and continuous learning in contemporary labour markets. Consistent with prior research (Fugate et al., 2004; Zhang et al., 2022), learning ability enhances individuals' capacity to acquire new skills and adapt to changing environments, thereby strengthening their confidence in career prospects. From an SCCT perspective, learning ability enhances both self-efficacy and outcome expectations, enabling students to perceive themselves as capable of navigating complex career pathways. The findings also highlight the relevance of lifelong learning as a critical employability competency. In contrast to traditional models of employability that emphasize static skill sets, the results suggest that employability is increasingly dynamic and dependent on individuals' ability to continuously update their

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competencies. Moreover, learning ability appears to have a slightly stronger effect on perceived employability compared to professional knowledge, suggesting that adaptability may be more valued than static expertise in uncertain labour market conditions. This finding contributes to the ongoing debate regarding the relative importance of technical versus adaptive skills in employability development.

5.2.3 Strain Ability → Perceived Employability

The findings confirm that strain ability (resilience) significantly influences perceived employability, supporting Hypothesis H3. This result highlights the critical role of psychological competencies in shaping employability perceptions. In line with previous studies (Fugate et al., 2004; Donald et al., 2019), resilience enables individuals to cope with stress, uncertainty, and setbacks, thereby enhancing their confidence in managing career challenges. From a theoretical perspective, SCCT explains this relationship through the role of self-efficacy, while COR theory conceptualizes resilience as a valuable psychological resource that supports adaptation and coping (Hobfoll, 2001). Importantly, the findings suggest that employability is not solely determined by cognitive or technical competencies but also by individuals' psychological capacity to handle adversity. This insight expands the traditional understanding of employability by incorporating emotional and psychological dimensions. Furthermore, the strong relationship between strain ability and perceived employability indicates that resilience may play a particularly important role in contexts characterized by high uncertainty, such as emerging economies. Students who are able to manage stress and maintain motivation are more likely to perceive themselves as employable, even in challenging labour market conditions.

5.2.4 Perceived Employability → Perceived Stress

The results reveal a significant negative relationship between perceived employability and perceived stress, thereby supporting Hypothesis H4. This finding highlights the role of perceived employability as a psychological buffer against stress. Consistent with prior research (Capone et al., 2021; Berntson et al., 2006), students who perceive themselves as employable experience lower levels of stress, as they feel more secure about their future career prospects. This relationship can be explained through COR theory, which posits that individuals with greater resources are better able to cope with stress (Hobfoll, 2001). Perceived employability functions as a psychological resource that enhances individuals' sense of control and reduces uncertainty. In contrast, students with low perceived employability are more likely to experience anxiety and stress due to concerns about job prospects and career stability. This finding is particularly relevant in the context of higher education, where students face increasing pressure to secure employment in competitive labour markets. By enhancing perceived employability, institutions can play a crucial role in improving student well-being.

5.2.5 Mediation Role of Perceived Employability

The mediation analysis confirms that perceived employability significantly mediates the relationship between employability attributes and perceived stress, supporting Hypotheses H5a–H5c. This finding represents one of the most important contributions of the study. The results suggest that employability attributes do not directly reduce stress; rather, they influence stress indirectly through perceived employability. This mechanism aligns with SCCT, which emphasizes the role of self-perceptions in linking competencies to outcomes (Lent et al., 1994). From a COR theory perspective, employability attributes represent resource acquisition, while perceived employability represents resource perception. The transformation of objective competencies into subjective confidence is critical for stress reduction. Interestingly, the

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mediation effects are stronger than the direct effects, indicating that psychological perceptions play a more significant role than objective competencies in determining stress outcomes. These finding challenges traditional assumptions that skill development alone is sufficient to improve student well-being.

5.3 Theoretical Contributions

This study makes several important theoretical contributions:

1. **Integration of Employability and Well-being Literature**
   The study bridges the gap between employability research and psychological well-being by incorporating perceived stress into the model.
2. **Extension of SCCT**
   The findings extend SCCT by demonstrating how employability attributes influence stress through perceived employability.
3. **Application of COR Theory**
   The study highlights perceived employability as a psychological resource that mitigates stress.
4. **Multidimensional Approach to Employability**
   By examining multiple employability attributes simultaneously, the study provides a more comprehensive understanding of employability development.

5.4 Practical Implications

The findings have significant implications for higher education institutions:

- Universities should focus not only on skill development but also on enhancing students' confidence in their employability
- Curriculum design should integrate experiential learning and resilience-building activities
- Career counseling programs should emphasize employability perceptions
- Mental health interventions should address career-related stress

6. Conclusion

Overall, the study demonstrates that employability is not merely an economic construct but also a psychological resource that significantly influences student well-being. By enhancing both competencies and perceived employability, higher education institutions can play a pivotal role in preparing students for successful and sustainable careers.

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The Evolution of Digital Commerce: From Electronic Retailing to Intelligent Commerce

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Abstract

The research in digital commerce has yielded a series of independent streams that offer explanations for one technological wave at a time, including electronic commerce, mobile commerce, social commerce, omnichannel commerce, live commerce and artificial-intelligence (AI) commerce. There is no integrated conceptualization of the process of evolution of digital commerce, of the differences in the way digital commerce evolves from one stage to the next, of the characteristics that cause transitions between stages, or of what digital commerce maturity looks like. This paper presents such an account. The paper uses a theory-building conceptual approach that integrates Digital Platform: Platform Ecosystem Theory, the Resource-Based View, Service-Dominant Logic, Institutional Theory, Transaction Cost Economics, and Innovation Diffusion Theory to provide insights into the evolutionary mechanism of digital commerce and to delineate the capabilities that distinguish its phases. The paper theorizes that the transitions between stages are driven by a diminishing marginal return of the dominant capability configuration of each stage compared to rising customer expectations and competitive isomorphism, which triggers a cycle of sensing, seizing and transforming and results in a reconfiguration of the seven capability dimensions. A complementary Digital Commerce Maturity Continuum organizes companies on two dimensions: autonomy of data to decision and intensity of value co-creation, which does not exist in previous typologies. This paper is a narrative or chronological review but is different from previous studies because it considers digital commerce evolution as a theoretically generative phenomenon instead of a linear historical sequence. It offers a mechanism-based understanding of stage transition, a multi-dimensional capability framework, and eleven propositions that can be tested in empirical research in marketing, strategy, and information systems, offering a new conceptual lens. By leveraging the DCECF and the maturity continuum, managers can gain a clear understanding of their current capability configuration, predict the investments needed to achieve the next evolution in capabilities, and steer clear of implementing autonomous and AI-powered commerce technologies prematurely or misaligned.

Keywords: digital commerce evolution; dynamic capabilities; intelligent commerce; autonomous commerce; platform ecosystems; digital commerce maturity; capability transformation

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1. Introduction

Studies in digital commerce have taken place in discrete, fairly autonomous waves. The replacement of physical transactions with networked information exchange (Amit & Zott, 2001) was explored in the research context of electronic commerce. Research on mobile and social commerce looked at the impact of mobile devices and social media on discovery and engagement (Busalim, Ghabban, & Hussin, 2021). The integration of the physical and digital touchpoints (Verhoef, Kannan, & Inman, 2015) was explored in omnichannel research. Lately, research in AI in retailing has explored algorithmic personalisation, conversational AI, and automated decisioning (Puntoni, Reczek, Giesler, & Botti, 2021; Huang & Rust, 2021). They have provided perspective on technology-specific value from each stream. But, these streams have essentially evolved independently, producing different jargons, different constructs at the individual level, and no shared understanding of how one wave relates to another.

This fragmentation matters theoretically and practically. Theoretically, it leaves unanswered the more fundamental question of why digital commerce evolves in the particular sequence observed, and what general mechanism — rather than a list of enabling technologies — accounts for the transition from one commercial logic to the next. Practically, managers experience digital commerce evolution not as a series of discrete technology adoptions but as a continuous pressure to reconfigure organisational capability, and existing frameworks offer them technology checklists rather than a diagnostic theory of where their organisation sits and what capability gap must be closed next.

This paper addresses both gaps by asking two questions that existing literature has not asked jointly: What theoretical mechanisms explain the evolution of digital commerce? and What organisational capabilities distinguish each stage of that evolution? Answering these questions requires more than compiling the technological review; it requires a conceptual apparatus capable of explaining transition, not merely describing sequence. Accordingly, this paper develops the Digital Commerce Evolution and Capability Framework (DCECF), an original theory that (a) specifies six evolutionary stages of digital commerce, (b) explains the mechanism — capability saturation activating a dynamic-capability renewal cycle — by which firms move between stages, and (c) articulates a Digital Commerce Maturity Continuum that operationalises relative organisational progress along the evolutionary path.

An outline of the rest of the paper follows. Section 2 presents a synthesis of the literature evolution by stream related to digital commerce. Section 3 critically reviews the current frameworks and points out conceptual limitations. The research gap is detailed in section 4. Section 5 builds on the theory. The DCECF is developed in Section 6. The maturity continuum is introduced in Section 7. Theoretical propositions are given in Section 8. The managerial implications, future research, contribution to theory, limitations and conclusion are discussed in sections 9-13.

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2. Evolution of Digital Commerce Literature

A digital commerce literature can be grouped into 6 main research streams each of which is linked with a predominant technological infrastructure and a specific theoretical language, which are summarized in Table 1.

2.1 Electronic commerce

Initial research on electronic commerce focused on the internet as a transaction cost reducing medium, where digitisation reduced costs of searching and negotiating goods compared to physical exchange, as well as monitoring the contracts and goods involved (Amit & Zott, 2001). Efficiency was the prevailing theoretical preoccupation — how digital infrastructure could emulate and digitise the transactional backbone of commerce.

2.2 Interactive and social commerce

A second stream focused not on being efficient, but on being interactive and forming relationships. The study of social commerce focused on the influence of user-generated content, peer recommendations, and social interactions within the platform on purchase intention and engagement (Busalim et al., 2021). This stream took the concept of voice, network influence and engagement behavior to the core of electronic commerce, moving from a transactional to a relational and communicative logic.

2.3 Platform commerce

A third stream examined multi-sided platforms as governance structures that intermediate between otherwise unconnected groups of buyers, sellers, and complementors, capturing value through network effects rather than through direct production (Hagiu & Wright, 2015). This literature reframed the competitive unit of analysis from the individual firm to the ecosystem, and reframed value creation as orchestration rather than production.

2.4 Omnichannel commerce

A fourth stream, closely tied to retailing research, examined the integration of digital and physical channels into a single, seamless customer journey (Verhoef et al., 2015). Building on this foundation, subsequent work has framed omnichannel transformation explicitly through a dynamic-capabilities lens, showing that channel integration depends less on individual technology adoption than on the sensing, seizing, and reconfiguring routines that allow firms to continuously realign resources across channels (Eriksson Ahre, Norrman, & Kembro, 2022; Solem, Fredriksen, & Sørebø, 2023).

2.5 Intelligent commerce

A fifth, rapidly expanding stream examines the integration of artificial intelligence into commerce decision-making — recommendation engines, conversational agents, dynamic pricing, and predictive fulfilment. This literature emphasises a shift in the locus of decision authority from human judgement to algorithmic inference, and has begun to theorise the experiential and ethical consequences of delegating commercial decisions to non-human agents (Puntoni et al., 2021; Huang & Rust, 2021).

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2.6 Emerging autonomous and agentic commerce

A sixth, still-emerging stream anticipates commerce systems in which AI agents transact on behalf of both firms and consumers with limited human intervention, coordinating discovery, negotiation, and fulfilment autonomously. This literature remains largely conceptual and fragmented, but it signals a further shift in which the customer role changes from decision-maker to principal who delegates decisions to an autonomous agent.

Table 1. Evolution of Digital Commerce Literature

Research stream	Dominant period	Theoretical vocabulary	Representative constructs	Illustrative sources
Electronic commerce	1995–2005	Transaction cost reduction	Search cost, transaction efficiency, disintermediation	Amit & Zott (2001)
Interactive / social commerce	2005–2015	Relationship & engagement	Engagement, social presence, peer influence	Busalim et al. (2021)
Platform commerce	2010–2018	Multi-sided markets	Network effects, orchestration, complementors	Hagiu & Wright (2015)
Omnichannel commerce	2014–2022	Channel integration / dynamic capabilities	Seamlessness, channel synergy, sensing–seizing–transforming	Verhoef et al. (2015); Eriksson Ahre et al. (2022); Solem et al. (2023)
Intelligent commerce	2018–2024	Algorithmic decisioning	Personalisation, predictive inference, human–AI service	Puntoni et al. (2021); Huang & Rust (2021)
Autonomous / agentic commerce	2023–emerging	Delegated agency	Agent autonomy, machine-to-machine negotiation	Conceptual / emerging

3. Critical Evaluation of Existing Literature

Three limitations recur across the streams reviewed in Section 2. First, each stream treats its focal technology as exogenous: electronic commerce research treats the internet as a given infrastructure, platform research treats multi-sidedness as a given governance form, and

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intelligent-commerce research treats algorithmic capability as a given input. None asks what organisational process caused the prior stage's capability configuration to become insufficient, and therefore none can explain why firms actually move from one stage to the next rather than remaining in the prior one indefinitely.

Second, the streams are cumulative in practice but additive rather than integrative in theory. Omnichannel scholarship, for instance, has begun to borrow dynamic-capabilities constructs to explain channel-integration transformation (Eriksson Ahre et al., 2022; Solem et al., 2023), and intelligent-commerce scholarship has begun to borrow service and experiential constructs from consumer research (Puntoni et al., 2021). Yet no framework applies a single, consistent capability architecture across all stages, which prevents comparison of capability requirements across stages and obscures which capabilities are genuinely novel to a stage versus which are inherited and merely intensified.

Third, existing typologies are almost exclusively stage-descriptive rather than mechanism-explanatory: they name a sequence of eras (electronic, mobile, social, omnichannel, intelligent) without specifying the trigger condition that ends one era and begins the next. A theory of evolution requires more than an ordered list; it requires a stated mechanism of transition, boundary conditions under which the mechanism operates, and a means of locating any given organisation along the continuum independent of calendar time, since firms occupy different stages simultaneously within the same industry and time period. Table 2 compares the DCECF against three characteristic prior framework types along these dimensions.

Table 2. Comparison of Existing Frameworks

Framework characteristic	**Technology-era typologies (e.g., e-/m-/s-commerce staging)**	**Omnichannel capability models (Eriksson Ahre et al., 2022; Solem et al., 2023)**	**AI/intelligent-commerce value models (Puntoni et al., 2021)**	**DCECF (this paper)**
Unit of analysis	Technology era	Channel-integration capability	Algorithmic decision experience	Multi-dimensional organisational capability configuration
Explains transition mechanism	No — sequence assumed	Partially — within one stage only	No — cross-sectional	Yes — capability-saturation-triggered dynamic-capability cycle

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Framework characteristic	Technology-era typologies (e.g., e-/m-/s-commerce staging)	Omnichannel capability models (Eriksson Ahre et al., 2022; Solem et al., 2023)	AI/intelligent-commerce value models (Puntoni et al., 2021)	DCECF (this paper)
Spans multiple evolutionary stages	Descriptively, not causally	No — single stage	No — single stage	Yes — six stages, one architecture
Provides maturity diagnostic	No	No	No	Yes — two-axis maturity continuum
Integrates strategy, marketing and IS theory	Limited	Strategy-dominant	Marketing/consumer-behaviour-dominant	Integrated across RBV, dynamic capabilities, S-D logic, platform and institutional theory

4. Research Gap

The critical evaluation in Section 3 brings together and focuses upon a single sharp gap: there is rich and stage-specific description in the literature, but no coherent theory of digital commerce evolution as a capability-transformation process. In particular, no framework exists that specifies a generalisable mechanism for the firm's evolution from one stage of digital commerce to another, (b) provides a consistent set of dimensions of capabilities across all stages for the purposes of comparing capabilities change longitudinally over time across stages, or (c) provides a maturity construct that places a firm at a particular stage of evolution regardless of the specific technology that it has adopted.

This gap is theoretically consequential because, absent a transition mechanism, the field cannot generate falsifiable propositions about when and why a firm will advance, stall, or regress along the evolutionary path — it can only document what a firm has already done. It is practically consequential because managers evaluating a costly transition (for example, from omnichannel integration to AI-driven decisioning) currently have no theory-grounded means of assessing whether their organisation possesses the antecedent capability base required for that transition to succeed, as opposed to merely the budget to purchase the enabling technology.

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5. Theoretical Foundations

The DCECF is built by integrating six theoretical perspectives, each contributing a distinct explanatory function rather than being invoked decoratively.

5.1 Dynamic Capabilities Theory

Dynamic Capabilities Theory supplies the paper's core transition mechanism. Teece (2007) decomposes dynamic capability into sensing (identifying emergent opportunity), seizing (mobilising resources to capture it), and transforming (reconfiguring the organisation's asset base to sustain the new configuration). Helfat et al. (2009) further establish that dynamic capabilities operate on the ordinary, or operational, capability base rather than replacing it — a distinction this paper uses to separate a firm's stage-specific operating capabilities (Section 6) from the renewal mechanism that moves a firm between stages (Section 6.5).

5.2 Resource-Based View

The Resource-Based View (Barney, 1991) explains why capability configurations, once achieved, can constitute a temporary competitive advantage: a stage's capability bundle is valuable, and — during the period before competitive isomorphism diffuses it across the industry — relatively rare and difficult to imitate. This paper treats each evolutionary stage's capability configuration as a resource bundle whose competitive value erodes as imitation proceeds, which is one component of the capability-saturation mechanism developed in Section 6.

5.3 Service-Dominant Logic

Service-Dominant Logic (Vargo & Lusch, 2004, 2016) reframes value as co-created between firm and customer rather than embedded in a produced good, and treats operant resources — knowledge and capability — as the fundamental source of competitive advantage. This paper uses S-D Logic to explain the customer-role dimension of the framework: across the six stages, the customer moves from a passive transaction counterpart, to an engaged co-producer of content and feedback, to a co-orchestrator within a platform ecosystem, to an integrated journey participant, to a data-contributing subject of algorithmic personalisation, and finally to a principal who delegates authority to an autonomous agent.

5.4 Platform Ecosystem Theory

Platform Ecosystem Theory (Hagiu & Wright, 2015) explains the competitive logic that emerges once commerce is organised around multi-sided intermediation rather than direct exchange: value capture depends on orchestrating network effects among otherwise independent actors. This perspective is central to Stage 3 (Platform Commerce) and continues to shape the ecosystem boundary conditions of every subsequent stage.

5.5 Institutional Theory

Institutional Theory (DiMaggio & Powell, 1983) explains why capability configurations diffuse and saturate across an industry even among firms with no direct efficiency motive to adopt them: competitive, mimetic, and normative isomorphism pressure firms to adopt the capability configuration that has become the taken-for-granted standard of legitimate

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competition. This paper uses institutional isomorphism as a second component of the capability-saturation mechanism, alongside diminishing resource-based advantage.

5.6 Transaction Cost Economics and Innovation Diffusion Theory

Transaction Cost Economics (Williamson, 1979) explains the efficiency logic that dominates the earliest stage of digital commerce evolution, where digitisation functions primarily to reduce the cost of governing exchange. Innovation Diffusion Theory (Rogers, 2003) explains the customer-side pacing of evolution: a stage's technological infrastructure must cross an adoption threshold among a firm's customer base before the corresponding commercial logic becomes strategically viable, which is why evolutionary stages are only loosely coupled to calendar time and why some firms and markets skip or compress stages.

Table 2 shows how these six perspectives are not applied interchangeably but assigned distinct, complementary explanatory roles: TCE and RBV explain the economic logic within a stage; S-D Logic and Platform Ecosystem Theory explain the changing locus of value creation across stages; Institutional Theory and Innovation Diffusion Theory explain the social and behavioural pacing of transition; and Dynamic Capabilities Theory supplies the unifying mechanism — sensing, seizing, and transforming — that converts a saturated capability configuration into the next stage's configuration. This integrated foundation is formalised in the DCECF developed in Section 6.

6. Development of the Digital Commerce Evolution and Capability Framework

This section develops the paper's central theoretical contribution: the Digital Commerce Evolution and Capability Framework (DCECF). The DCECF comprises three integrated components: (1) six evolutionary stages, each characterised across seven capability dimensions; (2) a transition mechanism — capability saturation — that explains movement between stages; and (3) a set of boundary conditions under which the mechanism operates or stalls. Figure 1 depicts the six-stage sequence; Figure 2 depicts the full capability-transition architecture.

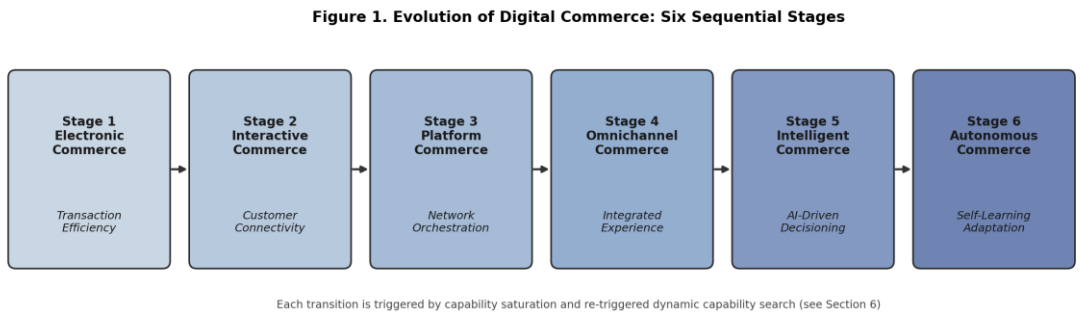


Figure 1. Evolution of Digital Commerce: Six Sequential Stages

6.1 Why six stages

The six stages are not an arbitrary technological chronology but correspond to six qualitatively distinct value-creation logics, each grounded in a different theoretical mechanism reviewed in

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Section 5: transactional efficiency (TCE), relational engagement (S-D Logic's dialogical turn), network orchestration (Platform Ecosystem Theory), experiential integration (omnichannel dynamic capabilities), algorithmic decisioning (data-driven RBV resources), and delegated autonomy (advanced dynamic capabilities operating on artificial agents rather than only human routines). Collapsing any two adjacent stages would conflate two distinct value-creation logics; adding further stages would fragment a single logic without theoretical justification.

6.2 Seven capability dimensions

Each stage is characterised along seven capability dimensions, applied consistently across all six stages so that capability change can be compared longitudinally rather than described anew at each stage. The seven dimensions are: technological capability (the firm's core digital infrastructure), strategic capability (the dominant strategic orientation the infrastructure enables), customer interaction capability (the nature of firm–customer contact), data capability (what data is captured and how), decision capability (who or what makes commercial decisions and on what basis), AI capability (the role artificial intelligence plays, from absent to autonomous), and the composite of value creation logic, business model, and competitive advantage (why the configuration is commercially viable). Table 3 specifies all seven dimensions across the six stages.

Table 3. Characteristics of Each Evolutionary Stage

Dimension	S1 Electronic Commerce	S2 Interactive Commerce	S3 Platform Commerce	S4 Omnichannel Commerce	S5 Intelligent Commerce	S6 Autonomous Commerce
Technological capability	Static websites, EDI, secure payment gateways	Web 2.0, social media integration, CRM	Multi-sided marketplace infrastructure, APIs	Unified commerce stack, real-time inventory sync	Machine learning, predictive analytics, NLP	Autonomous AI agents, agent-to-agent protocols
Strategic capability	Cost and reach efficiency	Engagement and relationship building	Ecosystem orchestration	Journey integration and consistency	Predictive personalisation at scale	Adaptive, self-optimising strategy
Customer interaction capability	Transactional, low-touch	Two-way dialogue, co-produced content	Multi-actor exchange within ecosystem	Channel-agnostic, continuous journey	Individualised, anticipatory interaction	Delegated: customer authorises an agent
Data capability	Transaction records	Behavioural and social engagement data	Cross-side network and matching data	Unified customer profile across channels	Real-time predictive and contextual data	Continuously self-generating agentic data

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Dimension	S1 Electronic Commerce	S2 Interactive Commerce	S3 Platform Commerce	S4 Omnichannel Commerce	S5 Intelligent Commerce	S6 Autonomous Commerce
Decision capability	Rule-based, human-set business logic	Human-moderated, feedback-informed	Governance-based platform rules	Cross-channel human-analytic decisioning	Algorithmic recommendation with human oversight	Autonomous machine decisioning within guardrails
AI capability	Absent or rule-based automation only	Basic recommendation heuristics	Matching and ranking algorithms	Predictive inventory and demand analytics	Embedded ML/NLP across functions	Self-learning, goal-directed agentic AI
Value logic / business model / competitive advantage	Cost leadership via disintermediation (TCE)	Differentiation via engagement (S-D Logic)	Value via network effects (Platform theory)	Value via seamlessness (Dynamic capabilities)	Value via predictive precision (RBV — data as rare resource)	Value via autonomous adaptation (advanced dynamic capabilities)

6.3 Boundary conditions and managerial challenges by stage

Boundary conditions for each stage are also specific to that stage; they are the market and organisational context in which the stage's logic is still possible; and managerial problems that tend to trigger the next stage are also typical of each stage. The boundary condition in Electronic Commerce is the presence of secure digital payment and logistics systems, and the managerial challenge is to develop the foundation of digital trust. The boundary condition in Interactive Commerce is that the customer base is sufficiently active on social and communicative platforms (Rogers, 2003); and the managerial challenge is to scale engagement, while maintaining the brand's control. The condition for the success of Platform Commerce is the emergence of a critical mass of complementary actors, while the managerial challenge is to manage it both in terms of openness and governance. In Omnichannel Commerce, the boundary condition is organisational readiness to break-down the barriers between channels, while the managerial challenge is to integrate different data and incentive structures among the previously separate channel units (Solem et al., 2023). In Intelligent Commerce, the condition of the boundary is data quality and volume that allow for the creation of reliable models, while the challenge of the managerial aspect is to keep customer trust when relying on algorithms for decision making (Puntoni et al., 2021). The challenge in Autonomous Commerce is the presence of interoperable agentic protocols and the existence of a regulatory regime that allows delegated machine transactions, the boundary condition is the presence of a set of decisions that no individual human authorises.

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6.4 Research opportunities by stage

Each stage also opens stage-specific research opportunities that this paper's integrated architecture makes newly visible. At the Electronic–Interactive boundary, research can examine which specific relational capabilities most efficiently convert transactional customers into engaged co-producers. At the Interactive–Platform boundary, research can examine how single-sided engagement capability is repurposed into multi-sided orchestration capability. At the Platform–Omnichannel boundary, research can examine how ecosystem governance logic is reconciled with the tighter, single-firm control required for seamless journey integration. At the Omnichannel–Intelligent boundary, research can examine the organisational conditions under which unified customer data becomes a trainable predictive asset rather than a static repository. At the Intelligent–Autonomous boundary — the least-studied transition — research can examine the ethical, contractual, and identity conditions under which customers and firms are willing to delegate transactional authority to autonomous agents.

6.5 The transition mechanism: capability saturation and the sensing–seizing–transforming cycle

The DCECF's central theoretical claim is that transition between stages is triggered by capability saturation: the point at which a stage's dominant capability configuration yields diminishing competitive return because (a) its resource-based rarity has eroded through institutional isomorphism as rival firms imitate the configuration (Barney, 1991; DiMaggio & Powell, 1983), and (b) customer expectations, paced by diffusion among the customer base (Rogers, 2003), have risen to treat the configuration as a baseline requirement rather than a differentiator. Capability saturation does not by itself produce transition; it produces a sensing signal. Consistent with Teece (2007) and Helfat et al. (2009), this signal activates a three-phase dynamic-capability cycle. In the sensing phase, the organisation identifies an emergent technological and behavioural opportunity beyond its current capability configuration. In the seizing phase, the organisation reallocates resources — reorganising data architecture, retraining personnel, renegotiating platform or channel relationships — to capture the opportunity. In the transforming phase, the new capability configuration is institutionalised as the firm's operating capability base, at which point the stage-specific capabilities described in Table 3 for the new stage become the firm's ordinary operating capabilities, and the cycle becomes newly available to run again once that configuration in turn saturates.

This mechanism has three implications not available in prior stage-descriptive typologies. First, it predicts that transition speed is a function of the intensity of institutional isomorphism within a firm's competitive set, not merely of technology availability: firms in more imitative, transparent industries will saturate and transition faster than firms in opaque or fragmented industries. Second, it predicts that firms lacking a functioning dynamic-capability cycle — that is, firms that sense emergent opportunity but cannot seize or institutionalise it — will remain in a saturated stage despite having access to the next stage's enabling technology, which explains empirically documented cases of stalled digital transformation. Third, it predicts that stages can, in principle, be skipped or compressed when a firm enters a market late and can seize a mature configuration directly, without passing through the resource-based advantage window enjoyed by earlier movers.

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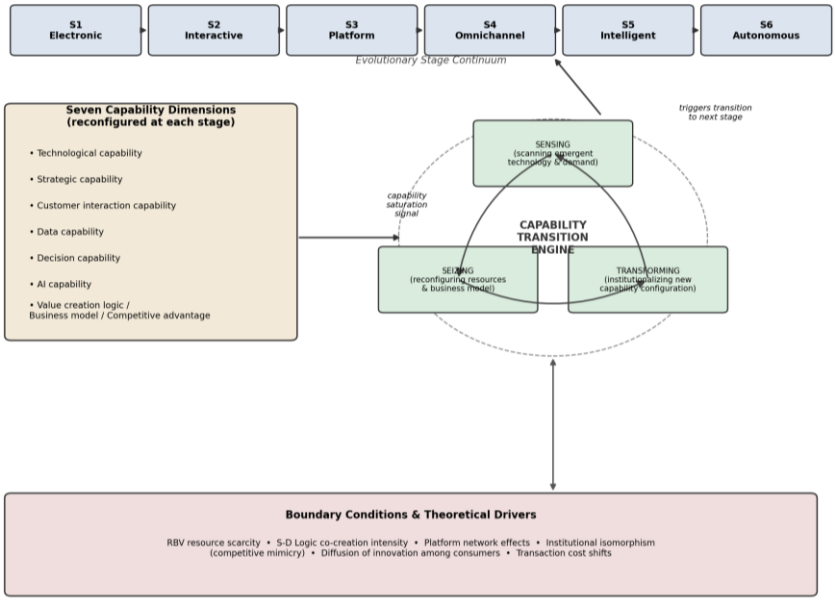


Figure 2. Digital Commerce Evolution and Capability Framework (DCECF)

6.6 Capability transformation across stages

Table 4 summarises how each of the seven capability dimensions is transformed, rather than merely accumulated, at each stage transition, underscoring that evolution involves qualitative reconfiguration and not simple capability addition.

Table 4. Capability Transformation Across Stages

Transition	What is reconfigured	What is carried forward	Primary theoretical driver
S1 → S2	Decision logic shifts from firm-controlled to dialogue-informed	Transactional infrastructure and trust baseline	S-D Logic co-creation turn
S2 → S3	Unit of competition shifts from firm to ecosystem	Engagement and relational data capability	Platform Ecosystem Theory
S3 → S4	Governance tightens from open ecosystem to unified single-firm journey control	Network orchestration skills, repurposed internally	Dynamic capabilities (Eriksson Ahre et al., 2022; Solem et al., 2023)
S4 → S5	Decision authority shifts from human-	Unified cross-channel data architecture	RBV — data as rare, inimitable resource

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Transition	What is reconfigured	What is carried forward	Primary theoretical driver
	analytic to algorithmic-predictive		
S5 → S6	Decision execution shifts from human-supervised algorithms to delegated autonomous agents	Predictive models and trained data assets	Advanced dynamic capabilities operating on artificial agents

7. Digital Commerce Maturity Continuum

The six DCECF stages describe qualitatively distinct capability configurations, but organisations do not move discretely from one configuration to the next; they occupy intermediate positions as they sense, seize, and transform. The Digital Commerce Maturity Continuum, shown in Figure 3, operationalises this graduated progress along two theoretically derived axes.

7.1 Two maturity axes

The horizontal axis, data-to-decision autonomy, captures the extent to which commercial decisions are driven by data and algorithmic inference rather than human judgement, reflecting the RBV-grounded shift in decision capability documented in Table 3. The vertical axis, value co-creation intensity, captures the depth of interdependence between the firm, the customer, and the wider ecosystem in generating value, reflecting the S-D Logic and Platform Ecosystem Theory foundations of the framework. Positioning a firm on both axes — rather than assigning it a single discrete stage label — allows the continuum to capture hybrid organisations that, for example, have highly autonomous fulfilment decisioning but low customer co-creation, or vice versa, a nuance a discrete-stage label would obscure.

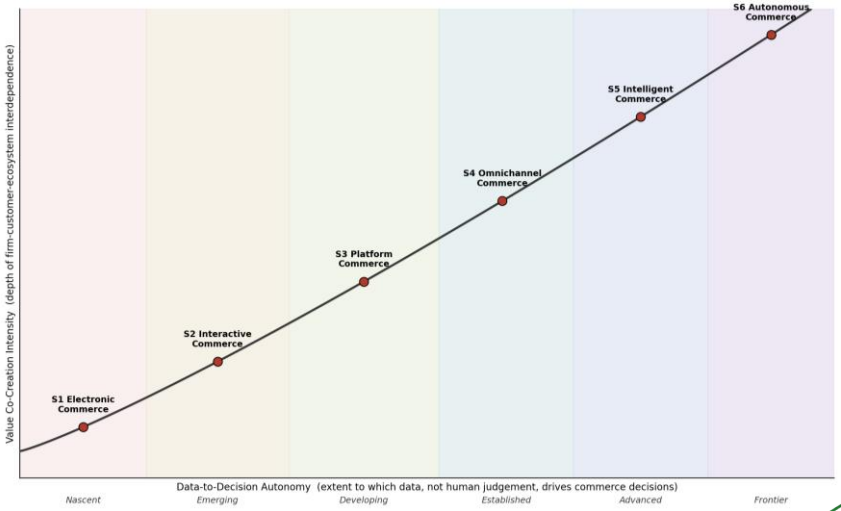


Figure 3. Digital Commerce Maturity Continuum

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7.2 Maturity bands

Six maturity bands — nascent, emerging, developing, established, advanced, and frontier — partition the continuum and correspond approximately to the six DCECF stages, but are deliberately continuous rather than discrete so that an organisation's position can be tracked incrementally as it accumulates capability, rather than only recognised retrospectively once a full stage transition is complete. This continuity also allows the continuum to serve a diagnostic function: an organisation can identify which of the seven capability dimensions in Table 3 is lagging its overall position, and target capability investment accordingly, rather than investing indiscriminately across all seven dimensions at once.

7.3 Distinctiveness from prior maturity models

Existing digital-maturity instruments in the information-systems and marketing literatures typically assess maturity against a single composite score or against technology-adoption checklists. The continuum developed here differs in two respects. First, its two axes are derived directly from the theoretical foundations in Section 5 rather than from ad hoc survey items, which allows the continuum's predictive claims to be tied back to Dynamic Capabilities Theory, RBV, and S-D Logic rather than treated as an atheoretical index. Second, because the continuum shares its seven capability dimensions with the DCECF stage architecture in Table 3, a firm's position on the continuum can be directly linked to a specific capability-investment agenda, rather than functioning only as a descriptive benchmark.

8. Theoretical Propositions

The DCECF and the maturity continuum generate eleven propositions that are, in principle, empirically testable using longitudinal case, survey, or archival methods. The propositions are grouped into three sets: mechanism propositions (P1–P4), capability-configuration propositions (P5–P8), and boundary-condition propositions (P9–P11).

8.1 Mechanism propositions

Proposition 1: A firm's dominant digital commerce capability configuration will transition to the next DCECF stage only after that configuration reaches capability saturation, operationalised as declining marginal competitive differentiation despite stable or increasing capability investment.

Proposition 2: The speed of a firm's transition between DCECF stages is positively associated with the intensity of institutional isomorphism (competitive imitation) within its industry, and negatively associated with industry fragmentation and opacity.

Proposition 3: Firms possessing a functioning sensing–seizing–transforming cycle will transition between DCECF stages even without possessing superior access to the enabling technology, whereas firms lacking such a cycle will remain in a saturated stage despite possessing that access.

Proposition 4: Late-entrant firms are more likely than incumbent firms to skip or compress intermediate DCECF stages, because late entrants can seize an already-matured capability configuration directly rather than passing through the earlier stage's resource-based advantage window.

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8.2 Capability-configuration propositions

Proposition 5: A firm's decision capability (Table 3) will not advance to the Intelligent Commerce configuration unless its data capability has first reached the unified, cross-channel state characteristic of Omnichannel Commerce.

Proposition 6: Customer willingness to co-create value (S-D Logic) will mediate the relationship between a firm's technological capability and its realised strategic capability at each DCECF stage, such that identical technology investments yield divergent strategic outcomes depending on customer co-creation intensity.

Proposition 7: Firms that advance AI capability (Table 3) faster than they advance customer interaction capability will experience lower customer trust than firms that advance the two capabilities in tandem.

Proposition 8: A firm's position on the value co-creation intensity axis of the Digital Commerce Maturity Continuum will predict customer retention more strongly than its position on the data-to-decision autonomy axis, particularly in service-intensive commerce contexts.

8.3 Boundary-condition propositions

Proposition 9: Transition from Platform Commerce to Omnichannel Commerce will be attenuated in firms whose organisational structure retains autonomous, incentive-misaligned channel units, regardless of the technological capability available to integrate those channels.

Proposition 10: Transition from Intelligent Commerce to Autonomous Commerce will be moderated by the maturity of interoperable agentic protocols and the permissiveness of the regulatory environment governing delegated machine transactions, such that firms in equivalent capability positions will transition at different rates across regulatory jurisdictions.

Proposition 11: Firms that attempt to seize a DCECF stage's capability configuration before their customer base has crossed the corresponding innovation-diffusion adoption threshold (Rogers, 2003) will realise lower returns on capability investment than firms that time seizing to follow customer-side diffusion.

9. Managerial Implications

The DCECF offers managers a diagnostic rather than a prescriptive tool. Using Table 3, managers can locate their organisation's current position on each of the seven capability dimensions independently, rather than assuming a single organisation-wide stage label, since it is common for data capability and decision capability to advance unevenly. Using the maturity continuum (Figure 3), managers can identify whether the organisation's principal gap lies in data-to-decision autonomy, in value co-creation intensity, or in both, and can direct capability investment accordingly rather than adopting the next stage's headline technology indiscriminately.

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The capability-saturation mechanism (Section 6.5) further implies that premature seizing — adopting a later stage's technology before the current stage's capability configuration has genuinely saturated, or before the customer base has diffused sufficient familiarity with it (Rogers, 2003) — is likely to yield poor returns. This has direct relevance to current enthusiasm for AI-driven and autonomous commerce technologies: the framework suggests that firms should verify that their Omnichannel-stage data capability is genuinely unified before investing heavily in Intelligent-stage predictive decisioning, and should verify mature governance and trust infrastructure before delegating transactional authority to autonomous agents (Stage 6).

Finally, because Proposition 2 predicts faster transition among firms facing intense competitive imitation, managers in less transparent or more fragmented industries should not assume that slower observed industry-wide adoption of a new stage's capabilities reflects lack of opportunity; it may instead reflect weaker isomorphic pressure, meaning first-mover advantage from proactive capability investment may be larger and more durable in such industries.

10. Future Research Directions

The DCECF opens a future research agenda organised around the propositions in Section 8 and summarised in Table 5. Priority areas include longitudinal case research tracing firms through capability saturation and transition in real time, rather than retrospectively; comparative industry studies testing whether isomorphism intensity predicts transition speed (P2); and measurement development for the maturity continuum's two axes, which currently lack validated multi-item scales. The least understood transition — from Intelligent to Autonomous Commerce — merits particular attention because it raises theoretical questions beyond those addressed by the six perspectives integrated in Section 5, including questions of legal and ethical accountability when no human directly authorises a given transaction, and questions of how consumer trust is built toward a delegated agent rather than toward a firm or a human-supervised algorithm.

Table 5. Future Research Agenda

Proposition(s)	Research question	Suggested method	Theoretical contribution if supported
P1, P3	Can capability saturation be observed as a leading indicator of stage transition before the transition is complete?	Longitudinal multi-case study with repeated capability audits	Establishes saturation as an antecedent rather than a post hoc label
P2	Does industry-level isomorphism intensity predict transition speed across firms in the same stage?	Cross-industry comparative panel study	Links institutional theory constructs to observable transition timing

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Proposition(s)	Research question	Suggested method	Theoretical contribution if supported
P4	Do late entrants systematically skip DCECF stages, and with what performance consequences?	Archival study of market entrants across industries	Tests boundary conditions of first-mover resource-based advantage
P5, P6	Does data-capability maturity causally precede successful AI-capability adoption?	Field experiment or matched-sample archival design	Clarifies capability sequencing implied by Table 4
P7, P8	How does the pace of AI-capability advancement relative to interaction-capability advancement affect trust and retention?	Survey with time-lagged customer trust measures	Extends S-D Logic and AI-service literatures to a longitudinal capability context
P9	Does internal channel-unit misalignment attenuate omnichannel transition independent of technology availability?	Comparative case study within multi-unit retailers	Extends dynamic-capabilities omnichannel research (Solem et al., 2023) to organisational structure
P10, P11	How do regulatory and diffusion boundary conditions moderate transition to Autonomous Commerce?	Cross-jurisdictional comparative and diffusion-timing study	Establishes institutional and diffusion boundary conditions for the newest evolutionary stage

11. Theoretical Contributions

This paper makes three distinct theoretical contributions. First, it reframes digital commerce evolution from a technological chronology into a capability-transformation process explained by a specified mechanism — capability saturation activating a sensing–seizing–transforming cycle — thereby converting a descriptive literature into one capable of generating falsifiable propositions about transition timing and conditions (Section 6.5, Section 8).

Second, it integrates six previously separate theoretical perspectives — Dynamic Capabilities Theory, the Resource-Based View, Service-Dominant Logic, Platform Ecosystem Theory, Institutional Theory, Transaction Cost Economics, and Innovation Diffusion Theory — into a

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single architecture in which each perspective is assigned a distinct, non-redundant explanatory role rather than being invoked as decorative theoretical justification (Section 5).

Third, it contributes the Digital Commerce Maturity Continuum as a construct distinct from prior stage-based typologies, because its two axes are theoretically derived rather than atheoretically indexed, and because it is designed to connect directly to the same seven capability dimensions used in the stage architecture, allowing diagnosis and stage description to share a common conceptual vocabulary (Section 7).

12. Limitations

As a conceptual paper, the DCECF has not been empirically tested; its propositions (Section 8) are offered as a research agenda rather than as established findings, and their support or disconfirmation must be established through the empirical designs summarised in Table 5. The six-stage architecture, while theoretically justified (Section 6.1), necessarily simplifies a more continuous underlying reality, and some firms and industry contexts may exhibit hybrid or non-linear configurations not fully captured by a six-stage model. The framework also draws primarily on retail and consumer-facing commerce literature; its applicability to business-to-business and industrial commerce contexts, where transaction cost and platform dynamics differ, warrants separate theoretical development. Finally, because Stage 6 (Autonomous Commerce) is still emerging, its characterisation in Table 3 is necessarily more speculative than that of the other five stages, and should be treated as a theoretically motivated projection rather than an empirically grounded description.

13. Conclusion

This paper set out to answer a question the existing digital commerce literature has documented extensively but never directly theorised: what mechanism explains why digital commerce evolves, and what capabilities distinguish each stage of that evolution? The Digital Commerce Evolution and Capability Framework answers both questions by integrating dynamic capabilities, resource-based, service-dominant, platform, institutional, transaction cost, and diffusion perspectives into a single architecture built around a specified transition mechanism — capability saturation triggering a sensing–seizing–transforming cycle — and a consistent seven-dimension capability structure applied across six evolutionary stages. The accompanying Digital Commerce Maturity Continuum operationalises this architecture as a diagnostic tool that locates organisations along two theoretically grounded axes rather than within a single discrete label. Together, the framework and continuum reframe digital commerce evolution as a theoretically generative phenomenon, offering researchers a mechanism to test and managers a diagnostic to apply as commerce continues its trajectory from electronic transaction toward autonomous, agentic exchange.

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Mathematical Models Helping Organizations in Day-to-Day Decision Making: A Conceptual Study

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Abstract

Organizations operate in increasingly complex environments characterized by limited resources, uncertain demand, competitive pressures, cost constraints, and rapidly changing customer expectations. In such circumstances, managerial decision-making based solely on intuition and experience may not always provide the most effective solution. Mathematical models offer systematic approaches for representing organizational problems, analysing alternative courses of action, and identifying solutions that optimize available resources. This conceptual paper examines the role of mathematical models in supporting day-to-day organizational decision-making. The paper reviews the application of linear programming, transportation and assignment models, inventory models, queuing models, forecasting models, decision trees, network models, simulation, and multi-criteria decision-making techniques. It argues that mathematical models help managers address routine operational decisions concerning production planning, workforce allocation, inventory control, transportation, scheduling, capacity utilization, pricing, budgeting, and resource allocation. The study further discusses the relationship between mathematical modelling and managerial judgment, emphasizing that models should complement rather than replace human decision-making. The review indicates that the usefulness of a mathematical model depends upon appropriate problem formulation, reliable data, realistic assumptions, model validation, sensitivity analysis, and managerial understanding of results. The paper concludes that mathematical models constitute an important decision-support mechanism that can improve efficiency, consistency, transparency, and rationality in organizational decisions. Their increasing integration with spreadsheets, business analytics, artificial intelligence, and digital technologies is likely to further strengthen their relevance to contemporary management.

Keywords: Mathematical Models, Managerial Decision Making, Operations Research, Linear Programming, Optimization, Decision Support, Resource Allocation, Business Analytics, Simulation, Management Science.

1. Introduction

Decision-making is one of the most fundamental functions of management. Managers at strategic, tactical, and operational levels continuously make decisions concerning production, purchasing, inventory, finance, marketing, human resources, transportation, scheduling, capacity, and customer service. The quality of these decisions directly influences

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organizational efficiency, profitability, competitiveness, and sustainability. Traditional managerial decision-making has frequently relied on experience, intuition, judgment, and qualitative information. Although these elements remain important, modern organizations increasingly operate with large quantities of quantitative information and face complex constraints that cannot always be evaluated effectively through intuition alone. Mathematical models provide a systematic means of translating real-world organizational problems into logical and quantitative representations.

Operations Research (OR) emerged as a formal discipline for applying scientific and mathematical approaches to complex decision problems. Linear programming became one of its foundational techniques, followed by transportation, assignment, network optimization, inventory, queuing, simulation, game theory, dynamic programming, and decision analysis. Contemporary operations research continues to apply mathematical models to complex systems in both public and private organizations.

A mathematical model is a simplified representation of a real-world situation using variables, parameters, equations, inequalities, and relationships. It enables decision-makers to examine alternative solutions under specified constraints. For example, a manufacturing organization may use a linear programming model to determine the quantity of different products that should be manufactured when labour, machine capacity, and raw materials are limited.

Similarly, a retailer can use inventory models to determine appropriate ordering quantities, while a transportation company can use network models to identify cost-effective routes. A bank may apply queuing models to improve customer service, and an organization may use forecasting models to estimate future demand.

The importance of mathematical models lies not merely in obtaining numerical answers but in improving the decision-making process. A well-designed model forces managers to clearly define objectives, identify constraints, establish relationships among variables, and evaluate alternative solutions. Little (1970), in his influential concept of a "decision calculus," emphasized that managerial models should be understandable, robust, adaptable, and capable of incorporating both numerical information and managerial judgment.

The development of digital technologies has further increased the practical usefulness of mathematical models. Spreadsheet software, optimization packages, enterprise systems, business analytics, cloud computing, and artificial intelligence have made sophisticated models more accessible to managers. Consequently, mathematical modelling is no longer restricted to specialist operations researchers; managers can increasingly employ analytical tools in routine organizational decisions. The present conceptual paper therefore examines how mathematical models assist organizations in their day-to-day decision-making and discusses their major applications, benefits, limitations, and future relevance.

Objectives of the Study

The paper aims to:

1. Examine the concept and significance of mathematical models in organizational decision-making.
2. Identify major mathematical models used in routine managerial decisions.
3. Examine their applications across different organizational functions.

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4. Discuss the benefits and limitations of mathematical modelling.
5. Explain how mathematical models can complement managerial judgment.
6. Identify emerging opportunities for integrating mathematical models with analytics and artificial intelligence.

2. Review of Literature

2.1 Mathematical Modelling and Management Decision-Making

Mathematical modelling has a long association with management science and operations research. Dantzig's development of linear programming provided organizations with a systematic method for allocating scarce resources among competing activities. His work demonstrated how optimization could be applied to production, transportation, allocation, and other managerial problems.

Hillier and Lieberman describe the operations research modelling process as involving problem definition, data collection, mathematical formulation, solution, testing, implementation, and evaluation. Their treatment demonstrates that mathematical models are useful across linear programming, transportation, assignment, network optimization, dynamic programming, integer programming, nonlinear programming, game theory, and decision analysis.

Little (1970) further argued that managerial models should not become excessively complicated. A useful model must be sufficiently simple for managers to understand while remaining robust and adaptable to changing information.

2.2 Linear Programming Models

Linear Programming (LP) is one of the most widely used mathematical approaches for resource allocation. A general LP problem can be represented as:

Maximize or Minimize:

$$Z = c_1x_1 + c_2x_2 + \ldots + c_nx_n$$

Subject to organizational constraints such as:

$$a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \leq b_1$$

and

$$x_1, x_2, \ldots, x_n \geq 0$$

Organizations use LP to determine optimal product mixes, production quantities, labour allocation, advertising budgets, procurement decisions, and distribution plans. Its principal advantage is that it converts competing organizational objectives and constraints into a structured optimization problem.

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2.3 Transportation and Assignment Models

Transportation models help organizations determine the least-cost method of moving goods from multiple sources to multiple destinations. Typical applications include:

- Distribution planning
- Warehouse allocation
- Logistics
- Supply-chain management
- Delivery scheduling

Assignment models allocate resources to activities in an optimal manner. For example, employees can be assigned to jobs, salespersons to territories, or machines to production activities. Hillier and Lieberman's treatment identify transportation and assignment problems as important applications of mathematical optimization in organizational decision-making.

2.4 Inventory Models

Inventory represents a significant investment for manufacturing, retail, and distribution organizations. Mathematical inventory models help determine:

- How much to order.
- When to order.
- How much safety stock to maintain.
- How to balance ordering and holding costs.

The Economic Order Quantity (EOQ) model is a classic example:

$$\mathbf{EOQ} = \sqrt{(2DS/H)}$$

where **D** represents annual demand, **S** represents ordering cost, and **H** represents annual holding cost per unit. Although modern inventory systems may involve considerably more sophisticated models, the underlying objective remains the efficient balance of cost, availability, and risk.

2.5 Queuing Models

Queuing models are useful whenever customers, employees, vehicles, or information wait for service. Applications include:

- Banks
- Hospitals
- Call centres
- Restaurants
- Airports
- Retail stores
- Government service centres

Queuing models help managers determine appropriate service capacity by balancing customer waiting time against the cost of additional service resources.

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2.6 Forecasting Models

Forecasting models assist organizations in estimating future demand, sales, costs, inventory requirements, workforce requirements, and financial performance. Methods may include:

- Moving averages
- Exponential smoothing
- Regression models
- Time-series analysis

Forecasting does not eliminate uncertainty but enables managers to prepare alternative plans and reduce the risk associated with future conditions.

2.7 Decision Trees and Decision Analysis

Decision trees provide a graphical representation of alternative decisions and possible future outcomes. They are particularly useful when organizations face uncertainty and risk. A decision tree allows managers to examine:

Decision → Possible Events → Probabilities → Outcomes

Decision analysis therefore provides a structured mechanism for comparing alternative strategies under uncertain conditions.

2.8 Simulation Models

Simulation involves constructing a model of a real-world system and experimenting with different scenarios. Organizations can use simulation to examine:

- Production systems
- Queues
- Supply chains
- Financial risks
- Staffing levels
- Service operations
- Emergency response systems

Simulation is particularly useful when analytical solutions are difficult or when managers want to evaluate "what-if" scenarios without disturbing actual operations.

2.9 Multi-Criteria Decision Models

Organizational decisions frequently involve multiple objectives. For example, supplier selection may depend simultaneously on price, quality, delivery reliability, technology, and sustainability. Multi-Criteria Decision-Making (MCDM) techniques such as the Analytic Hierarchy Process (AHP) enable managers to evaluate alternatives against multiple criteria. AHP and related approaches have become established tools for decision problems involving interacting criteria and alternatives.

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3. Findings, Discussion and Summary

3.1 Findings

The conceptual review produces several important findings.

First, mathematical models improve the structure and discipline of managerial decision-making. They require managers to explicitly identify objectives, variables, constraints, and relationships.

Second, mathematical models support efficient resource allocation. Linear programming and related optimization techniques help organizations allocate scarce resources among competing alternatives.

Third, mathematical models improve operational efficiency. Transportation, assignment, inventory, queuing, and scheduling models can reduce costs and improve utilization of organizational resources.

Fourth, mathematical models support decision-making under uncertainty. Forecasting, simulation, probability models, and decision trees allow managers to evaluate alternative scenarios and potential risks.

Fifth, mathematical models improve consistency and transparency. Decisions based on clearly specified assumptions and procedures can be examined, reproduced, and communicated more effectively.

Sixth, mathematical models increasingly complement business analytics. Historical and real-time data can be incorporated into optimization models to produce more responsive decisions.

3.2 Discussion

The findings demonstrate that mathematical models should not be regarded as purely technical instruments. They constitute an important component of managerial decision support. The effectiveness of modelling, however, depends upon the quality of the model and the assumptions underlying it. A mathematically sophisticated model can produce misleading results if the input data are inaccurate or if important real-world factors are excluded. Little's concept of managerial decision calculus is particularly relevant in this context. A useful managerial model should be understandable, robust, controllable, adaptable, and communicable. Consequently, mathematical modelling should be combined with managerial experience. The model provides analytical discipline, while managers contribute contextual knowledge, organizational understanding, ethical judgment, and practical feasibility. Modern technology is creating further opportunities. The integration of mathematical optimization with artificial intelligence and machine learning can enable organizations to move from descriptive analysis towards predictive and prescriptive decision-making. Recent developments in automated mathematical programming even explore the possibility of translating natural-language business problems into operations-research models, although such approaches remain subject to accuracy and validation challenges.

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3.3 Managerial Implications

Managers should consider mathematical modelling as a practical decision-support capability rather than an exclusively mathematical exercise. Organizations should:

- Develop analytical skills among managers.
- Encourage evidence-based decision-making.
- Integrate mathematical models with ERP and business analytics systems.
- Regularly validate model assumptions.
- Conduct sensitivity analysis before implementation.
- Combine quantitative results with managerial judgment.
- Use scenario analysis when uncertainty is substantial.
- Ensure that model outputs remain understandable to decision-makers.

3.4 Limitations

The study is conceptual and does not empirically measure the financial or operational impact of specific mathematical models within individual organizations. Different industries may also require substantially different modelling approaches. Furthermore, mathematical models necessarily simplify reality and may not fully capture human, cultural, political, or ethical dimensions of organizational decisions.

3.5 Future Research Directions

Future empirical studies may examine:

- The impact of mathematical modelling on organizational productivity.
- Use of optimization models in Indian MSMEs.
- AI-integrated mathematical decision systems.
- Mathematical models for sustainable supply-chain management.
- Predictive and prescriptive analytics in managerial decision-making.
- Human–AI collaboration in optimization-based decisions.
- Use of mathematical models in ESG and sustainability decisions.

4. Conclusion

Mathematical models have become an important foundation of modern organizational decision-making. From production planning and inventory management to transportation, staffing, forecasting, scheduling, and strategic resource allocation, mathematical models provide managers with systematic mechanisms for evaluating alternatives and identifying efficient solutions. The central contribution of mathematical modelling is not simply the production of a numerical answer. Rather, it is the creation of a disciplined decision process in which objectives, constraints, assumptions, alternatives, and consequences are explicitly examined. The continuing development of business analytics, artificial intelligence, cloud computing, and digital decision-support systems is further increasing the accessibility and usefulness of mathematical models. Nevertheless, models should complement rather than replace managerial judgment. Therefore, the most effective organizational decision-making approach is likely to emerge from the combination of **mathematical modelling, reliable data, technological capability, and human managerial wisdom**. In this integrated form,

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mathematical models can become powerful instruments for improving organizational efficiency, responsiveness, transparency, and sustainable performance.

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Reimagining Higher Education through Artificial Intelligence and Disruptive Technologies: A Comprehensive Review

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Abstract

The higher education sector has been radically transformed by the emergence of disruptive technologies, which have reshaped traditional teaching and learning methodologies. This paper investigates different disruptive technologies, such as block chain, artificial intelligence (AI), machine learning, and virtual reality (VR) etc. usage on higher education. These technologies are transforming the delivery of education, improving accessibility, and promoting personalised learning experiences. Block chain technology provides secure credentialing and transparent academic records, while Artificial Intelligence and machine learning facilitates adaptive learning platforms that accommodate the unique requirements of each student. Immersive learning environments are enabled by Virtual reality, which enables experiential education that transcends the limitations of physical classrooms. The integration of these technologies also presents challenges, such as the need for substantial infrastructural investment, faculty training, and concerns regarding data privacy, despite the numerous benefits. This paper investigates diverse disruptive technologies providing higher education institution with the ability to strategically navigate this changing landscape in order to improve educational outcomes and maintain their competitiveness in the digital era.

KEYWORDS: Higher Education, Block chain technologies, Artificial Intelligence, Disruptive Technologies

1. Introduction

As we live in the age of digitization, enormous quantities of information are easily accessible through innovative technologies, real-time information networking, for instance, the World Wide Web, Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Wide Area Networks (WANs). Rapid pace at which the industry climate shifts has continuously

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advocated for and acknowledged the need for developments and accelerating innovations. The new technologies allow organizations to be more integrated and customizable. 21st-century organizations eventually start investing in information and communication technologies (ICT) to accomplish this goal and achieve an economic advantage by investing large amounts of funds on hardware equipment's, technology, communication systems, database, and professional staff. In addition to being available at work, information technology is also becoming more and more common in homes and other public spaces (Martin et al., 2005).

Information technology (IT) is a facilitator for organizational practices and procedures, according to Turban, Rainer, and Potter (2001). Therefore, every professional employee must know about IT from the perspective of his or her area of expertise. Considerably, Fary (1984) predicted that in the twenty-first century, most employees want the usage of computers along with communication networks, so this would be a downside for those who are unable to use these innovative technologies. Palvia, Palvia, and Zigli (1992) reported that several organizations, particularly institutions of higher education, are informed of these constantly evolving problems and are actively seeking technological solutions as not only a collection of computational devices but also a strategic technique for organization's advancement, well-being and bring organizations together. Petrides (2000) further indicated that information technology is now an essential part of organizations, especially in universities, as institutions of higher learning aim to uphold the goals of success, efficacy, and competitive advantage.

IMPORTANCE OF INFORMATION TECHNOLOGIES IN MODERN HIGHER EDUCATION

The field of information technology (IT) is pivotal in higher educational institutions offering a multitude of benefits that enhance the learning experience, administrative efficiency, and overall educational outcomes. Here are several reasons highlighting the importance of IT in higher education:

Overall, IT has become integral to the modern higher education ecosystem, fundamentally transforming how education is delivered, accessed, and managed, contributing significantly to the overall academic experience and success of students and institutions alike.

REVIEW OF SEVERAL INNOVATIVE DISRUPTIVE TECHNOLOGIES APPLIED TO THE UNIVERSITY ENVIRONMENT

This section defines several technologies that will be utilized during the study, including Innovative disruptive technologies, specifically within the realm of education, i.e. Moodle, Google Classrooms, Virtual Learning Environments (VLEs), Massive Open Online Course (MOOC) based Flipped Classrooms, Electronic Learning (e-learning) Platforms, Blended or Hybrid learning, Study Webs of Active-Learning for Young Aspiring Minds (SWAYAM), Electronic Yantra (e-Yantra), National Digital Library (NDL), Virtual Labs, UG/PG MOOCs, e-PG Pathshala, e-Content courseware and **Consortium for Educational Communication** – University Grants Commission (CEC-UGC) YouTube channel.

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To comprehensively determine the extent to which disruptive technological advances could standardize Higher Education, it is imperative to initially establish clear definitions of the terminology involved:

Table 2.1 Numerous reasons highlighting the importance of Information Technology in Higher Education		
S.no.	**Importance**	**Description**
1	**Enhanced Learning Experience**	IT tools, such as Learning Management Systems (LMS), online courses, multimedia resources, and educational apps, facilitate innovative teaching methodologies. They allow for personalized learning experiences, accommodating diverse learning styles and pacing for students.
2	**Access to Information and Resources**	IT enables quick access to vast repositories of knowledge and educational materials. Online libraries, databases, journals, and e-books expand the range of resources available to students and educators, regardless of their physical location.
3	**Collaborative Learning**	Technology fosters collaboration among students and educators. Tools like video conferencing, collaborative document editing, discussion forums, and social media platforms facilitate interaction and knowledge sharing among peers and with experts globally.
4	**Versatility and Availability**	The utilization of digital resources and online learning platforms offers adaptability in scheduling and accessibility to education for students who might have constraints due to location, work, or personal responsibilities.
5	**Data Management and Analytics**	IT systems aid in efficient data management, from student records to administrative information. Analyzing this data helps institutions identify trends, measure performance, and make data-driven decisions to enhance teaching and learning outcomes.
6	**Cost Efficiency**	While implementing IT infrastructure might have initial costs, in the long run, it can reduce expenses related to printed materials, administrative tasks, and infrastructure by streamlining processes and utilizing digital resources.
7	**Preparation for the Workforce**	Proficiency in IT tools and systems is crucial for success in many modern careers. Higher education institutions integrating IT into their curriculum adequately prepare students for the demands of the digital workforce.
8	**Innovation and Research**	IT facilitates research through access to online databases, collaboration tools for interdisciplinary studies, simulation software, and high-performance computing, aiding in ground breaking discoveries and advancements.
9	**Administrative Efficiency**	IT systems automate administrative tasks like registration, scheduling, grading, and resource allocation, saving time and reducing human errors.
10	**Adaptation to Technological Advancements**	Embracing IT in higher education ensures that institutions stay current with technological advancements, helping them staying innovative and pertinent in the swiftly changing educational environment.

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Table 3.1 Review of different disruptive technologies used in Higher Education			
S.no.	**Disruptive Technologies**	**Description**	**Reference**
1.	**Open Courseware**	Open Courseware (OCW) refers to educational materials developed by institutions and made available to the public at no cost through the Internet. The emergence of OCW projects can be traced back to the late 1990s. Initially gaining popularity in Europe and subsequently in the United States, they have now become a global platform for disseminating educational material.	Casewell et al. 2008
ii	**CEC-UGC YouTube channel**	The Consortium for Educational Communication, or CEC for short, is one of the University Grants Commission of India's Inter-University Centre. It was founded to meet the demands of universities and colleges via effective use of the television, an influential medium and the proper usage of developing ICT. Recognizing television's potential and power as a vehicle for spreading academic knowledge, the UGC launched the Countrywide Classroom Programs in 1984.	Sharma & Gupta, 2020
iii	**E-Learning Platforms**	The term "e-learning" originated in 1999 during a CBT systems seminar. Alongside this, other terms like "online learning" and "virtual learning" started to appear in an attempt to provide a precise definition. An e-learning platform is a collection of interactive web services that support and improve the administration and delivery of education by providing trainers, students, and other education-related stakeholders with information, tools, and resources. These platforms facilitate the democratisation of education by offering high-quality educational materials at cheap prices or even free of charge.	Smith & Brown (2021)
iv	**Moodle**	Educators and researchers can use Moodle, which was initially created by Martin Dougiamas, to build online courses with an emphasis on engagement and collaborative material creation. The original release of Moodle was on August 20, 2002, which is 21 years ago, and it is still being developed actively. It facilitates teachers to quickly provide graded assessments, tutorials, and preference, share documents, practice questions, symposiums, and conversation, and provide a platform for beginners.	Ajlan & Zedan, 2007
v	**Blended or Hybrid Learning**	The phrase "blended learning" was originally ambiguous, encompassing a diverse range of instructional strategies and technological tools in different combinations. The phrase gained more clarity in 2006, when Bonk and Graham published the first Handbook of Blended Learning. It is a form of education that integrates online educational resources	Graham & Robison, 2007

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		and potential involvement with traditional classroom techniques in a physical location. Therefore, the presence of both the instructor and the student is required, along with some degree of student agency over the course of events, including when, where, and how they unfold.	
vi	**Virtual Learning Environments (VLEs)**	In educational technology, a virtual learning environment (VLE) is an online platform that hosts the digital components of educational courses, introduced in 2007, typically within academic institutions. They organize materials, activities, and interactions within a course structure and define the various evaluation stages.	Johnson & White, 2022
vii	**MOOC based Flipped Classroom**	MOOCs, or Massive Open Online Courses, are an extensively researched advancement in remote education. They were initially offered in 2008 and gained significant popularity in 2012, earning the title of the "Year of the MOOC". They provide a new avenue for designing flipped learning. Teachers can leverage existing MOOCs to flip their classes. Students enrolled in on-campus courses are encouraged to engage in MOOCs provided by other universities under this model	Wang & Zhu, 2019
viii	**Virtual Labs**	The Ministry of Human Resource Development of India introduced the Virtual Labs programme as part of the National Mission on Education through Information and Communications Technologies. The initiative aims to provide students at all academic levels, ranging from undergraduates to doctorates, with the ability to remotely visit laboratories in diverse science and engineering disciplines.	Singh & Kumar, 2021
ix	**Google Classroom**	Google Classroom is a free educational platform that was developed by Google and released publicly on **12th August, 2014** for schools help streamline the process of creating, delivering, and evaluating assignments. The primary goal of Google Classroom is to maximize the efficiency of the process of exchanging files between educators and learners	Iftakhar, 2016
x	**e-Yantra**	The e-Yantra Innovation Challenge (eYIC) is an outstanding yearly competition that instructs student teams in essential skills through Massive Open Online Courses (MOOCs) prior to engaging them in solving practical problems and establishing enterprises It is a robotics outreach project sponsored by the IIT, Bombay' (Computer Science and Engineering Department). It is supported by the Indian Government, Ministry of Education as one part of the National Mission on Education via ICT (NMEICT). e-mission Yantra's aims to supplement current higher education institutions globally and use technology to	Sharma & Desai, 2020

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PSP Area, Sector-22, Maharaja Agrasen Chowk
Sector-22, Rohini, Delhi-110086

		solve local issues in several sectors, including agricultural, disaster management, trade, defence, residential, smart cities, and service sectors.	
xi.	**SWAYAM**	The SWAYAM programme was introduced by the Ministry of Education (formerly known as the Ministry of Human Resource & Development) on 9th July 2017. The objective is to offer a high-quality education to millions of students through e-learning courses. SWAYAM aims to bridge the digital divide among learners who have been largely unaltered by the digital age, preventing them from participating in the mainstream of the knowledge economy.	Gupta & Mehta, 2021
xii	**National Digital Library (NDL)**	The NDLI project was commenced in 2015 and officially introduced to the nation on June 19, 2018. The repository contains resources sourced from both national and international digital libraries, which can be accessed in English as well as Indian languages. It is an online collection of educational materials that is more than a search/browse repository; it also provides various services to the learner community. It is funded and supervised by the Government of India's Ministry of Education as part of its National Mission on Education through Information and Communication Technology (NMEICT).	Sen & Roy, 2020
xiii	**e-PG Pathshala**	e-Pathshala is an online platform created by the CIET and NCERT. The initiative was collaboratively launched in November 2015 by the Ministry of Human Resource & Development (now Ministry of Education), CIET, and NCERT. It is an e-learning portal managed by the Information Library Network (INFLIBNET) Centre and supported by the Ministry of Human Resource & Development of India.	Verma & Patel, 2019
Below mentioned technologies came in mid of the 20th century but its tremendous increase in the implementation started in the 21st century.			
xiv	**Artificial Intelligence (AI) and Machine Learning (ML)**	The terms "machine learning" and "artificial intelligence" first appeared in 1952 and 1956, respectively. AI-driven adaptive learning platforms provide tailored learning experiences by analysing the strengths and weaknesses of students. AI is utilised for the purposes of evaluating, generating personalised learning trajectories, and delivering instantaneous feedback.	Smith & Johnson, 2021
xv	**Augmented Reality (AR) and Virtual Reality (VR**	AR and VR have undergone continuous development and garnered widespread acceptance due to technological developments and their diverse uses in industries such as gaming, education, healthcare, and others. AR and VR technologies enable students to engage in immersive learning experiences by interacting with three-dimensional models or virtually exploring historical sites. They promote active	Cipresso et al. 2018

Prof. (Dr.) Vikram Bali
Director
Maharaja Agrasen Institute of Technology
PSP Area, Sector-22, Maharaja Agrasen Chowk
Sector-22, Rohini, Delhi-110086

		participation and comprehension in diverse academic disciplines.	
xvi	**Block-chain Technology**	The use of block-chain technology in education has been under investigation for several years, but it was not until the mid- to late-2010s that it began to acquire popular acceptance and large efforts were launched. Universities and educational institutions have started investigating the capabilities of block-chain technology to securely store and authenticate academic credentials, establish unalterable records of accomplishments, facilitate secure sharing of transcripts and certificates, and potentially enables new decentralised learning platforms and content distribution.	Patel & Kumar, 2020
xvii	**Gamification**	The adoption and recognition of gamification in education began to increase in the early 2010s. The objective of this method was to utilise gaming aspects and mechanics in educational environments to improve student involvement, motivation, and academic achievement. The objective of this method was to utilise gaming aspects and mechanics in educational environments to improve student involvement, motivation, and academic achievement.	
xviii	**Internet of Things (IOT)**	The implementation of Internet of Things (IOT) in education began to attract attention and be put into practice around the mid-2010s. In the years 2014–2015, educators and institutions initiated an examination of the capabilities of IOT devices and applications in educational environments. The IOT refers to the process of linking different devices and items to the internet, allowing them to gather and share data. IOT in education presents prospects for establishing intelligent classrooms, enhancing educational experiences, and optimising administrative operations in educational institutions.	Smith & Lee, 2019
xix	**Cloud computing**	The usage of and focus on cloud computing in education began to increase, notably during the late 2000s and early 2010s. The notion of cloud computing has been in existence for a considerable duration, but its incorporation into educational environments started to gain momentum during this timeframe. Cloud computing is the provision of computing services, such as storage, processing power, and apps, through the internet on a pay-as-you-go model instead of using local servers or personal devices.	Armbrust, 2010
xx	**Mobile learning**	The emergence of mobile learning additionally referred to as m-learning, gained significance during late 2000s & early 2010s due to the increasing prevalence and advancement of mobile technology. The advent of mobile learning was greatly influenced	Ally & Gardiner, 2017

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PSP Area, Sector-22, Maharaja Agrasen Chowk
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		by the introduction and widespread use of smartphones, tablets, and other portable devices that have internet connectivity and can run educational programmes and access online resources.	

3. CONCLUSION

Disruptive technologies are reshaping the landscape of higher education by challenging traditional methods of teaching and learning and introducing innovative ways to enhance educational outcomes. This paper has explored various disruptive technologies, including Artificial Intelligence (AI), Blockchain, Augmented Reality (AR) and Virtual Reality (VR), Massive Open Online Courses (MOOCs), and mobile learning platforms, highlighting their potential to transform educational practices.

The adoption of AI in education has enabled personalized learning experiences, allowing students to receive tailored content and feedback based on their individual needs. Blockchain technology, while still in its early stages, promises to revolutionize credentialing and secure data management, fostering greater transparency and trust in academic records. AR and VR offer immersive learning environments that can simulate real-world scenarios, thereby enriching the learning experience and increasing student engagement. MOOCs have democratized access to education, providing learners worldwide with opportunities to acquire knowledge and skills at little to no cost. Mobile learning has further facilitated anytime, anywhere access to educational resources, making learning more flexible and accessible.

Despite the potential benefits, the integration of these technologies into higher education also presents challenges, including issues related to equity, data privacy, and the need for adequate infrastructure and training. Furthermore, the effectiveness of these technologies in improving learning outcomes requires ongoing assessment and research.

As the higher education landscape continues to evolve, it is imperative for institutions to remain agile and open to adopting new technologies while critically evaluating their impact. Future research should focus on developing best practices for the implementation of these technologies and addressing the challenges that accompany their adoption. Ultimately, the successful integration of disruptive technologies in higher education holds the promise of enhancing the quality, accessibility, and relevance of education for students across the globe.

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Venture Capital Funding: A Catalyst for Start-up Scalability

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ABSTRACT

The rapid evolution of the startup ecosystem has been significantly influenced by the rise of venture capital (VC), which has emerged as a critical driver of growth and scalability for new enterprises. This paper explores the impact of venture capital on startup development, focusing on its role beyond mere financial support. Venture capital not only provides essential funding but also delivers strategic guidance, mentorship, and valuable industry connections, which are crucial for startups aiming to scale up rapidly and innovate within competitive markets. The study reviews existing literature on venture capital's effects on startups, and presents case studies of successful Indian startups such as Zomato, BYJU'S, Ola Cabs, and Flipkart. Key findings reveal that venture capital accelerates startup growth and market expansion. This study aims to contribute to the broader discourse on entrepreneurship, investment, and economic development by providing insights into the pivotal role of venture capital in shaping the future of startups.

Keywords: Venture Capital, Start-Up, India, Case Study

INTRODUCTION

The startup ecosystem has experienced substantial growth and transformation over the past few decades, driven by technological advancements, increased market opportunities, and innovative business models (Gompers & Lerner, 2001; Blank, 2013). Venture capital (VC) has emerged as a pivotal enabler of startup development and scalability, offering not only financial resources but also strategic guidance crucial for startups to grow, innovate, and compete effectively in increasingly competitive markets (Kortum & Lerner, 2000).

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Venture capital transcends mere funding; it acts as a catalyst for growth and innovation (Hellmann & Puri, 2002). VC firms invest in early-stage companies with high growth potential, providing financial support, mentorship, industry connections, and strategic advice (Gompers et al., 2020). This symbiotic relationship can significantly accelerate a startup's development, enabling rapid and effective scaling. The infusion of capital and expertise helps startups overcome initial challenges, refine their business models, and expand their market presence (Kaplan & Stromberg, 2004).

Understanding the impact of venture capital on startups is crucial for several reasons. For entrepreneurs, it provides insights into the benefits and challenges of seeking venture capital funding (Bottazzi & Da Rin, 2002). For venture capitalists, it highlights the areas where their involvement can make the most significant impact (Hsu, 2004). Additionally, policymakers and ecosystem stakeholders can utilize this knowledge to create a supportive environment that fosters startup growth and innovation (Lerner, 2010). Ultimately, this study aims to contribute to the broader discourse on entrepreneurship, investment, and economic development.

This study analyzes the role of venture capital in startup development and discusses various challenges faced by venture capital-backed startups. A conceptual framework approach is used to investigate the impact of venture capital on startup development. The research involves analyzing secondary sources, including scholarly articles, books, and industry reports, to construct a comprehensive foundation of existing knowledge on venture capital and startup growth. Academic databases such as Google Scholar and JSTOR were used to gather theoretical insights.

REVIEW OF LITERATURE

David, D.et al (2020) described that India has an estimated 26,000 startups, making it the third largest startup ecosystem in the world, recording consolidated inflows of over $36 billion in the past 3 years with 26 “unicorns” – startups valued over $1 billion. The Indian startup ecosystem has expanded rapidly through private investments, including seed, angel, venture capital, and private equity funds, with technical support from incubators, accelerators, and the government. The government, through the Startup India initiative, has played a pivotal role in creating an enabling environment.

Cavallo et al. (2019) suggest that VC funds positively affect the growth of digital new ventures, while there is limited evidence on the contribution of angel groups. Focusing on digital startups and scaleups, two key insights emerge. First, digital scaleups show a linear path of growth positively correlated with VC funding. Second, as the amount of funding increases, digital startups grow at first but shrink after surpassing an optimal level of $300,000 in investment.

Chandiok (2016) evaluated that the Indian startup ecosystem has significantly evolved, driven by massive funding, consolidation activities, evolving technology, and a burgeoning domestic market. From 3,100 startups in 2014 to projections of over 11,500 by 2020, this growth indicates a revolutionary shift in the Indian market.

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Malvika Garg and Suman Gupta (2021) describe that a growing number of funds, angels, incubators, accelerators, and academic programs are supporting the startup ecosystem. Over the last five years, India has strengthened its position as the third-largest startup ecosystem globally, witnessing the addition of over 1300 startups in 2019 alone. Seven new unicorns emerged, bringing the total to 26, underscoring the robust valuation and employment generation within this ecosystem.

Godha et al. (2020) explained that the startup ecosystem in India is built upon the pillars of investors, founders, and policymakers. The government's Startup India initiative and the widespread network of venture capitalists, angel investors, and incubators have led to the recognition of over 28,000 startups across the country by 2020, creating substantial employment and driving economic growth.

DATA PRESENTATION AND DISCUSSION

Venture capital is indispensable for startups aiming for rapid growth and industry disruption. Indian startups with robust business models increasingly attract VC funding to support global expansion plans. The study presents a series of case studies to illustrate the role of venture capitalists in the growth of Indian startups.

Case 1: Zomato

Founded in 2008, Zomato initially focused on restaurant discovery and reviews before expanding into food delivery. Through various funding rounds, including seed funding and Series A to C investments, Zomato expanded internationally and enhanced its technology platform. The challenges Zomato faced, such as regulatory compliance and competition, underscore the importance of proactive engagement with regulators, scalable technology, and continuous innovation.

Early Funding Rounds:

1. Seed Funding (2010): $1 million (Info Edge India Ltd) – Helped Zomato develop its platform and expand restaurant listings.
2. Series A (2011): $3.5 million (Info Edge India Ltd) – Expanded operations in India and invested in marketing.
3. Series B (2012): $10 million (Info Edge India Ltd) – Supported international expansion and mobile app development.
4. Series C (2013): $37 million (Sequoia Capital, Info Edge India Ltd) – Accelerated global expansion and technology platform enhancement.

Case 2: BYJU'S

Founded in 2011, BYJU'S is an edtech company that offers personalized learning programs. Early funding rounds enabled BYJU'S to develop technology, create educational content, and

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expand its reach. VC funding was critical for BYJU'S to scale operations, receive strategic guidance, and gain market validation.

Early Funding Rounds:

1. Seed Funding (2011): $2 million (Aarin Capital, Ranjan Pai, TV Mohandas Pai) – Enabled development of core technology and content.
2. Series A (2013): $9 million (Aarin Capital, Ranjan Pai) – Expanded content library and enhanced technology platform.
3. Series B (2015): $25 million (Sequoia Capital, Sofina) – Supported scaling operations and improving engagement.
4. Series C (2016): $75 million (Sequoia, Sofina, Chan Zuckerberg Initiative) – Accelerated international growth and product development.

Case 3: Ola Cabs

Founded in 2010, Ola Cabs offers various transportation services. Early funding rounds helped Ola develop its platform, expand services, and grow its driver network. VC support was vital for scaling operations and launching new services.

Early Funding Rounds:

1. Seed Funding (2010): $500,000 (Snapdeal founders) – Launched services in Mumbai and tested business model.
2. Series A (2011): $5 million (Tiger Global Management) – Expanded services and enhanced technology.
3. Series B (2013): $20 million (Matrix Partners India, Tiger Global) – Rapid expansion and new features development.
4. Series C (2014): $210 million (SoftBank Group, Tiger Global) – Increased driver network and launched new services like Ola Mini.

These case studies highlight the critical role venture capital plays in the development and scaling of startups. From Zomato's restaurant discovery platform to BYJU'S edtech innovations and Ola Cabs' rapid expansion in the transportation sector, venture capitalists provided more than just funding. Their involvement also extended to strategic guidance, operational support, and market validation, which were pivotal to each startup's growth.

THE ROLE OF VENTURE CAPITAL IN STARTUP GROWTH

1. Capital Infusion: Venture capital provides startups with essential funds to scale quickly, allowing them to expand into new markets, improve products, and enhance technology.
2. Strategic Guidance: VC firms offer mentorship, financial advice, and industry connections. Their guidance in regulatory compliance and innovation helps startups sustain long-term growth.

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PSP Area, Sector-22, Maharaja Agrasen Chowk
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3. Market Validation: Securing VC funding from reputable firms adds credibility to startups, making it easier to attract customers and partners.
4. Operational Support: VCs provide operational assistance, help refine business processes, and aid in managing rapid growth.

Venture capital played a crucial role in Startups' rapid rise to prominence. Substantial venture funding along with other strategic value addition allows them to expand rapidly, innovate continuously, and maintain a competitive edge in their respective industry.

CHALLENGES FROM VENTURE CAPITAL FUNDING

Venture capital funding is, no doubt, a strong booster for small businesses. It provides scalability to their innovative ideas. Despite this, Indian small businesses face huge challenges. such as the identification of right venture capital funds, challenge of Equity dilution , conflict of interest between fund provider and initial promoters, market adaptability for new innovation. etc

1. Identifying the Right VC Fund: Strategic guidance is just as important as financial support. Startups must identify VCs that align with their vision.
2. Equity Dilution: Founders must balance raising funds with maintaining control over their companies.
3. Pressure for Rapid Growth: Startups often face pressure to scale quickly, which may lead to unsustainable growth strategies.
4. Conflict of Interest: Differences between the founders' vision and VCs' high-return expectations can cause conflicts.
5. Market Adaptation: Expanding into new markets requires understanding local regulations and consumer behavior.
6. Regulatory Hurdles: Proactive engagement with regulators is essential for startups operating in highly regulated industries.

IMPLICATIONS

For **entrepreneurs**, this study underscores the importance of understanding the dynamics of venture capital and selecting the right investors who align with their vision and business goals. Entrepreneurs should also be prepared to leverage the expertise and networks that venture capitalists bring, recognizing that beyond funding, strategic guidance and industry connections are vital for long-term success.

For **venture capitalists**, the findings emphasize the need to provide more than just financial support. Successful investments often require active involvement in guiding startups through their growth phases, helping them navigate challenges, and ensuring they stay on the path to scalability and sustainability. Venture capitalists should focus on building strong, collaborative relationships with startups to maximize the potential for success.

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Finally, for **academics and researchers**, this study provides a foundation for further exploration into the nuances of venture capital's impact on startups. Future research could delve into the specific conditions under which venture capital is most effective, the role of different types of investors (e.g., angel investors versus venture capitalists), and the long-term outcomes for startups that receive venture capital funding.

CONCLUSION

Venture capital plays an instrumental role in the growth and success of startups, acting as more than just a financial lifeline. It provides the necessary capital, strategic guidance, industry connections, and market validation that enable startups to scale rapidly, innovate continually, and compete effectively in dynamic markets. The case studies of Zomato and BYJU'S underscore the transformative impact of venture capital on startup trajectories, demonstrating how timely investments and strategic support can propel a company from an idea to a market leader.

Through various stages of funding, venture capital helps startups overcome significant hurdles such as technological development, market expansion, and operational scaling. However, this relationship is symbiotic, requiring startups to be agile, innovative, and responsive to market and investor expectations. The success stories of Zomato and BYJU'S highlight that while venture capital is a powerful growth catalyst, the strategic decisions made by the startups themselves are equally crucial.

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Enabling Blockchain-Driven Supply Chains: Understanding Barrier Interrelationships Using TISM

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ABSTRACT

The successful adoption of blockchain technology (BCT) in supply chains faces numerous barriers that are interconnected, posing challenges for managers seeking to implement this innovation effectively. Although existing literature highlights these barriers, there is a lack of studies that explore the mutual relationships among them, which are crucial for informed decision-making. Theories such as Diffusion of Innovation (DOI), Technology Organization-Environment (TOE), and Technology Acceptance Model (TAM) offer valuable insights into the adoption process but fail to address the interrelationships between barriers. This research utilizes the Total Interpretive Structural Modelling (TISM) approach to develop a comprehensive framework that maps the contextual relationships among these barriers, thereby providing a deeper understanding of the dynamics involved in BCT adoption in supply chains. Unlike traditional models like Interpretive Structural Modelling (ISM), TISM not only identifies transitive relationships but also validates them through expert opinions, ensuring a more accurate and effective analysis. The study aims to contribute to the theoretical foundation by establishing a performance model that aids in better decision-making for blockchain adoption in supply chains.

Keywords: Blockchain Technology, Diffusion of Innovation (DOI), Technology Acceptance Model (TAM), Total Interpretive Structural Modelling (TISM)

INTRODUCTION:

A number of variables, such as evolving customer expectations, global economic shifts, technology breakthroughs, and sustainability concerns, are driving significant changes in the modern supply chain (SC). The SC is evolving into a more client-driven, customer-focused, and intelligent organization. With more people who are spread out geographically, it is getting more complex. An increasing number of businesses engaged in various industries across various regions are participating in the exchange of goods, services, and information.

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The requirement for technology that can improve information visibility throughout the supply chain is developing as a result of these changes and the chain's increasing complexity. Blockchain (BC) is one example of a technology like this. Real-time data recording, management, and updating can be facilitated by its supply chain integration. The fact that it is a decentralized technology means that a central authority is not necessary to oversee its operation, which is its primary advantage. Blockchain technology (BCT) provides a clear picture for all players and lessens data manipulation. It is incredibly effective in reducing supply chain complexity, but not enough study has been done to ensure that it is used successfully.

Intricacy in SC may lead to problems with transparency, fraud risk management, information verification, and traceability. The present supply systems are managed by centralized internal information management systems. In this case, a single point of failure might make the system extremely susceptible to errors, corruption, hacking, and external attacks. (Monfared and Abeyratne, 2016) Blockchain has been marketed by suppliers and manufacturers as a cutting-edge technology that could benefit businesses (Viriyasitavat et al. 2020). Blockchain is a new technology that the World Economic Forum (WEF 2015) predicts will have a significant impact on every country in the next ten years. Gao et al. (2018) believe that supply chain management will undergo a major transformation in the future due to blockchain technology.

This paper covers the research conducted by Deepak Mathivathanan et al., 2020, who use an alternative qualitative technique called Total Interpretive Structural Modelling (TISM) to construct a strategic framework that explains supply chain occurrences. Dubey et al. (2017) state that TISM supports the development of a contextual relationship-based performance model for the purpose of analyzing and understanding the interactions between the many barriers inhibiting the application of blockchain technology in supply chains. In addition to illustrating how obstacles interact, TISM provides an explanation for each connection in the hierarchical model.

LITERATURE REVIEW

Blockchain is an unchangeable distributed ledger technology (DLT) that is resistant to manipulation. It operates in a shared, synchronized environment where user verification and tracking are available for every transaction. It is an open, distributed, peer-to-peer network ledger that may be used to store and record data and transactions backed by cryptographic values (Choi, 2020a Chang and colleagues, 2019a) Blockchain is an open, network-accessible distributed digital shared ledger. It allows for a decentralized environment where users of the network can safely communicate with one another without the need of a trustworthy authority. As a result, it does away with the need for a central authority by storing and validating each transaction through distributed consensus.

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A blockchain is composed of a set of connected blocks. Every block contains both its unique ID and the hash of the previous block to guarantee transaction security. Each transaction in the network is irreversible once introduced to the network, time-stamped, logged chronologically, connected to the previous block, and validated by its users. Hash values link blocks that hold records, and the consensus process determines whether to add new blocks to the system. It is difficult to make any modifications to the distributed ledger without the approval of every member of a blockchain (BC).

There are certain features of BCT that makes it a highly useful technology for its implementation:

- IRREVERSIBILITY: Every blockchain has a precise, independently verified record of each and every transaction ever made. These records are unchangeable, and any modifications need approval from every participant in BC.
- TRANSPARENT- With network consensus, data is recorded, retained, and made public and traceable for the duration of its existence.
- DECENTRALIZED: Data in the system is stored, observable, and updateable throughout several systems.
- OPEN SOURCE : Access is provided by BC to all users on the network; however, access can be restricted by role or permission.
- IMMUTABLITIY: By offering time stamps and controls, blockchain maintains immutability.

BCT has the power to totally transform supply chain management (SCM) thanks to its attributes of transparency, authenticity, trust, and security as well as cost reduction, disintermediation, efficient operations, and lowered waste (Philipp et al., 2019; Gurtu and Johny, 2019). It is commonly acknowledged that the distributed nature of blockchain lowers the risks associated with contract disputes, expensive legal compliance, hacking, piracy, and vulnerability in the SC (Min, 2019; Arza et al., 2020; Zhang et al., 2020).

Furthermore, by guaranteeing the mitigation of unfavorable outcomes in SC, blockchain lessens the disruption caused by paradigm shifts (Ivanov et al., 2019). Blockchain has made it possible for China's international trade ports to process fewer requests by integrating and disseminating information among all parties involved (Tan et al., 2018). Efficiency, openness, and a reduction in paperwork are all benefits of integrating BC into SC for any firm.

As a result, the application of blockchain technology in SCs improves efficiency and reduces costs while also fortifying bonds among all stakeholders. Queiroz et al. (2019) claim that it also streamlines related business procedures and builds confidence.

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Theoretical Gap:

Existing studies have identified individual barriers to blockchain adoption but have not developed a comprehensive theoretical framework that explores the interrelationships between these barriers. The inability of traditional models (DOI, TOE, TAM) to analyze these interrelationships limits our understanding of how these barriers collectively impact the adoption of blockchain in supply chains.

PROBLEM STATEMENT:

Blockchain technology has the potential to significantly enhance transparency, efficiency, and traceability in supply chains. However, despite its substantial benefits, the adoption of blockchain in supply chains faces numerous obstacles, including technological, organizational, and environmental challenges. While theories such as Diffusion of Innovation (DOI), Technology Organization-Environment (TOE), and the Technology Acceptance Model (TAM) have been widely applied to study technology adoption, they do not adequately address the interconnected relationships between the barriers to blockchain adoption.

While individual barriers to blockchain adoption in supply chains have been identified in the literature, there is a lack of a comprehensive theoretical model that explains the mutual relationships between these barriers. The failure of traditional models like DOI, TOE, and TAM to analyze these interrelationships creates a gap in understanding how these barriers interact to affect the successful adoption of blockchain technology.

Research Problem:

The primary research problem is to investigate the mutual relationships between the barriers to blockchain adoption in supply chains and to develop a comprehensive theoretical framework using Total Interpretive Structural Modelling (TISM) that can explain these interrelationships.

Research Questions:

1. What are the key barriers to blockchain adoption in supply chains?
2. How do these barriers interrelate and influence each other?
3. How can the insights gained from TISM be used to develop strategies that facilitate the adoption of blockchain in supply chains?

The identified research problem aims to fill the gap in existing literature by developing a comprehensive theoretical model that explores the interrelationships between barriers to blockchain adoption in supply chains. By applying TISM, this research seeks to provide a deeper understanding of these barriers and their collective impact on the adoption process, offering valuable insights for both theory and practice.

METHODOLOGY:

The fundamental outlines of the TISM approach are as mentioned. The first step involves creating the sample and collecting the data is the first stage. Here, we list a number of obstacles

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to the effective deployment of blockchain in SCM by defining them and drawing on previous literature. Determining the contextual relationship between the barriers on the list is the next step. Pairwise contextual linkages are shown here. They are determined by consulting experts. For example, if Barrier B1 will affect Barrier B2, and so forth, along with the interpretation that goes along with it. Within the framework of our research, the elucidation of how Barrier B1 impacts Barrier B2, and so forth, is documented in the knowledge base matrix via expert discussions in terms of Yes/No responses along with the rationale supporting them; consequently, the interpretive knowledge base is developed.

In this case, the experts must supply the pairwise contextual relationships between each barrier. This further evolved the knowledge base into a table where each row corresponds to a comparable pair of barriers and the contextual relationship that currently exists between them. The Yes/No link between the compared barriers is interpreted logically and expressed as a "n x n" matrix, where n is the total number of obstacles that were taken into consideration for the study. Every (i,j)th cell has a value of either "1" or '0' is input depending on how much barrier Bi influences the barrier Bj, where '0' indicates the absence of an influential link between Bi and Bj and '1' indicates the presence of one.

Any potential transitivity is examined in the first reachability matrix that results from the logical interpretation of the Yes/No relationship. The knowledge base is renamed as "transitive link" for each potential transitive connection, and the interpretation column is populated with one or more elements for transitive relationship.There could be several indirect relationships. The transitivity check identifies these relations. The final reachability matrix is obtained and the transitive relations are recognized.

The next step involves level partitioning. The purpose of level partitioning is to determine where barriers should be placed at each level. Based on the driving and dependent powers of each barrier, the reachability set, antecedent set, and intersection set are calculated and arranged in a table. According to Mathiyazha Gan et al. (2013), the boundaries at the top of the hierarchical level do not extend beyond it. Each barrier's level is discovered via an iterative procedure akin to that used in ISM. The diagraph and the TISM model are based on these levels. The final reachability matrix, which is composed of entries on pairwise assessments owing to direct relationships along with some of the entries obtained from inferred transitive relationships, or the effective transitive relationships, is what the previous phase gives us.

The reachability, antecedent, and intersection sets for each barrier are produced from the final reachability matrix (Mathiyazhagan et al. 2013). The highest level (Level I) barrier is identified as the one for which the intersection set and the reachability set match, and the Level I barriers are eliminated from the set as a whole for the subsequent iteration table. Until all barriers have their matching levels assigned, this process is repeated.

Then, based on their levels, the barriers are graphically grouped and a diagraph is formed. The connections between them are shown as arrows according to the linkages found in the final reachability matrix. By translating all depicted interactions as "1" and leaving the remaining cells empty of entries, a binary interaction matrix based on the derived diagraph is produced.

The creation of the TISM model is the last phase. The resulting diagraph displays the information from the interpretative matrix across the corresponding linkages. In the final step,

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the validation of TISM model is done by using expert opinion to only accept meaningful pairwise comparisons and provide logic for each such comparison.

CASE PROBLEM AND ANALYSIS

This case study examines the obstacles to the successful adoption of blockchain technology (BCT) in supply chains and the interrelationships between these barriers. The study utilizes the Total Interpretive Structural Modelling (TISM) approach to explore these connections, with the goal of providing insights that will guide managers in making informed decisions about implementing BCT.

Blockchain technology can play a vital role in cultivating the supply chains by bringing more transparency, track recording, effectiveness and efficiency. However, adoption of this new technology is hindered by several barriers, which may be broadly categorized as Technological empowerment challenges, organization's unwillingness, challenges related to environmental sustainability. While existing theories like the Diffusion of Innovation , Technology Organization-Environment framework, and Technology Acceptance Model provide useful insights into technology adoption, however they fail in interpreting the among the identified barriers. This research adopted TISM which successfully addresses these shortfalls and establishes a transitive relationship between barriers along with providing a strategic framework for understanding their interplay.

The study identified the following key barriers in adoption of blockchain through extensive literature review and keyword search with expert consultation. Experts were academic researchers, industrial strategic managers, policy makers etc. The barriers identified were broadly categorised in three groups: Technological empowerment challenges, organization's unwillingness, challenges related to environmental sustainability.

Technological empowerment challenges: High implementation costs, lack of interoperability, data privacy concerns.

Organizational unwillingness: Resistance to change, lack of skilled personnel, inadequate leadership support.

Environmental sustainability challenges: Regulatory uncertainties, lack of industry standards, external stakeholder resistance.

The experts were asked to create their own reachability matrices to identify the direct and indirect relationships among the identified barriers. Then these scores were aggregated to represents the final reachability matrix. The steps followed were

Structural Self-Interaction Matrix (SSIM): Experts evaluated the pairwise relationships between barriers to create the SSIM.

Reachability Matrix: The SSIM was converted into a reachability matrix, and transitive relationships were identified.

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Level Partitioning: The barriers were partitioned into different levels based on their driving power and dependence.

Diagraph Construction: A diagraph was created to visualize the hierarchical relationships among the barriers, with arrows indicating the direction of influence.

Expert Validation: The transitive relationships identified in the TISM model were validated by experts to ensure accuracy and relevance.

RESULT ANALYSIS

Technological Barriers: High implementation costs were identified as an initial barrier. High Implementation cost also influences technological barriers like lack of interoperability. Data privacy is also a big challenge because of lack of interoperability as unified incorporation of Blockchain across systems could be responsible for breaching sensitive data.

Organizational Barriers: Resistance to change proven to be the primary key barrier in this class followed by the influencing the lack of skilled personnel and inadequate leadership support. Therefore, the research indicates that the training and employee empowerment could play a significant role in adoption of such type of technologies. The other reason behind the organizational Barriers could be the inadequate leadership support.

Environmental Barriers: Regulatory uncertainties were identified as a significant barrier that influenced external stakeholder resistance and lack of industry standards. The diagraph highlighted that external stakeholder resistance is both a driver and a dependent barrier, influenced by regulatory uncertainties and contributing to the lack of industry standards.

CONCLUSION AND SUGGESTIONS

This case study demonstrates the effectiveness of the TISM approach in analyzing the complex interplay between barriers to blockchain adoption in supply chains. The findings provide valuable insights for managers and policymakers, enabling them to make informed decisions that facilitate the successful integration of blockchain technology.

Further research could involve empirical validation of the TISM model using real-world data and exploring the application of the model in different industries. Additionally, the integration of TISM with other analytical methods, such as Structural Equation Modelling (SEM), could enhance the robustness of the findings.

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Job Crafting as a Pathway to Eudaimonic Well-Being: A Self-Determination Theory-Based Conceptual Framework

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Abstract

Employee well-being has become a significant focus in organisational research yet much of the literature only focuses on the satisfaction, positive affect, and the absence of strain, which provide very limited insights into eudaimonic well-being that focuses on optimal work-life, personal development, purpose, and the realisation of one's potential. While research on job-crafting has shown that employees are not simply passive recipients of predetermined job characteristics, but can actively modify aspects of their job to better adapt in work and role that fit to their needs, abilities and aspirations. While the two streams of research are compatible, there is a lack of context to understand the ways in which job crafting may contribute to eudaimonic well-being. Drawing on Self-Determination Theory (SDT), the present paper develops a conceptual framework highlighting that satisfaction of basic psychological needs for autonomy, competence, and relatedness as driving forces that can link job crafting with eudaimonic well-being. The various forms of job crafting enable employees to take ownership of their work, to be effective and to have meaningful relationships with others that in turn contribute to fulfilling the need and hence to eudaimonic functioning. The framework also recognises that the benefits of job crafting are dependent on the organisation. By shifting attention from whether job crafting makes employees feel better to how employees actively shape work in ways that enable them to function and develop more fully, this paper offers an eudaimonic interpretation of job crafting and identifies directions for future research on proactive work design and sustainable employee well-being.

Keywords: job crafting; eudaimonic well-being; Self-Determination Theory; basic psychological needs; autonomy; competence; relatedness; employee well-being

1. Introduction

Employee well-being has moved from being a peripheral issue to a central one in contemporary organisational research (Warr, 2007). Changing work settings, technological change, high workloads, and increasingly fluid career structures have intensified the awareness of how work is contributing to and detracting from employees' well-being (Sonnentag, 2018). However, the majority of the literature on well-being is still focused on a hedonic view of well-being, with job satisfaction, positive feelings, happiness, or even stress and burnout, or reducing negative experiences as the main drivers of success (Diener, 1984; Schaufeli & Bakker, 2004). While good feelings and working well are important, the eudaimonic perspective offers a more general perspective (Ryan & Deci, 2001). Eudaimonic approaches focus on human potential, purposeful work, self-development, autonomy, meaningful engagement, and positive

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relationships (Waterman, 1993; Ryff, 1989). In this way, work is a source of well-being not only because it can create enjoyable jobs but because it is an area in which people can take on agency, learn skills, be in good relationships, and have meaningful objectives (Huta & Ryan, 2010). This is especially true because employees are now exercising more agency over how they feel and do their job (Wrzesniewski & Dutton, 2001). Prior work design models have typically viewed jobs as structures designed by the organisation and experienced by employees (Hackman & Oldham, 1976). But more recent research has shown that employees play a role in shaping their work (Berg, Dutton, & Wrzesniewski, 2008). Job crafting captures this proactive role that describes changes to tasks, relationships, and cognitive processes that individuals make by themselves (Wrzesniewski & Dutton, 2001). People can change what they do, how they interact with others, and how they perceive the significance of their work (Tims, Bakker, & Derks, 2012). Work engagement, job happiness, meaningfulness, performance, and low stress have been associated with job crafting and have been shown to be optimal for employees (Petrou, Demerouti, & Schaufeli, 2018). However, there is still a question that has not been answered: Can employees craft their jobs not merely to make work more satisfying, but to create conditions that enable them to function and flourish more fully?

We propose that eudaimonic well-being provides a particularly appropriate lens through which this question can be addressed. Job crafting is a form of individual agency in how one creates work, whereas eudaimonic well-being is the realisation of human capabilities and functioning (Ryan & Deci, 2001; Ryff, 1989). The theoretical connection between the two therefore extends beyond the possibility that job crafting simply generates positive feelings. By changing aspects of their jobs, employees may actively create work environments that better support autonomy, competence, meaningful relationships, development, and purposeful functioning (Deci & Ryan, 2000).

Yet the pathway connecting these constructs requires theoretical explanation. Why should changing one's tasks, relationships, or perceptions of work contribute to deeper forms of well-being?

This question is addressed through the lens of Self-Determination Theory (SDT; Deci & Ryan, 2000; Ryan & Deci, 2017). SDT posits that the most successful functioning requires satisfying three fundamental psychological needs: autonomy, competence, and relatedness (Deci & Ryan, 2000). We propose that job crafting can be a system of bottom-up mechanisms in which employees create work experiences to meet these needs. In doing so, employees may exercise a greater degree of autonomy, deploy and develop skills, and better form meaningful relationships with others. That satisfaction of these needs is the psychological basis of eudaimonic functioning (Ryan & Deci, 2001). Thus, this paper makes three contributions. First, it expands the job crafting literature by pointing out eudaimonic well-being as a theoretically significant outcome far beyond the commonly studied job satisfaction and engagement measures. Second, it identifies psychological need satisfaction as a mechanism of why job crafting is likely to enhance eudaimonic well-being. Third, it develops an integrated conceptual framework that connects various forms of job crafting to autonomy, competence, and relatedness and contributes to more precise theoretical predictions about how employee-driven change in work might be conducive to flourishing.

2. Job Crafting: Employees as Active Designers of Work

Job crafting was introduced by Wrzesniewski and Dutton (2001) to explain how employees actively change the boundaries and meaning of their work. Rather than treating employees as property of formal job design, job crafting recognises that people can still exercise agency in

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their job roles. Wrzesniewski and Dutton defined three types of job crafting: task crafting, relational crafting, and cognitive crafting.

Task crafting involves altering the number, type, scope, or manner of work activities. Employees may voluntarily take on new responsibilities, emphasize particular tasks, or modify how existing activities are performed. **Relational crafting** is changing the nature or extent of the interaction with others at work. People might wish to work with certain peers, clients, students, patients, supervisors, etc. that make their work more positive and meaningful to them. **Cognitive crafting** is changing how people think and view their work. An employee may move from viewing individual tasks as isolated activities to understanding them as contributing to a broader purpose.

Job Demands-Resources (Tims & Bakker, 2010) has provided a more professional view of job crafting, where employee proactively change the job demand and resources to better fit into the role. Despite differences between conceptualizations, a common principle remains: employees possess some capacity to actively shape their work environment rather than simply adapt to it.

The vast majority of the literature has been about whether job crafting improves conventional work outcomes. However, job crafting could also have a great impact that goes beyond making employee more engaged and productive. When an employee can sync their work with personal goals, values, strength and aspirations match job crafting with your own work goals, strengths, ambitions, and relationships, then the employees are not just making their work better but they are also shaping the conditions under which they function as individuals.

This possibility creates an important connection with eudaimonic well-being.

3. Moving from Feeling Good to Functioning Well

Employee well-being is not a unitary phenomenon. There is a good distinction between hedonic and eudaimonic sense of well-being.

Hedonic sense of well-being involves happiness, pleasure, satisfaction and the balance of positive and negative affect. Social and economic constructs such as job satisfaction and positive affect are representative of such a tradition. From this hedonic point of view, a good job is one that allows employees to have positive feelings and not to have too bad experiences.

Eudaimonic well-being, on the other hand is a different question. It is not only about whether they feel good but whether they are actually functioning well. Eudaimonic approaches focus on the realisation of one's potential in life, growth in living life, autonomy, mastery and relationships. Ryff's (1989) model of psychological well-being, for example, focuses on autonomy, environmental mastery, personal growth, positive relations with others, purpose in life and self-acceptance. Self-Determination Theory also identifies eudaimonic functioning as autonomous action, psychological need satisfaction, growth, and integration. This difference matters in the workplace. An employee might be very satisfied in a job and at the same time, that job is without any growth, purpose or self-realisation. Conversely, demanding work may occasionally generate discomfort while simultaneously providing strong opportunities for mastery, personal development, contribution, and meaningful accomplishment.

Consequently, assessing the value of job crafting only through satisfaction or positive affect may underestimate its deeper implications.

When employees modify their jobs, they may be attempting to bring work into closer alignment with who they are and who they want to become. Taking responsibility for challenging

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assignments can create opportunities for growth. Developing new relationships may generate connection and contribution. Reinterpreting routine activities in relation to a broader social purpose may enhance meaning. These experiences correspond closely with the eudaimonic conception of optimal functioning.

We therefore propose:

Proposition 1: Job crafting is positively associated with employees' eudaimonic well-being.

However, this general relationship does not explain the psychological process through which crafting translates into eudaimonic functioning. Self-Determination Theory provides such an explanation.

4. Self-Determination Theory as the Explanatory Mechanism

Self-Determination theory posits that people have three basic psychological needs: autonomy, competence, and relatedness, which are when satisfied helps to motivate and develop psychological growth, integration and well-being (Deci & Ryan, 2000; Ryan & Deci, 2017).

Autonomy is experiencing one's actions as volitional and self-endorsed. It doesn't mean independence; it means that one's behaviour is in line with one's values and choices.

Competence is being able to interact with your environment, build abilities, and overcome obstacles.

Relatedness is about experiencing connection, belonging, shared care, and meaningful relationships with others.

SDT contends that these needs are fundamental psychological nutriments. Environments supporting their satisfaction facilitate optimal functioning, whereas environments that systematically frustrate them undermine well-being.

The literature on SDT research examines how organisational conditions, such as leadership, managerial autonomy support, or job design, promote psychological need satisfaction. Job crafting offers an alternative bottom-up perspective, where the employees are not just waiting for organisations to make need-supportive workspaces for their work but the employees can, within certain areas of work, proactively change aspects of their work so it is more need-supportive for them.

This creates the central theoretical argument of this paper:

Job crafting represents a proactive mechanism through which employees participate in constructing the psychological conditions necessary for their own eudaimonic functioning.

The three basic needs provide more specific pathways for explaining this process.

5. Job Crafting and Autonomy: Crafting Work That Feels Self-Endorsed

Job crafting inherently involves an element of agency. When employees voluntarily modify aspects of their work, they move beyond merely complying with prescribed role expectations and exercise discretion regarding how their work is performed or understood.

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Task crafting may particularly facilitate autonomy. An employee who changes the sequence of tasks, adopts a personally preferred approach, or voluntarily assumes responsibilities aligned with personal interests may experience greater ownership of work. Even where formal job autonomy is limited, small changes in work methods may increase employees' sense that they are active agents rather than passive executors of organisational demands.

Cognitive crafting can also contribute to autonomy by enabling individuals to interpret work in ways consistent with personally held values. Two employees may perform identical tasks while construing their significance differently. When employees connect routine activities to personally meaningful goals, their motivation may become more internally endorsed. Importantly, autonomy in SDT does not require unrestricted freedom. Employees can experience autonomy while operating within organisational constraints when they understand and personally endorse the reasons for their actions. Thus, job crafting may facilitate autonomy even when the formal boundaries of the job remain largely unchanged. Autonomy is closely connected with eudaimonic functioning because living and acting in accordance with personally endorsed values represents an important aspect of psychological authenticity and self-realisation.

We therefore propose:

Proposition 2: Job crafting promotes eudaimonic well-being by enhancing employees' satisfaction of the basic psychological need for autonomy.

6. Job Crafting and Competence: Crafting Opportunities for Growth

Job crafting can also contribute to eudaimonic well-being to help employees develop and express competence. People have a lot of different abilities, interests and developmental needs, and a job description can't always match them perfectly. With task crafting, employees can seek challenging jobs, take on new tasks, apply undervalued skills or invent new ways to accomplish their work. These changes create opportunities for mastery.

For example, a person who is willing to take on a new project may be more involved in the beginning. But the hard work of mastering those demands can provide a sense of capability and growth. From a purely hedonic standpoint, additional work might be bad for you because it takes longer. But from a eudaimonic point of view, appropriately challenging experiences might be good for you as you grow and develop. And that is why eudaimonic well-being is an important result of job crafting research.

Not every good crafting activity makes work easier and pleasure more immediate. Some forms of crafting may involve deliberate challenge seeking, experimentation, learning and sometimes uncomfortable work, but ultimately, help in human development.

Thus:

Proposition 3: Job crafting promotes eudaimonic well-being by enhancing employees' satisfaction of the basic psychological need for competence.

7. Job Crafting and Relatedness: Crafting Meaningful Connections

Work is inherently relational. People work with colleagues, supervisors, customers, students, clients, and other stakeholders. The quality and the meaning of these interactions can be decisive in whether work is isolating or socially important.

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Relational crafting allows employees to purposefully create their relationships. They may become more involved with those from whom they learn, more collaborative, be more helpful to their colleagues, or better connected with the beneficiaries of the work they do. Such crafting also gives more meaning to having connected people and sharing caring experiences. But relational crafting can also help employees to see the human impact of their work.

A person who has relationships with beneficiaries, for instance, might even feel more connected and understand better how they help others. Cognitive crafting can be part of this process to enable staff to see the work they do as a larger team and not as a single job. Relatedness is a third connection between crafting and well-being as positive relationships and help to others are key to eudaimonic functioning.

Accordingly:

Proposition 4: Job crafting promotes eudaimonic well-being by enhancing employees' satisfaction of the basic psychological need for relatedness.

8. An Integrated Conceptual Framework

Bringing these arguments together, we propose that job crafting contributes to eudaimonic well-being through the satisfaction of basic psychological needs.

The basic framework can be represented as:

Job Crafting → Basic Psychological Need Satisfaction → Eudaimonic Well-Being

At a more differentiated level:

Task Crafting → Autonomy and Competence

Relational Crafting → Relatedness

Cognitive Crafting → Autonomy and Meaningful Functioning

These relationships should not be interpreted as mutually exclusive. Task crafting may also influence relatedness, relational crafting may facilitate competence through learning relationships, and cognitive crafting may affect all three needs. Nevertheless, distinguishing the dominant pathways provides greater theoretical precision than treating job crafting as an undifferentiated predictor of well-being.

The central mediation proposition is therefore:

Proposition 5: Satisfaction of the basic psychological needs for autonomy, competence, and relatedness mediates the positive relationship between job crafting and eudaimonic well-being.

The model changes the theoretical interpretation of job crafting. Rather than conceptualizing crafting simply as a strategy for obtaining more job resources, the proposed framework positions employees as active participants in constructing conditions conducive to their own development and optimal functioning.

9. The Boundaries of Beneficial Job Crafting

Although job crafting is proactive, it should not automatically be assumed to generate positive consequences. Employees operate within organizational systems involving interdependence,

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formal responsibilities, professional standards, and resource constraints. Crafting that maximizes individual preferences while disregarding these constraints may create role conflict, workload redistribution, coordination difficulties, or negative consequences for colleagues.

The benefits of job crafting for eudaimonic well-being should therefore depend partly on whether the organizational environment provides sufficient latitude for constructive crafting.

Job autonomy is particularly relevant. When employees have discretion regarding how they organize and perform work, crafting attempts are more likely to be accepted and successfully implemented. Conversely, highly standardized or tightly controlled environments may restrict employees' ability to modify tasks and relationships.

Similarly, **organizational and supervisory support** may determine whether crafting is interpreted as desirable initiative or inappropriate deviation from prescribed roles. Supportive environments may legitimize experimentation and encourage employees to align work with their strengths and developmental needs.

This suggests:

Proposition 6: The positive relationship between job crafting and psychological need satisfaction is stronger in work environments characterized by greater job autonomy and organizational support.

The inclusion of contextual conditions is important because eudaimonic well-being should not be framed solely as an employee's personal responsibility. Employees can exercise agency, but the capacity to craft work remains embedded within structural and relational conditions created by organizations.

10. Discussion

10.1 Theoretical Contributions

The proposed framework adds to the research on job crafting and employee well-being in several ways. First, it expands the outcome domain of job crafting and explicitly includes eudaimonic well-being. Recently, job crafting research has provided important evidence for engagement, satisfaction, performance, and burnout. But these outcomes are not a complete picture of how employees view work as a place for learning, agency, meaningful work, and the discovery of potential. Using the eudaimonic perspective shifts the focus in job crafting from "Does job crafting make employees feel better at work?" to "Does job crafting allow employees to function and develop more fully through work?"

Second, the paper provides a theoretical mechanism for the connection between job crafting and eudaimonic well-being. But simply establishing that proactive changes to work predict well-being is not enough to explain why such a relationship exists. We use SDT to argue that job crafting leads to well-being when it allows one to fulfill autonomy, competence, and relatedness.

Third, the framework provides a bottom-up understanding of psychological need satisfaction. Organizations have historically been interested in whether managers, leadership styles, or the organization's formal job characteristics meet employee needs. Our model suggests that employees can even be involved in making their work more need-supportive. So, need satisfaction is not just something that organizations provide to employees, but they can work on it if they will and in the right circumstances.

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Fourth, our framework indicates that there is a clear and important difference between hedonic and eudaimonic effects of crafting. Some crafting practices, particularly those around challenge seeking and development, might temporarily increase effort while at the same time increasing competence and growth as a person. So, assessing such behaviors purely on the basis of immediate satisfaction or strain would be incomplete.

10.2 Practical Implications

The framework has implications for organisations that wish to develop sustainable employee well-being. In many organisations, well-being processes are in fact based on positive or negative experiences in order to minimise negative experiences of employees. But though helpful, these methods may put employees on the receiving end of organisational well-being initiatives.

The framework in this paper suggests that organizations can also create a culture that allows employees to participate in shaping work that meets their psychological needs. Managers can facilitate constructive job crafting by giving appropriate discretion, encouraging employees to work with their strengths, enabling development of relationships, and talking about the larger significance of employees' work. But encouraging employees to design their jobs should not be an alternative to responsible organisational work design. Poorly designed jobs are not always repaired by chance and can never be fixed by individual initiative. Organisations have to provide the right demands, resources, treatment, and psychologically supportive working conditions. Job crafting should complement rather than replace organisational-level work design.

11. Directions for Future Research

The framework creates several opportunities for empirical investigation.

Future studies should first look at whether basic psychological need satisfaction mediates the relationship between different forms of job crafting and eudaimonic well-being. Because job crafting and well-being might work in concert, longitudinal research would be particularly valuable. More eudaimonic workers with high psychological well-being might have more psychological resources for future crafting, resulting in a potential gain cycle.

Second, researchers should look at task, relational, and cognitive crafting differently. Task crafting may have particularly strong implications for autonomy and competence, while relational crafting may be particularly relevant for relatedness. Testing these differentiated pathways would clarify how job crafting plays a role in well-being in more detail.

Third, we should also address the costs and limits of crafting. Excessive challenge crafting, for one thing, may eventually lead to overwhelming workloads. Relational crafting could create exclusionary networks, and task crafting may be a route that shifts unwanted tasks to colleagues. Therefore, the relationship between crafting and well-being may not always be linear. Contextual factors need to be taken into consideration. Job autonomy, leadership support, occupational norms, interdependence, and organizational climate might determine when employees are able to turn crafting intentions into need-supportive work experiences.

Finally, the framework should be cross-disciplinary and look at occupation-specific work. Crafting may be highly different for highly autonomous knowledge workers and workers who work in well-established or regulated work cultures or in safety-sensitive environments. Cross-occupational research can thus clarify the boundary conditions of the proposed relationships.

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12. Conclusion

Employees do not just do jobs; they shape them. This has made job crafting a major focus in modern work design research. But crafting may not simply bring better job satisfaction or engagement. By changing what people do, whom they interact with and how they understand their work, employees may set up circumstances in which they can be more independent, competent, have meaningful relationships and work more effectively.

Drawing on Self-Determination Theory, we argue that satisfaction of the basic psychological needs for autonomy, competence and relatedness is the psychological bridge between job crafting and eudaimonic well-being. The framework thus sees job crafting as a process of proactive work design through which employees can contribute to the building of work experiences that promote growth and performance. The main point is simple but also theoretically important: employees can create not only better jobs but also opportunities for themselves to be a better person and to work better in a better job.

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Adoption and Employment of Artificial Intelligence (AI) in India: An economic analysis across different sectors

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Abstract

"Artificial Intelligence is ready to disrupt our world, with the advent of high-level machines capable of performing tasks at higher speed and machines that are capable of thinking, learning, perceiving, problem solving and decision making, AI presents opportunities to complement and supplement human intelligence and enrich the way people live and work." (NITI Ayog, 2018). Automation and artificial intelligence usage is now almost everywhere. The new industrial revolution, sometimes referred to as "industrial revolution 4.0," with the advent of AI may lead to both future job growth and large job losses. AI has both beneficial and negative effects on employability globally in the modern world. This paper explores how AI affects employability, particularly in India, as well as the potential and difficulties it presents. The Indian economy is developing quickly and is impacted by global issues. India's technology sector has undoubtedly grown significantly, but the primary goal is still to promote talent development and AI adaption. AI is a "double-edged sword" since technology has the ability to replace repetitive tasks while also opening doors for upskilling and shifting the economy toward higher-value employment. AI has the potential to improve employability globally and can readily automate current duties. With the development of AI, repetitive daily jobs are probably going to decrease. Additionally, new employment roles are emerging as a result of AI, and old jobs are changing as a result of AI. "Reskilling and Adapting AI" is crucial. AI has a complex effect on employment in India; in some industries, it results in both job growth and job displacement. Diverse effects can be observed in India's many industries, which will be covered in this paper. Causes of unemployment and a look at Monetary Policy approach to reduce unemployment via repo-rate will also be a part of discussion of this paper and finally role of government and data from existing reports will be discussed all in Indian context.

Keywords

Artificial Intelligence; Automation; Shifting Skills; Displacement; Employment; Transformation;

Sectoral Analysis; Digital Economy; Labor Market

JEL Classification

O33, J23, J24, L86, J21

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Introduction

Artificial intelligence is a topic that is discussed worldwide and is a constantly developing field. Businesses are spending a lot of money implementing AI and contemporary technology. Some jobs are changing, some are going extinct, and new ones are developing as a result of AI. AI has enormous potential to raise worker productivity by automating monotonous everyday operations and freeing up personnel to concentrate on important areas that require critical thinking and concentration. This will ultimately increase the firm's total output. India has a large pool of highly qualified IT workers, and nations like the US can hire engineers from India for relatively little money roughly 60–70% less. According to a comprehensive assessment published by the World Economic Forum 2023, automation and artificial intelligence might cause India to lose 5.1 million jobs by 2025; the industrial and retail sectors will be most affected. Ironically, 2023 World Economic Forum research claims that by 2025, AI will generate 2.3 million employment opportunities in India, mostly in the IT, energy, and healthcare sectors. About 200,000 AI specialists in India are still missing, according to Analytics India Magzine India still needs to get past this obstacle. According to a comprehensive analysis by the "National Association of Service and Software Providers (NASSCOM), the AI sector is predicted to increase by 30% per year and reach a significant valuation of $25 billion before 2025." However, there are still certain obstacles, such as a lack of understanding and acceptance, a shortage of AI specialists, a lack of qualified labor, and ignorance of the unorganized sector. AI has a mixed effect on employability in India; it causes job losses but also creates chances for competent workers, which boosts the country's economy. Building a clear artificial intelligence ecosystem and closing the skill gap can benefit India. Following the arrival of AI, the Indian economy has seen both job potential and job displacement. Jobs involving routine operations like data entry and administrative work has decreased in industries like IT and BPO because these jobs are easily mechanized. The government's top priority is still upskilling.

In India, the government is essential to the management of the AI ecosystem. Fairness, openness, and regulation are necessary to safeguard workers' rights, and ethical considerations are also present. AI has benefited industries like banking, finance, healthcare, and agriculture, but the informal sector is suffering from high job displacement, which will be covered in this paper. The main topic of debate in this paper is India's future with AI.

Review of the Literature

"The future is artificial intelligence, but we need to make sure it's the future we want." -Tim Cook

AI is a topic of conversation everywhere, and numerous research on AI and employment have already been carried out globally. One of the most hotly contested issues in the world is the relationship between AI and jobs. Research shows that AI boosts worker productivity, but opinions on how it affects occupations vary. There are also government reports on the subject.

Nowadays, automating repetitious chores with the help of Machine learning and robotic process automation (RPA) technologies is popular. According to World Economic Forum research, 42% of present company functions will be automated globally by 2025, with clerical positions experiencing the largest global decline. Chatbots, virtual agents, coding helpers, and

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other contemporary AI tools and techniques are helping a number of industries expand by concentrating on key areas.

"The odds are never in India's favor to rise and with the age of AI a sentiment rooted in India's demographic advantage and growing capabilities," the CEO of Github previously stated. However, risks and ambiguity persist. India's labor force is expanding, and the country's population is predicted to reach 1.66 billion by 2050. Additionally, there are issues with job displacement, skill mismatch, income inequality, and the growing trend of informality due to the development of AI, ML, deep learning, robotics, and digital platforms, as well as the expectation of future labor force growth.

According to Frey and Osborne's 2017 report, automation may eventually replace about 47% of American occupations. According to their research, repetitive and routine jobs are more vulnerable to automation. On the other hand, Acemoglu and Restrepo's 2020 study contended that automation affects both productivity and displacement. According to their analysis, automation has the potential to replace ordinary work and lower employment in some areas, but technology innovation also boosts employment by generating new industries, professions, and the need for skilled labor, which helps to partially offset job losses.

According to research by a number of Indian writers, AI is anticipated to benefit practically every sector of the Indian economy. Upskilling and adapting to contemporary technology are necessary for people to get the most.

Artificial intelligence (AI) has the potential to eliminate millions of jobs, but it is also anticipated to create new opportunities in fields like data analytics, AI development, cybersecurity and digital services (World Economic Forum, 2023). In order to assist workers in adjusting to technological change, the research highlights the significance of reskilling and lifelong learning.

AI has enormous potential to boost productivity in India, particularly in industries like manufacturing, healthcare, education, and agriculture. However, it also cautions that people without digital skills may encounter difficulties finding work (NITI Ayog, 2018). In a similar vein, AI is more likely to change employment than to totally replace them, according to the ILO (International Labor Organization, 2023).

India has the fastest rate of AI adoption, above the worldwide average. The Indian AI market is expected to grow to $17 billion by 2027 (BCG Report, 2024), which is encouraging. While AI has great potential, it also poses challenges. From adoption to execution, strategic management of AI is necessary.

According to recent studies, the effects of AI vary by industry. For example, demand for IT and financial services has increased, while demand for manufacturing and clerical professions has decreased. Because they frequently lack access to digital infrastructure and training, informal workers are particularly vulnerable.

AI does not entirely eliminate occupations; rather, it transforms the nature of work, according to research by numerous authors and reports that are accessible online. AI has enormous job-creation potential. The only goal is to reskill or upskill in accordance with the requirements. In the future, there will be more job opportunities than job losses. India must be "AI Ready."

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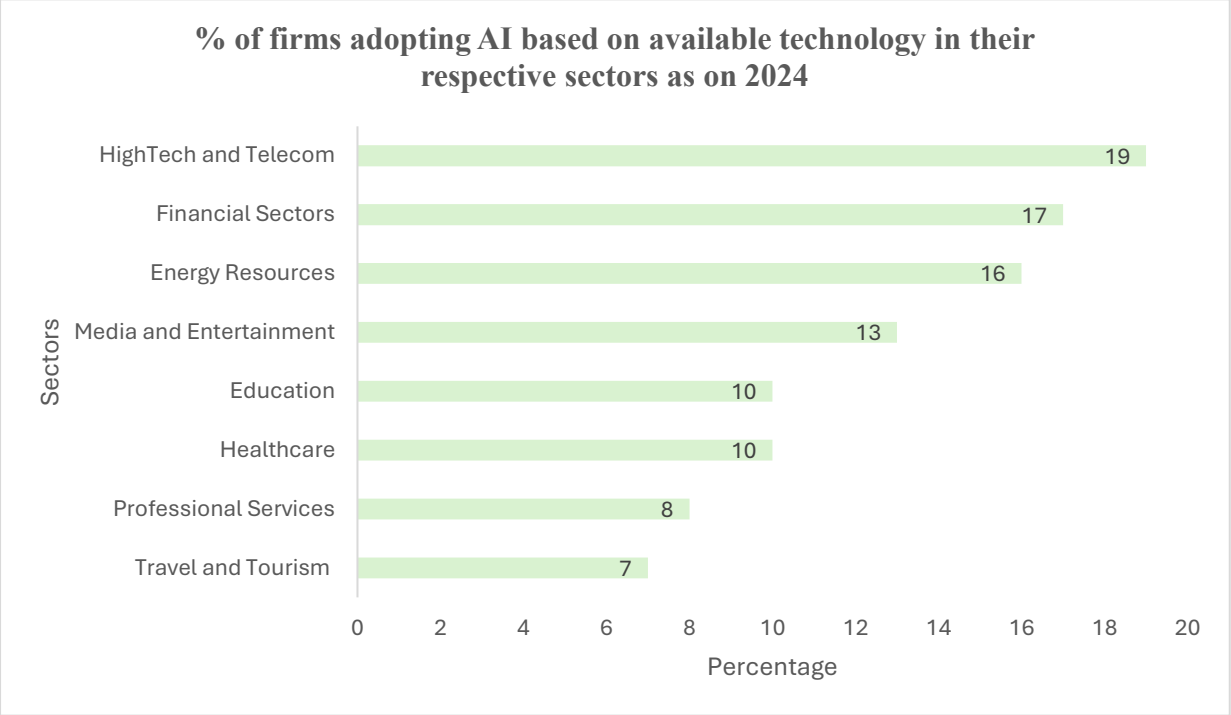
Research Gap

This study, which aims to investigate how AI adoption affects employment across specific sectors of the Indian economy, was motivated by the discovery that there is a lack of literature regarding the sectoral impact of AI on employment and little data available for developing countries like India. This paper also aims at identifying the link between AI and unemployment as not much of the literature is available on the same.

Research Objective

- Impact of AI on employment potential in India, sectoral analysis.
- To study whether AI complement or replace labor.
- Policies India should adopt.
- To study sectors that are most expose to AI.
- Monetary Policy approach to unemployment.

Firms adopting AI based on available technology in their respective sectors as on 2024



"India is leading in AI adoption at 30% surpassing global average of 26%." (BCG Report,2024) High tech and telecom firms shows the highest percentage of AI adoption of 19% followed by financial sectors 17% and energy resources 16% while travel and tourism showed the least adoption of only 7%. Service sector is the most affected by AI adoption (BCG Report, 2024).

"In order to unlock full potential and realize available opportunities of AI in India three priorities should be there: Transform at Scale, Innovate with depth and Diffuze inclusively. Indias has a projected $17Bn AI market by 2027, a good growing startup ecosystem and 80%

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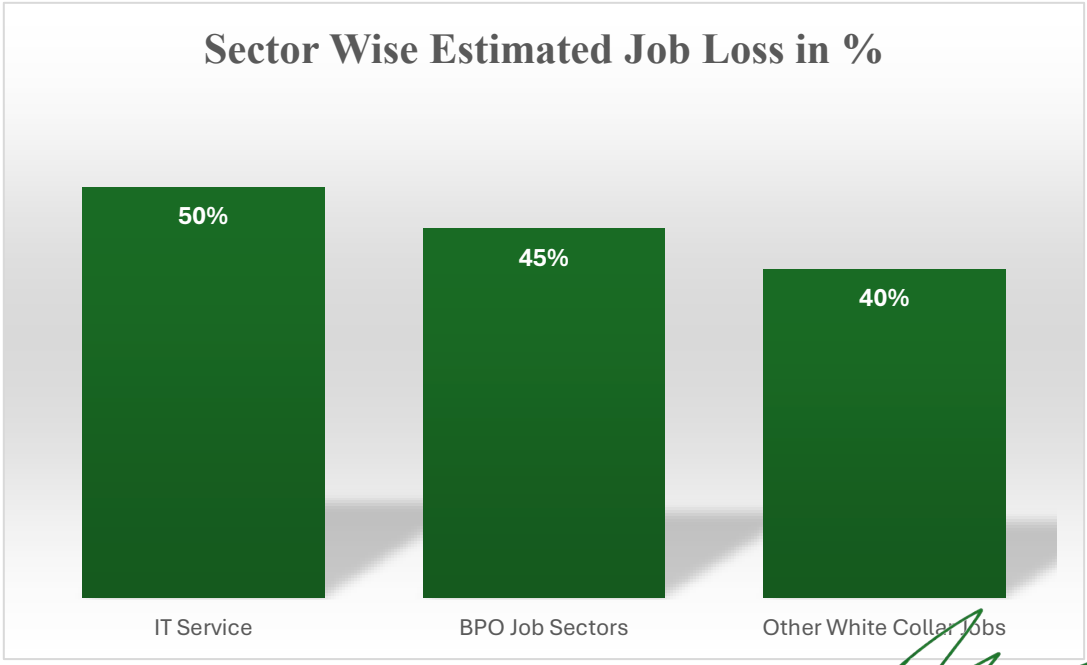
of the organizations citing AI as priority which means AI is expected to increase Indian GDP and market in future". (India's Triple Imperative BCG, 2025)

How Organizations in India are using AI today? (2024)

Automation of IT process	45%
Automation of Business Processes	31%
AI Monitoring and Governance	30%
Business Analytics and Intelligence	30%
HR and Talent Acquisition	28%
Security and Threat Detection	36%
Sustainability	30%
Financial Planning and Analytics	30%
Fraud Detection	28%

As per BCG report 2024 organizations are increasingly adopting AI as can be seen from the above table AI is being used for automation of IT process with the highest percentage 45% while for HR, talent acquisition and fraud detection services it is being used at the lowest i.e 28% only. Organizations are actively adopting AI as a part of their workings in order to gain good and timely results. As per survey it was found that with the help of AI workers are saving one full day of work in a week which is a good sign. AI is expected to increase productivity further. But, due to the advent of AI and automation routine jobs are at highest risk which is a threat of AI.

Projected Impact of AI on White Collar Jobs in India



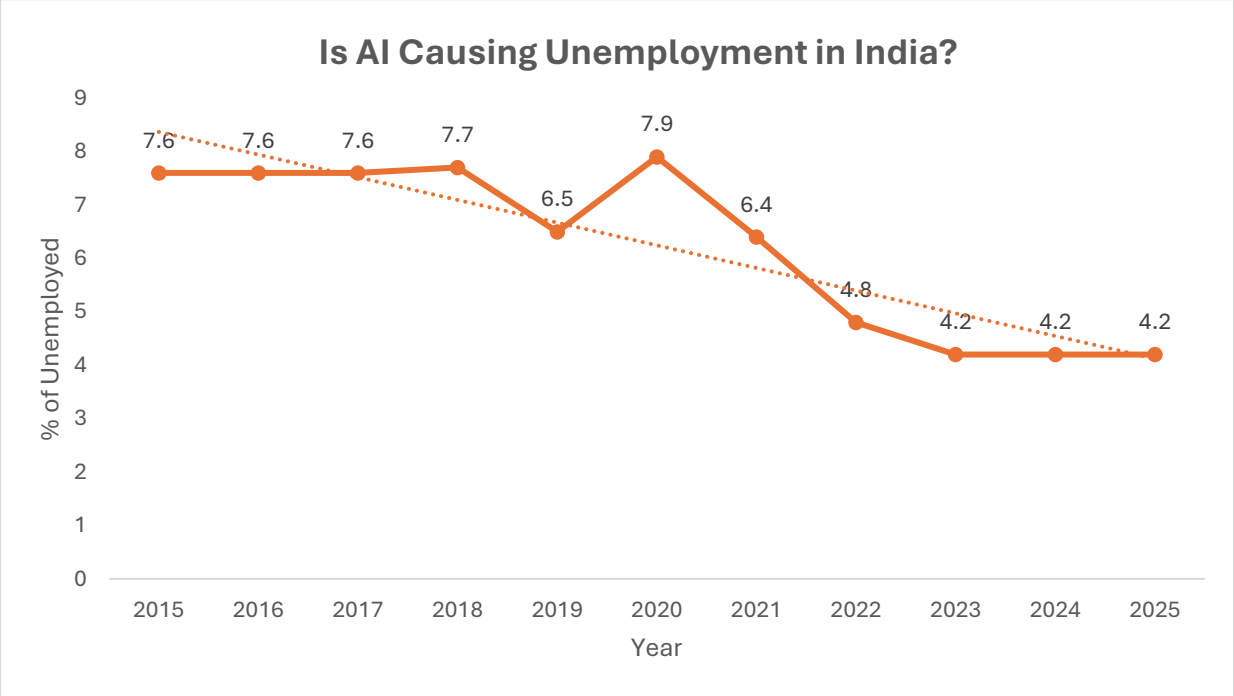
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AI is ready to disrupt the job market. Initially, routine jobs were at a high risk of displacement but now as per the International Monetary Fund Report, 2024 high skill jobs like in IT sector which were earlier considered to be immune to automation are now at risk. The IT and BPO sector which employees over 10 million people are at risk now. As per world bank 2025 "Unlike previous waves of automation, AI has the potential to displace a range of non-routine, white collar service sector jobs. AI is expected to significantly impact white collar jobs in India. As can be seen from the chart IT sector is expected to lose approximately 50% jobs to AI and automation. BPO sector is expected to lose 45% jobs, jobs like customer service and data entry can be easily automated and other white-collar jobs like HR, operations etc. are expected to lose 40% jobs due to AI and automation. This shows potential threat of AI in India.

Is AI Causing Unemployment in India?

AI is now thought to be the cause of India's unemployment. Many believe that AI is eliminating jobs in India. Administrative and clerical jobs have been shown to be diminishing during the last ten years. Large tech firms are spending enormous sums of money implementing contemporary technology. Many repetitive operations can be automated with the use of AI, allowing businesses to save time and concentrate on important areas.

Since most occupations in today's society are being mechanized to save time and money, the younger generation or those just entering the workforce are most exposed to AI. In general, employment in India is threatened by automation.



Source: International Labor Organization dataset

The overall unemployment rate as a percentage of the labor force is displayed in this graph. The graph indicates that for the previous ten years, unemployment has been on the decline. The COVID-19 pandemic was the cause of the significant changes that occurred between 2019 and 2021. The COVID-19 epidemic caused the unemployment rate to reach its highest point in

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2020, at 7.9%. In India, the pandemic caused people to change careers and adopt a work-from-home mentality. People moved back to their hometowns, which led to job losses as well. Many people lost employment that they couldn't do from home. Unemployment has been trending downward since 2020. It has stayed at 4.2% over the last three to four years, which is encouraging, but India still needs to improve.

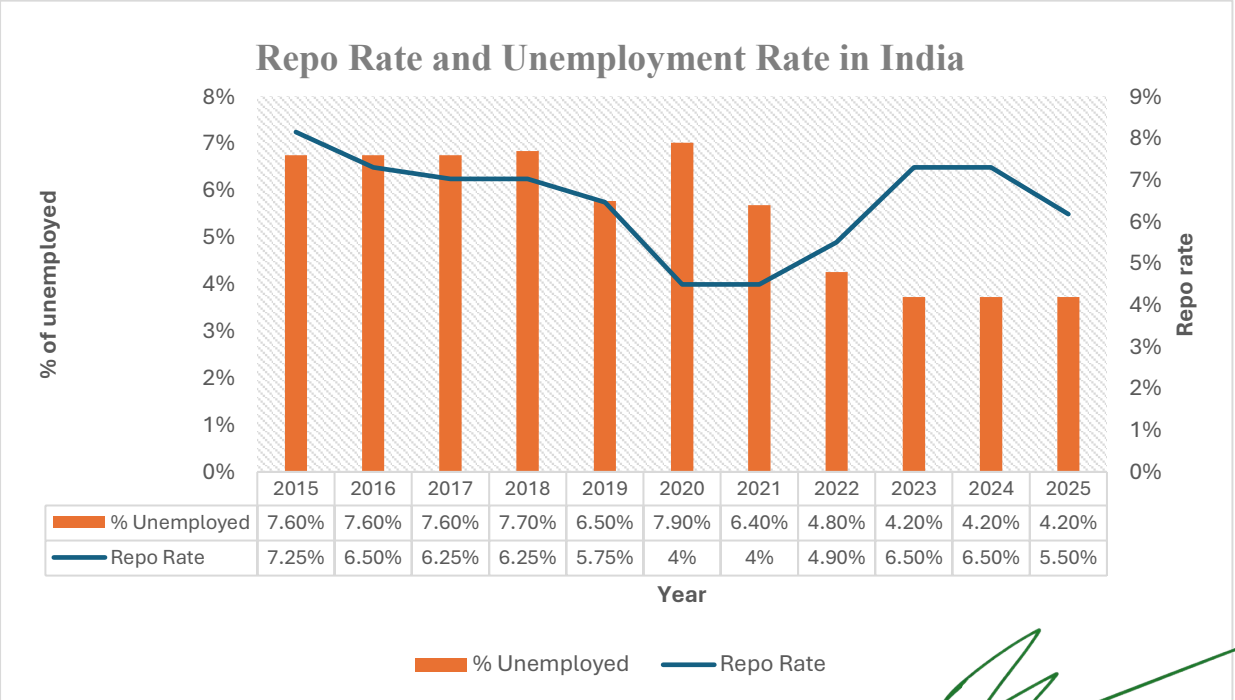
AI is currently believed to be the cause of unemployment in India however statistics shows that this is not entirely the case. There are also additional factors, such as changing monetary policy. Even though AI is to blame for India's unemployment, there are other issues that must be addressed.

It is crucial to remember that, despite its drawbacks, AI may also increase production and employment. Businesses may now concentrate more on important areas rather than becoming bogged down in repetitive work. Automation makes it possible to complete everyday chores in a matter of seconds, which is beneficial. Productivity is rising overall. Among the benefits of AI are fewer efforts, fewer workers, increased skills, and efficiency.

Monetary Policy and Employment

The Macroeconomic objective of any Monetary Policy is to achieve price stability, full employment and Economic Growth. Employment is a key economic variable that is influenced by monetary policy through its impact on aggregate demand, investment, consumption and business activity. At the times of need central bank of any country adopts expansionary or contractionary monetary policy as per the requirement.

Any nation's employment situation is managed by monetary policy. Increased loan availability, increased aggregate demand and consumption, increased corporate investment, and eventually increased hiring and employment are all benefits of an expansionary monetary policy. Conversely, a contractionary monetary policy has the opposite effect.



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
% Unemployed	7.60%	7.60%	7.60%	7.70%	6.50%	7.90%	6.40%	4.80%	4.20%	4.20%	4.20%
Repo Rate	7.25%	6.50%	6.25%	6.25%	5.75%	4%	4%	4.90%	6.50%	6.50%	5.50%

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Source: RBI Repo Rate, World Bank Unemployment Rate

The graph illustrates that there isn't always a direct correlation between the repo rate and unemployment. Employment outcomes are also influenced by fundamental labor market characteristics and external shocks like the COVID-19 epidemic. Repo rates declined until 2020 as the RBI adopted an accommodative monetary policy. The COVID-19 pandemic's effects, which momentarily impaired the regular transmission of monetary policy, are shown in the rapid rise in unemployment during 2020.

Therefore, it might be said that monetary policy may not always be able to counteract economic upheaval. Even as the repo rate rose starting in 2022, unemployment progressively decreased, indicating that broader economic development and reopening rather than just monetary policy had an impact on the labor market recovery.

Impact of AI on Employability in Various Sectors

AI has a potential to boost India's GDP a lot by 2025. These three important industries consumer and retail, banking and finance, and agriculture are predicted to account for almost 40% of overall value. AI is helping all three of these sectors. Due to effective production planning and output, farmers are seeing a rise in income. While the consumer and retail sectors can benefit from improved customer experience and targeted marketing, the BFSI industry can use AI for financial modelling and credit underwriting.

Agriculture

Adoption of AI has led to significant growth in the agricultural sector. Improved soil monitoring, prompt pest and weed identification, improved weather forecasts, production scheduling, drone-based crop health management, AI based crop pricing, and more access to funding. AI data-driven farming is becoming more prevalent in Indian agriculture. Over time, Indian agriculture's total output has grown due to AI's reduction of stress. AI is being used in agriculture by several firms. By 2025, the Indian agritech industry is predicted to be valued between $30 and $35 USD, and it is anticipated to draw significant investment in the future. AI has therefore had a beneficial effect on India's agricultural sector.

Manufacturing Sector

AI is automating many repetitive tasks in manufacturing industries leading to job displacement but also increasing employment for those who are skilled and manage machines well. AI is not completely capable of replacing humans as some tasks need critical thinking and deep analysis which only humans can do.

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Service Sector

This sector is witnessing substantial AI adoption particularly in customer service through the use of chatbots and virtual assistants. AI improves customer experience and also streamlines operations and optimizes resource allocation allowing business to operate more efficiently. White collar jobs are at the highest risk presently.

Healthcare Sector

AI is making significant progress in healthcare sector AI driven diagnostic tool, medical imaging analysis and predictive analysis on enhancing the accuracy and efficiency of healthcare services. More AI powered technology medicine platforms are improving access to healthcare in rural and remote areas addressing the challenge of healthcare delivery in vast and diverse country like India.

Financial Sector

This sector is rapidly embracing AI technologies like HDFC's Eva (Electronic Virtual Assistant) AI powered chatbots, fraud detection with AI, risk assessment, credit underwriting and personal financial services etc. Financial sector has seen rapid growth in terms of revenue post AI.

Education

AI is transforming education sector in India by enabling personalized learning, personal tutoring and enhanced grading experience. AI might lead to job loss of certain routine jobs but has a potential to increase job opportunities in education sector as well. Students or learners are now capable of studying on their own with the help of modern technology, doubts can be solved quickly. Teachers are also getting benefitted as with the help of AI they can deliver quality lectures, assessment system has improved etc.

AI is being used in practically every industry. With the aid of contemporary AI technology, businesses are seeing improvements in worker productivity, reduced effort, timely completion of tasks, and better accuracy all of which are positive indicators of economic growth. AI is expected to greatly expand the Indian economy in the future. AI is now used in practically every industry, including manufacturing, banking, healthcare, education, and research. These industries are expanding tremendously with artificial intelligence. AI is now available in even the most rural Indian village and is expanding. AI is connecting, simplifying, and making life easier.

Initiatives like IndiaAI guided by "*Making AI in India and making AI work for India*". The cabinet approved this with a budget outlay of Rs 10,371.92 crore over next five years is showing positive results.

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Sector-22, Rohini, Delhi-110086

Centre of Excellence for AI is also helping India a lot in this AI transformation. These initiatives are helping by providing AI knowledge accessible and affordable to all and ensuring AI uplifts the society as a whole.

As per the Press Information Bureau 2025 report "Over 6 million people are employed in tech and AI sector India." "On NASSCOM AI Index India scores 2.45 out of 4, showing that 87% of the companies are using AI." "Leading sectors in AI adoption include industrial and automotive, consumer goods and retail, banking, financial services and insurance, and healthcare together they contribute to around 60% of the total AI value." India hosted AI summit 2025 as well in order to show India's AI capabilities.

Data and Studies

• Digital interventions, including AI, are expected to retrain and reskill some 40–45 million Indian workers by 2025. (Ministry of Electronics and Information Technology, 2019) Additionally, 20 million new employment opportunities are anticipated, mostly in industries like manufacturing, transportation and logistics, agriculture, and IT-BPO. AI has the potential to improve job quality by automating repetitive tasks and enabling workers to participate in more meaningful and better employment.

• Automation may cause up to 60 million workers in India's manufacturing sector to lose their jobs by 2030 (Mckinsey India Institute), posing a danger on Indian economy.

• According to the global ed-tech business Great Learning's Upskilling Trends Report 2024–2025, 67.5% of engineers believe that AI is negatively affecting their professions, while 87.5% think that upskilling is essential to protecting their livelihoods in the face of disruption.

• The National Strategy for AI was introduced by NITI Ayog in 2018 with an emphasis on utilizing AI for inclusive growth. Healthcare, education, agriculture, smart cities, and mobility are the five main areas identified in the strategy for action. The government hopes to use AI's potential to boost development and raise citizens' quality of life by focusing on these industries.

Role of Government

Government plays an important role in allowing AI to reach its potential. Ethical considerations are there with the use of AI. There should be fair use of AI and complete transparency. Government can help by providing a well-defined ecosystem in which AI can flourish. Pradhan Mantri Kaushal Vikas Yojana (PMKVY), Future Skills, Youth for Unnati and Vikas with AI (YUVAI) which mandates students of age 8-12 to be taught AI are various schemes to increase AI adoption and upskilling in India. Capacity building and skill development, AI for all campaigns, Proper education and training, devise social policy and more Indian specific studies are some policy suggestions. Over time India has launched many initiatives like IndiaAI Mission, establishing center of excellence, providing computer infrastructure to remote areas and making AI facility affordable and accessible to all. NITI Ayog's AI for inclusive societal development sets the roadmap for using technology to empower informal sector 2025 is a step forward towards making informal workforce contribute their share to the economy.

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Conclusion

AI is promising as well as problematic, it has a transformative potential. Over time AI resulted in both job losses and job opportunities with the help of automation daily routine tasks can be performed easily, informal sector is vulnerable as it does not get direct training and skill building but government is taking steps in order to make informal sector use AI and work to their full potential. Indian economy witnessed more positive impact of AI. Almost every sector grew, with the help of modern tools and techniques various jobs can be done in seconds. Use of chatbots and virtual agents benefitted service sector by allowing workers to focus more on areas that need critical thinking and evaluation.

AI does not completely destroy a job rather it transforms it. In order to be able to stand in modern AI driven industries individuals are expected to timely upskill. AI for all is the prime motive of the government. Government plays a crucial role in establishing well defined AI ecosystem.

It is important to note that not all jobs will be replaced by AI in India, Robots cannot perform all the functions, certain jobs will be displaced due to intelligent automation but jobs that require critical decision making will still require human expertise as highlighted by experts. AI is expected to improve Indian infrastructure and benefit Indian economy by contributing well to its GDP but AI is also expected to create job loss in next 5 to 10 years ahead as a result of AI driven transformations as per the studies.

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Algorithmic Nudging in Online Shopping: Analyzing the Relationship Between Dark AI Patterns and Consumer Impulsive Buying Susceptibility

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1. Abstract

Online retail platforms increasingly use artificial intelligence (AI) to shape purchasing behavior, yet the extent to which this deployment of AI affects consumers' impulsive tendencies remains empirically underexplored. Drawing on a survey of 441 online shoppers, this study examines the relationship between impulsive buying tendency and vulnerability to AI-based manipulative design — termed Dark AI Patterns. Two composite indices, one capturing susceptibility to Dark AI Patterns and one capturing impulsive buying tendency, were constructed from Likert-scale items and tested using Pearson's correlation coefficient. A statistically significant, moderate positive correlation emerged between the two constructs ($r = 0.55$, $p < .001$), indicating that consumers more susceptible to algorithmic persuasion tactics also report more impulsive purchasing behavior. These findings link impulsive buying research with the emerging literature on Dark AI Patterns and offer empirical basis for advocating restraint in the design of persuasive online shopping systems.

Keywords: *Impulsive buying, Dark AI Patterns, artificial intelligence, online shopping.*

2. Introduction

As online retail has expanded and artificial intelligence has become embedded in digital marketplaces, algorithmic processes now exert a growing influence on consumer purchase decisions. Recommendation engines, content personalization, time-pressure cues, and the broader category of manipulative design known as Dark AI Patterns are reshaping how consumers interact with online stores — and, in doing so, may be encouraging impulsive purchasing.

Research on impulsive buying has traditionally examined situational, technological, and psychological drivers, yet the manipulative potential of artificial intelligence within this behavior has received comparatively little attention. Empirical evidence connecting impulsive online buying to consumers' vulnerability to AI-driven influence remains scarce.

This study tests the association between impulsive online buying behavior and susceptibility to AI-based manipulation, contributing to a clearer distinction between legitimate persuasion and unethical manipulation in online retail. The findings provide quantitative evidence of the link between these two phenomena and a foundation for further research on how Dark AI Patterns shape impulsive consumer decision-making. This study advances Dark AI Patterns as a behavioral determinant of impulsive buying and embeds algorithmic manipulation within the

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theoretical framework of digital decision-making, addressing a linkage the consumer behavior literature has yet to establish.

3. Literature Review

3.1. Determinants of Impulsive Buying

A substantial body of theoretical and empirical work has examined the drivers of impulsive purchasing. Situational and structural elements — the shopping environment, marketing cues, and product category attributes — consistently shape impulsive consumer decisions (Tanveer et al., 2022; Kurt et al., 2022).

Internal and external cues alike prompt spontaneous consumer reactions (Virvilaitė et al., 2011), and in digital settings this extends to transaction convenience, information availability, and interface design (Ling & Yazdanifard, 2015; Wang et al., 2022).

Specific configurations of situational and cognitive elements can trigger impulsive buying in retail settings (Prashar et al., 2015), and meta-analytic evidence confirms recurring patterns of these determinants across market contexts (Iyer et al., 2020; Zhao et al., 2022). Cultural factors further account for variation in impulsivity across populations (Kacen & Lee, 2002).

A second set of determinants is individual and emotional, rooted in lifestyle, personality, and impulsivity as a relatively stable characteristic. Purchase-related feelings and perceived risk can either amplify or dampen impulsive tendencies (Lee & Yi, 2008), while the gap between the urge to buy impulsively and actual purchasing behavior appears to be situationally conditioned (Badgaiyan & Verma, 2015).

Self-control and hedonic motivation carry comparable weight (Badgaiyan & Verma, 2014), and certain consumer lifestyles predispose individuals toward more frequent impulsive buying (Ocel et al., 2023). In tourism services specifically, personality factors and emotional states shape impulsive decisions (Ahn & Kwon, 2022).

As a personality trait, impulsivity moderates transaction completion intentions in online buying (Asokan-Ajitha, 2021), and research on online travel purchases underscores the weight of internal individual characteristics in shaping impulsivity (Chih et al., 2012). These findings raise a further question: whether AI technology itself can function as either a protective safeguard or a manipulative tool (Prokopowicz, 2024).

More recent work incorporates social and technical context into the analysis of impulsive purchasing. Shopping in the company of others heightens the likelihood of impulsive decisions through normative and emotional mechanisms (Luo, 2005), and segmentation approaches based on situational characteristics reveal distinct consumer groups with differing vulnerability to impulsive cues (Mihić & Kursan, 2010).

Technology acceptance models take on particular importance amid market digitalization, clarifying how system usability and ease of use shape online purchase decisions (Azizah et al., 2022). The COVID-19 pandemic likewise exposed the role of internal constraints in emerging markets, where mobility restrictions intensified impulsive online buying (Lavuri, 2023). Taken together, impulsive purchasing emerges from the interaction of situational, social, technical, and personality-based factors, with the relative strength of each shifting alongside market conditions and economic development (Zhao et al., 2022).

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PSP Area, Sector-22, Maharaja Agrasen Chowk
Sector-22, Rohini, Delhi-110086

Joining these strands lead toward a common structure: situational, individual, and technological determinants rarely function as isolated triggers but interact to produce a given purchasing episode, so the same shopping environment can provoke very different reactions depending on which consumer traits it activates. Store atmospherics or scarcity messaging carry force largely because they interact with a consumer's existing disposition toward impulsivity — a person low in trait impulsivity may register a countdown timer and discount it, while a highly impulsive consumer may treat the same cue as decisive. This interaction helps explain why the impulsive buying literature has moved gradually from cataloguing discrete determinants toward modeling how situational stimuli and individual susceptibility combine, and it sets up the question this study pursues: when the situational stimulus is generated and adapted by an algorithm rather than fixed by store design, does the same interaction hold, or does the adaptive, personalized nature of AI-driven cues change how forcefully they act on consumers already prone to impulsive decisions?

3.2. AI-Powered Purchase Decision Manipulation

Artificial intelligence tools have fundamentally altered consumer decision-making processes, functioning simultaneously as decision-support systems and as vehicles for manipulation. AI systems capable of modeling and predicting user behavior can shape the outcomes of consumer decisions (Sabour et al., 2025).

Theoretically, recommendations, content personalization, and selective information display give AI tools leverage over consumer psychology and behavior (Lemsieh & Abarar, 2024). When recommendation processes operate with algorithmic autonomy, the system's perceived objectivity rises — increasing users' propensity to select from the recommended options (Fan & Liu, 2022).

Personalization grounded in behavioral data analysis increases decision influence in online shopping, often without the user's awareness (Mohsin, 2024). Generative AI acting as a purchasing counselor can shape choices as well, synthesizing viewpoints into compelling product narratives (Lei & Liu, 2025). Customer trust in AI systems compounds this effect, amplifying their influence on purchase decisions (Leite, 2024).

This literature converges on a shared risk: the line between decision assistance and manipulation blurs readily under conditions of information asymmetry and limited user awareness.

A distinguishing feature of this literature, relative to earlier work on situational determinants, is the asymmetry between the party generating the cue and the party responding to it. A store's use of a limited-stock sign is visible and, in principle, verifiable by any shopper who chooses to look; an AI system's decision to surface a particular product, price, or urgency message to one user and not another is not. That asymmetry is what elevates these mechanisms from ordinary marketing communication to the category of Dark AI Patterns, since the consumer has no comparable vantage point from which to judge whether a recommendation reflects their own preferences or the platform's commercial interest. Established behavioral research on scarcity and social proof therefore transfers only partly to this setting: the psychological mechanism may be familiar, but the informational conditions under which it operates are not.

Digital competence plays an ambivalent role in this dynamic — it can guard against influence just as readily as it can deepen vulnerability to sophisticated persuasive tactics. AI-based manipulative marketing strategies, in turn, may drive unethical consumer behavior (Qadri et al., 2025).

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Conversational and companion AI systems raise a related concern: by fostering parasocial connections and emotional engagement, they can employ emotional manipulation to steer decisions (De Freitas et al., 2025). Proposed regulatory responses center on algorithmic transparency and greater organizational accountability for consumer-support technologies (Paterson, 2022).

The use of AI in purchase decisions thus sits at an unresolved tension between the effectiveness of personalization and the risk of manipulation — one that warrants further theoretical and empirical attention.

4. Research Methods

This study aims to establish the association between impulsive online shopping behavior and consumer susceptibility to AI-based purchasing manipulation — Dark AI Patterns.

Specifically, it tested whether a stronger propensity toward impulsive, unplanned purchases correlates with greater vulnerability to algorithmic influence strategies — time pressure, limited-availability messaging, and AI-generated suggestions — leading to the following hypothesis:

Ha: Purchase impulsivity and susceptibility to Dark AI Patterns are positively correlated

The research questions addressed the degree of impulsive buying behavior in the study population, the level of susceptibility to AI-based manipulation, and the nature of the relationship between the two. Data were collected via an anonymous online questionnaire administered to online shoppers, using a diagnostic survey design, yielding a final sample of 441 respondents.

The measurement instrument was developed based on a review of the literature on impulsive buying (e.g. Beatty & Ferrell, 1998; Rook & Fisher, 1995; Verplanken & Herabadi, 2001; Verhagen & van Dolen, 2011) and on the persuasive mechanisms in online shopping environments collectively termed as Dark AI Patterns (e.g. Aggarwal, Jun & Huh, 2011; Chen, 2008; Hostler et al., 2011; Liang et al., 2006). The questionnaire captured shoppers' responses to time-pressure signals, algorithmic suggestions, and limited-availability notifications, alongside their impulsive buying habits, with each item measured on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree). The developed instrument was pilot tested, refined and then used for data collection.

Scale items for measuring susceptibility to Dark AI Patterns

1. When I see a countdown timer on a product page, I feel pressure to complete my purchase quickly.
2. Time-limited discount offers make me more likely to buy immediately without comparing alternatives.
3. I have completed a purchase specifically because a deal appeared to be about to expire.
4. Messages indicating limited stock (e.g., "only 2 left") make me want to buy before checking other options.
5. Low-stock alerts increase my sense of urgency to purchase.
6. Seeing that many other customers viewed or bought a product increases my confidence in buying it.
7. "Customers also bought" or similar prompts strongly influence what I add to my cart.
8. I am more likely to purchase items a website labels as "popular" or "trending."

Prof. (Dr.) Vikram Bali
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9. I often purchase items recommended to me by a website's algorithm, even when I hadn't planned to buy them.
10. Personalized recommendations based on my browsing history increase my likelihood of purchasing.

Scale items for measuring impulsive Buying Behavior

1. I often buy products spontaneously, without planning to.
2. I frequently make purchases I hadn't intended to make when I started browsing.
3. I buy things based on how I feel in the moment rather than what I actually need.
4. I find it hard to resist buying something I like, even when it isn't on my shopping list.
5. My purchases are often the result of a sudden urge rather than careful consideration.
6. I tend to add extra items to my cart that I hadn't originally intended to buy.
7. "I saw it, I bought it" describes how I often shop online.
8. I make online purchase decisions quickly, without much deliberation.

Two composite indices were constructed from these responses: a Dark AI Patterns Susceptibility Index, capturing susceptibility to limited-stock messages, time pressure, and social recommendation cues, and an Impulsive Buying Index, capturing spontaneous and unplanned purchasing decisions.

5. Results

Table 1 presents descriptive statistics and the correlation between susceptibility to Dark AI Patterns and impulsive buying behavior (N = 441).

Table 1. Descriptive statistics and correlation between susceptibility to Dark AI Patterns and impulsive buying behavior.

Variable	**Mean**	**Standard deviation**	**Minimum**	**Maximum**	**N**
Susceptibility to AI manipulations (Dark AI Patterns Index)	2.999	0.848	1.00	5.00	441
Impulsive buying (Impulsivity Index)	2.997	0.838	1.00	5.00	441
Dark AI Patterns → Impulsivity shopping (Pearson r)	—	—	—	r = 0.55	441

Source: Author's calculations

These results directly address the relationship between susceptibility to Dark AI Patterns and impulsive shopping levels across the 441 respondents.

The Dark AI Manipulation Susceptibility Index averaged 2.999, pointing to a moderate level of susceptibility to algorithmic influence techniques such as time pressure, limited-availability messages, social recommendations, and dynamic interface elements. Its standard deviation of 0.848 reflects considerable variability across respondents, suggesting a study population far from homogeneous in how it responds to these mechanisms.

Prof. (Dr.) Vikram Bali
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PSP Area, Sector-22, Maharaja Agrasen Chowk
Sector-22, Rohini, Delhi-110086

The range of scores captures this diversity directly: a minimum of 1.00 identifies respondents fully resistant to the techniques examined, while a maximum of 5.00 identifies others who reported extreme susceptibility to Dark AI Patterns.

The Impulsive Buying Index followed a nearly identical pattern, averaging 2.997 and indicating a moderate level of spontaneous purchasing in the sample, with a standard deviation of 0.838 signaling variation comparable to that observed for susceptibility to AI manipulation.

Here too the full scale was represented, from a minimum of 1.00 among highly rational, planned purchasers to a maximum of 5.00 among those reporting frequent, highly impulsive buying.

Cronbach's alpha assessed internal consistency: the Dark AI Patterns Susceptibility Index showed very high reliability ($\alpha = 0.921$) and the Impulsive Buying Index showed high reliability ($\alpha = 0.887$), together confirming that both composite indicators were adequate for further statistical analysis.

Both indices were calculated as arithmetic means of their assigned scale items, and Pearson's linear correlation coefficient was applied to assess the relationship between them. The analysis revealed a positive relationship between susceptibility to AI-based manipulative mechanisms and impulsive buying behavior ($r = 0.55$). By Cohen's interpretation criteria, this coefficient reflects a moderate-to-strong effect, pointing to substantial covariation between the two constructs. Given the cross-sectional design, this result establishes a statistical association between the two phenomena without supporting causal inference.

The Pearson correlation between the two indices was statistically significant and positive ($r = 0.55$, $p < .001$): respondents more susceptible to AI-based manipulative mechanisms reported correspondingly higher levels of impulsive purchasing behavior.

6. Discussion

These findings speak to the role of AI-based manipulation in consumer purchasing decisions in several ways. The sample showed a moderate overall level of susceptibility to Dark AI Patterns, coupled with considerable variability across respondents.

Time pressure, limited-availability messages, and algorithmic recommendations thus appear to be common features of the online shopping environment, even as their influence varies from consumer to consumer.

Impulsive buying itself emerged as an important, though not dominant, component of online consumer behavior, and its relationship to susceptibility to Dark AI Patterns was clearly positive: as susceptibility to algorithmic influence rises, so does the tendency toward unplanned purchases.

Set against the wider correlational literature on consumer behavior, a coefficient in this range is neither trivial nor overwhelming: it places susceptibility to Dark AI Patterns among the more consequential known correlates of impulsive buying, comparable in magnitude to associations previously reported for situational cues such as store atmospherics and time pressure, yet well short of the near-deterministic relationship sometimes assumed in commentary on algorithmic manipulation. It indicates that algorithmic influence is a meaningful contributor to impulsive purchasing without displacing the individual, situational, and technological factors already established in this literature; the two sets of determinants are best understood as operating alongside one another rather than as competing explanations.

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This pattern also speaks to the interaction proposed earlier between situational stimuli and individual disposition. If Dark AI Patterns operated purely as a novel situational trigger, unrelated to a consumer's underlying tendency toward impulsivity, the correlation with the Impulsive Buying Index would be expected to sit closer to zero. A moderate, positive association instead suggests that algorithmic cues engage the same underlying disposition documented in earlier situational and individual-difference research, rather than creating a wholly separate behavioral pathway — positioning Dark AI Patterns not as a phenomenon requiring an entirely new behavioral model, but as a technologically mediated instance of determinants already well documented in the impulsive buying literature.

The results demonstrate the co-occurrence rather than causation — the cross-sectional design permits the conclusion that greater susceptibility to Dark AI Patterns is associated with more impulsive buying behavior, but not that one causes the other.

7. Conclusions

These results carry clear managerial implications for the responsible use of artificial intelligence in online sales. Algorithmic pressure techniques — countdown timers, limited-availability messages, intensive social recommendation cues — warrant cautious, moderate use, particularly toward users who show higher susceptibility to impulsive purchasing.

Interface design should balance short-term sales objectives against long-term customer relationships built on trust, transparency, and perceived control over the decision-making process. Leaning too heavily on Dark AI Pattern mechanisms may lift short-term conversion at the cost of customer satisfaction and brand reputation.

Strategically, AI-based solutions should support consumer decision-making rather than dominate it. Communicating personalization principles clearly, giving users control over recommendations, and limiting time-pressure stimuli in high-risk impulsive-purchasing situations together foster long-term customer loyalty and reinforce a company's standing as a socially responsible organization — an advantage that carries added weight as consumer awareness grows and AI regulation emerges.

Future research should extend this relationship using more diverse methodologies; experimental and quasi-experimental designs, in particular, would allow actual purchasing decisions to be observed under controlled conditions and support causal inference.

A further direction lies in moderating variables — digital literacy, algorithm awareness, trust in AI — that may differentiate susceptibility to Dark AI Patterns, alongside cross-sectoral and cross-cultural comparisons and closer attention to the long-term effects of algorithmic persuasion on customer loyalty, consumer well-being, and the ethical and regulatory dimensions of AI in online shopping.

8. Limitations

Several limitations bear on the interpretation of these findings. The survey method yields intentions data — respondents reported perceived rather than actual purchasing behavior — and the cross-sectional design precludes causal inference about the relationship between susceptibility to Dark AI Pattern manipulation and impulsive buying.

The purchasing context in which respondents made decisions was also uncontrolled, which complicates interpretation of their exposure to algorithmic stimuli. And while the sample was

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sufficient for statistical analysis, it represents a specific respondent population, so generalizing the results to all consumer groups will require further comparative research.

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Effectiveness of Online Channels of Distribution in the Brown Goods Industry of India

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Abstract

The rapid growth of e-commerce and digital technologies has significantly transformed the distribution landscape of the brown goods industry in India. Brown goods, including consumer electronics such as televisions, smartphones, laptops, audio systems, and home entertainment devices, are increasingly being sold through online platforms. This research paper examines the effectiveness of online channels of distribution in the Indian brown goods industry by analyzing consumer behavior, market trends, operational efficiencies, challenges, and strategic implications. The study is based on secondary data collected from industry reports, academic literature, and market research publications. The findings reveal that online distribution channels have improved market reach, pricing transparency, customer convenience, and supply chain efficiency. However, issues related to trust, logistics, product authenticity, after-sales service, and consumer preference for physical inspection continue to affect the sector. The study concludes that an integrated omnichannel strategy is essential for sustainable growth in India's brown goods industry.
Keywords: Brown goods, online distribution channels, e-commerce, consumer electronics, omnichannel retailing, India, digital marketing, supply chain.

1. Introduction

The Indian retail sector has undergone substantial digital transformation during the last decade due to increasing internet penetration, smartphone adoption, digital payment infrastructure, and changing consumer preferences. Online distribution channels have emerged as an important medium for selling consumer electronics and brown goods. Brown goods refer to electronic consumer durables such as televisions, mobile phones, laptops, cameras, speakers, gaming consoles, and related accessories.

Traditionally, brown goods in India were sold through exclusive brand outlets, multi-brand retailers, distributors, and local electronics stores. However, platforms such as Amazon India, Flipkart, and brand-owned websites have significantly altered the distribution structure.

India's e-retail industry has experienced rapid growth because of affordable mobile data, rising digital literacy, and improvements in logistics infrastructure. Industry reports indicate that India has become one of the fastest-growing online shopper markets globally, with increasing participation from Tier-II and Tier-III cities. Therefore, the effectiveness of online distribution channels in the brown goods industry has become a significant area of academic and managerial investigation.

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2. Objectives of the Study

The objectives of the study are:

- To analyze the growth of online distribution channels in the Indian brown goods industry.
- To examine factors influencing consumer preference for online purchase of brown goods.
- To evaluate the effectiveness of online channels in terms of accessibility, pricing, convenience, and customer satisfaction.
- To identify challenges associated with online distribution of brown goods.
- To suggest strategies for improving online channel effectiveness in India.

3. Research Methodology

The study is descriptive and analytical in nature. It is based primarily on secondary data collected from:

- Research journals
- Industry reports
- Company reports
- Market surveys
- Government publications
- News articles and databases

The data has been interpreted using qualitative analysis to understand patterns, trends, opportunities, and limitations associated with online distribution channels in the brown goods industry.

4. Conceptual Framework

4.1 Brown Goods Industry

Brown goods include electronic and entertainment-oriented consumer durable products such as:

- Smartphones
- Televisions
- Audio systems
- Laptops
- Tablets
- Gaming devices
- Cameras
- Home entertainment systems

The industry is characterized by rapid technological innovation, short product life cycles, and intense competition.

4.2 Online Channels of Distribution

Online distribution channels involve selling products through internet-based platforms including:

- E-commerce marketplaces

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- Brand-owned websites
- Mobile commerce applications
- Social commerce platforms
- Digital marketplaces

These channels facilitate direct interaction between manufacturers, sellers, and consumers.

5. Growth of Online Distribution Channels in India

India's e-commerce ecosystem expanded significantly between 2015 and 2024. According to industry reports available in 2024, India emerged as one of the world's fastest-growing e-retail markets.
Several factors contributed to the growth of online channels:

5.1 Rising Internet Penetration

Affordable smartphones and low-cost mobile data increased internet accessibility across urban and rural India. Millions of consumers shifted towards digital shopping platforms.

5.2 Expansion into Tier-II and Tier-III Cities

E-commerce platforms successfully penetrated smaller towns where access to organized electronics retailing was limited. A substantial proportion of online orders originated from non-metro cities.

5.3 Influence of COVID-19

The COVID-19 pandemic accelerated consumer adoption of online shopping by restricting physical retail operations and increasing reliance on digital platforms.

5.4 Growth of Digital Payments

The rapid adoption of UPI, mobile wallets, and internet banking strengthened online transactions, although cash-on-delivery continued to remain important in many regions because of trust-related concerns.

6. Effectiveness of Online Channels in Brown Goods Distribution

6.1 Wider Market Reach

Online platforms enable companies to reach consumers across geographical boundaries without establishing physical stores. This significantly reduces distribution costs and expands customer access.

6.2 Pricing Transparency

Online channels allow consumers to compare prices, specifications, reviews, and discounts across multiple sellers. Competitive pricing strategies increase customer attraction towards e-commerce platforms.

6.3 Convenience and Accessibility

Consumers can purchase products anytime and anywhere through smartphones and websites. Doorstep delivery and multiple payment options further enhance convenience.

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6.4 Product Variety
Online channels provide access to a broader range of products compared to physical stores. Consumers can access multiple brands, configurations, and price ranges.

6.5 Data-Driven Marketing
E-commerce platforms utilize artificial intelligence, consumer analytics, and recommendation systems to personalize shopping experiences and improve customer engagement.

6.6 Operational Efficiency
Online distribution channels improve inventory management, demand forecasting, and logistics coordination through digital integration.

6.7 Influence on Consumer Decision-Making
Customer reviews, ratings, influencer marketing, and social media promotions significantly impact purchase decisions in the brown goods industry.

7. Consumer Behavior Toward Online Purchase of Brown Goods
Consumer preference for online purchase of electronics is influenced by multiple factors:

7.1 Price Discounts and Offers
Heavy discounts during festive sales and promotional campaigns attract consumers toward online platforms.

7.2 Product Information Availability
Detailed specifications, video demonstrations, and customer reviews assist consumers in informed decision-making.

7.3 Trust and Security
Consumer trust remains a critical determinant of online purchase behavior. Security, privacy, and platform credibility influence transaction acceptance.

7.4 Convenience
Time-saving benefits and home delivery motivate consumers to choose online channels.

7.5 Return and Exchange Policies
Flexible return policies enhance consumer confidence and reduce perceived purchase risk.

8. Challenges Faced by Online Distribution Channels
Despite rapid growth, several challenges continue to affect online distribution effectiveness.

8.1 Lack of Physical Inspection
Many consumers prefer examining electronics physically before purchasing expensive products such as televisions and laptops.

8.2 Logistics and Delivery Issues
Damage during transit, delayed deliveries, and reverse logistics complexities affect customer satisfaction.

8.3 Counterfeit Products
Unauthorized sellers and fake products reduce consumer trust in online platforms.

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8.4 Dependence on Discounts
Frequent discounting affects profitability and intensifies price competition among sellers.

8.5 Trust Deficit
Cash-on-delivery remains popular because many consumers still lack confidence in online transactions.

8.6 After-Sales Service Issues
Installation delays, warranty claims, and customer support challenges negatively affect post-purchase satisfaction.

9. Role of Omnichannel Distribution
Many electronics brands are adopting omnichannel strategies that combine online and offline retailing. This model provides consumers with:

- Online product discovery
- Offline experience centers
- Click-and-collect facilities
- Unified customer service
- Seamless return management

Omnichannel integration enhances customer experience and reduces limitations associated with purely online distribution systems.

10. Findings of the Study
The major findings of the study are:

- Online distribution channels significantly transformed the Indian brown goods industry.
- Consumers increasingly preferred online platforms because of convenience, competitive pricing, and product variety.
- Tier-II and Tier-III cities emerged as major contributors to online electronics sales growth.
- Trust, security, and after-sales service remained critical concerns affecting online purchase decisions.
- Logistics efficiency and digital payment infrastructure played a crucial role in channel effectiveness.
- Omnichannel retailing emerged as one of the most effective long-term strategies for electronics companies.
- Online channels were more effective for standardized electronics products with strong brand recognition.

11. Suggestions
The following measures can improve the effectiveness of online channels in the brown goods industry:

- Strengthening logistics and delivery infrastructure.
- Enhancing product authenticity verification systems.
- Improving after-sales service and installation support.
- Increasing cybersecurity and payment protection mechanisms.
- Expanding vernacular and regional-language digital interfaces.
- Integrating online and offline retail operations through omnichannel strategies.
- Building consumer trust through transparent policies and reliable customer support.

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12. Conclusion

Online distribution channels revolutionized the brown goods industry in India by improving accessibility, convenience, product availability, and operational efficiency. E-commerce platforms enabled electronics manufacturers and retailers to expand their customer base across diverse geographical regions while reducing distribution costs. However, challenges such as trust issues, counterfeit products, logistics inefficiencies, and after-sales service limitations continued to affect consumer satisfaction.

The future of the Indian brown goods industry lies in omnichannel integration where online and offline channels complement each other to provide superior customer experience. Firms that effectively combine digital innovation with reliable service infrastructure are likely to achieve sustainable competitive advantage in the evolving Indian retail landscape.

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Veloce India: The Diwali Sales Volume Mandate

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1. The Looming Crisis

At 9:47 p.m. on the fourth of October, Ananya Rao sat alone in the glass-walled conference room on the eleventh floor of Veloce India's Andheri East office, staring at a spreadsheet that refused to reconcile no matter how many times she rebuilt the formula. As Vice President of Sales and Channel Development, she had eleven days left before the National Sales Kickoff in Goa, where she was contractually obligated to stand in front of four hundred distributor principals, regional sales managers, and the company's global COO — flown in from Amsterdam specifically for the occasion — and present a distribution plan that delivered on a number she did not believe was achievable.

The number was 45 percent. Year-on-year volume growth, offline channel, smartphones and smart TVs combined, to be substantially booked as primary sales before the close of the Diwali trading window on the third week of October. Corporate headquarters had not arrived at 45 percent through a bottoms-up channel capacity exercise. It had arrived at 45 percent because Veloce's global smartphone division had missed its worldwide unit target for two consecutive quarters, and India — now the company's third-largest market by volume — had been identified in an internal memo as the region with "the greatest unrealized headroom relative to category growth rates." The memo, forwarded to Ananya by her manager with no additional commentary beyond "pls action," had used the word headroom four times in two paragraphs.

Ananya's phone buzzed. It was a WhatsApp message from Rajiv Mehta, the general secretary of the Mumbai Metropolitan Electronics Distributors' Association and, not incidentally, the principal of Veloce's second-largest distributor in Maharashtra by throughput. She had been avoiding his calls since Tuesday.

"Ananya, we need to talk before Friday. If Veloce dumps any more stock on us to hit your Diwali number, I promise you the network collapses by New Year. Not a threat. A forecast. Call me."

She set the phone face-down on the table. The spreadsheet in front of her broke the 45 percent target into four columns — National Distributors, Regional Tier-1, Sub-dealer network, and Modern Trade — and beneath each column, in red, sat the gap between what the channel could plausibly sell through to end consumers (secondary sales) and what corporate needed booked

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into distributor godowns by month-end (primary sales) to satisfy the global reporting cycle. The gap, aggregated across the western region alone, exceeded ₹34 crore in inventory value. Somebody was going to have to hold that stock. The only question was who, and for how long, before the paper resolved into either sell-through or a write-down.

Her manager, Vikram Sood, the Managing Director for South Asia, had been characteristically blunt in their call that afternoon. “The number doesn't move, Ananya. It's already been committed to Amsterdam. What I need from you by Goa is a channel plan that gets us there without a front-page story in the Economic Times about distributor defaults. How you thread that needle is your job. That's why you have the title."

She had not told him about Rajiv's message. She was not yet sure she had an answer that would survive the telling.

2. Company and Market Background

Veloce India had entered the country nine years earlier as a mid-tier European electronics brand attempting to establish itself in a market long dominated by Korean incumbents and increasingly disrupted by domestic and Chinese online-first entrants. The company had built its India business on two product lines — mid-range and premium smartphones, and a rapidly expanding smart television portfolio — and had grown, largely through disciplined offline distribution, to a position of roughly 7.8 percent value share in smartphones and 11.2 percent in the smart TV category, according to the most recent quarter's industry tracker data circulated by the market research firm Veloce retained.

The competitive landscape had hardened considerably in the eighteen months preceding the case. In smartphones, Korean and Chinese incumbents continued to command the premium and value segments respectively, while a cluster of online-first brands — selling almost exclusively through e-commerce platforms with minimal offline distribution overhead — had captured disproportionate share in the sub-₹15,000 price band by undercutting brick-and-mortar pricing by anywhere from 8 to 15 percent. In smart TVs, the pattern was similar but more severe: e-commerce-native brands, unburdened by distributor margin structures, warehousing costs, or the working capital drag of a multi-tier offline network, had captured nearly a third of category volume in three years, forcing every offline-dependent player, Veloce included, into an uncomfortable strategic bind.

The company could not abandon its offline network — it remained the primary channel through which roughly 68 percent of Veloce's India revenue flowed, and it was the only channel that reached Tier-2 and Tier-3 towns where e-commerce logistics remained patchy and cash-on-delivery return rates ran high. But it also could not permit its offline pricing to drift too far from online pricing without triggering a wave of "showrooming," where consumers evaluated products at a General Trade outlet and then purchased the identical SKU online at a lower price, leaving the offline retailer with the cost of the sales floor and none of the margin.

This tension — a company structurally dependent on an offline network that its own pricing discipline was slowly starving — sat beneath every decision Ananya's team made, though it

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rarely appeared explicitly in the quarterly business reviews that corporate conducted. Those reviews measured sell-in. They did not, in any systematic way, measure the health of the channel that absorbed it.

3. The Architecture of the Distribution Channel

Veloce's offline network in India was organized in four tiers, a structure common across the consumer electronics industry but one whose internal mechanics were poorly understood outside the sales organization itself.

At the top sat eleven National Distributors (NDs), large trading houses — several of them multi-brand, some carrying competing electronics portfolios alongside Veloce's — who purchased directly from Veloce's regional warehouses on 21-day credit terms and held exclusive geographic rights across defined territories, typically an entire state or a metropolitan cluster. Below the NDs sat a layer of roughly 140 Regional and Tier-1 Distributors, smaller operations that purchased from the NDs rather than directly from Veloce, serviced districts within a state, and in most cases operated on thinner balance sheets and considerably less pricing leverage than the National Distributors above them. Below that sat an estimated 3,200 sub-dealers — small, often family-run electronics retailers in Tier-2 and Tier-3 towns, the kind of establishment where a shopkeeper knew his customers' names and extended informal credit to regulars during festival season. And running parallel to this entire tiered structure was General Trade proper: the kirana- adjacent electronics counters and independent mobile shops that made up the largest number of physical touchpoints for Veloce products but the smallest average order size per outlet.

Layered on top of this offline architecture — and increasingly cannibalizing it — sat Modern Trade (large-format retail chains, which purchased directly from Veloce on tighter margins but delivered volume predictability and brand visibility that the fragmented network could not match) and e-commerce, which had evolved from a marginal channel to nearly 24 percent of Veloce's total India volume within four years.

The distributor union's frustration, articulated most vocally by Rajiv Mehta, centered on a structural grievance that had been building for two years: National and Regional Distributors were increasingly being asked to absorb the same aggressive sell-in targets and short shelf-life risk as Modern Trade, without receiving Modern Trade's negotiated protections — price protection clauses, sale-or-return arrangements on unsold stock, and marketing development fund support that offset promotional discounting. "You are treating us like Croma and Reliance Digital, “Mehta had said at the regional distributor conclave in August, in a remark that had circulated widely within the sales organization afterward, "but you are not giving us their terms. We carry all of your risk and none of your protection.”

4. The Fracture Points (Margins & Credit)

The mechanics of the strain were, in Ananya's assessment, entirely traceable, which made them no less difficult to resolve.

Distributor gross margins on Veloce smartphones had compressed from approximately 5 percent at the start of the previous fiscal year to roughly 2 percent in the current quarter — a

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function of online price-matching pressure that had forced Veloce's own trade pricing team to repeatedly cut ex-factory prices to distributors in order to preserve offline price parity with e-commerce listings, without a corresponding reduction in the fixed operating costs (warehousing, last-mile logistics, sales staff, working capital financing) that distributors carried. A National Distributor moving ₹40 crore of Veloce inventory annually at a 2 percent margin was earning roughly ₹80 lakh in gross profit before operating costs — in several cases, per the informal channel checks Ananya's regional managers had run in September, insufficient to cover the interest expense on the working capital loans distributors had taken out to finance their Veloce inventory in the first place.

The credit picture compounded the margin problem. Sub-dealer payment cycles, contractually set at 30 days from the Regional Distributor, had stretched in practice to 55– 60 days across large parts of the Tier-2/3 network, as sub-dealers themselves absorbed slower sell-through and, in a growing number of cases, extended informal credit to their own retail customers during the festive season in order to compete with easy-financing options offered by e-commerce platforms. This meant Regional Distributors were financing 60 days of receivables from sub-dealers while owing Veloce (via the National Distributor layer) on a 21-day cycle — a structural mismatch that several Regional Distributors had begun describing, in conversations with Ananya's regional sales managers, as "financing Veloce's growth on our own balance sheet."

An email forwarded to Ananya on the last day of September, sent by a Tier-1 distributor in Nagpur to his Regional Sales Manager and escalated up the chain, captured the sentiment with more specificity than any internal report had managed:

> *"In August alone I have extended ₹1.2 crore in credit to eleven sub-dealers who are still not clear from July. If I do not extend, they buy from [competitor] instead, who is offering 45-day terms with no questions. If I extend, I cannot clear my own account with the ND on time, and then I am the one getting the calls from Veloce asking why my account is overdue. Somebody upstream needs to understand that I am not a bank. I am a distributor."*

Ananya had read the email three times. The word that stayed with her was not "collapse" or "boycott" — it was bank. The channel had, without anyone formally designing it that way, become an informal credit-extension mechanism for a consumer base increasingly accustomed to financed purchases, and no layer of that chain — sub-dealer, Regional Distributor, National Distributor, or Veloce itself — had the balance sheet to comfortably absorb the float.

5. The Sales Incentive Dilemma

The incentive structure governing Veloce's own field sales force made the fracture worse, and Ananya knew, because she had co-designed it two years earlier, that it had been built with entirely defensible logic that had simply not survived contact with current market conditions.

Forty percent of a Regional Sales Manager's quarterly variable pay was tied directly to primary sales — the value of stock billed into distributor accounts — measured against a quota that was itself derived from the corporate volume mandate, cascaded downward with minimal

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adjustment for regional channel capacity. A further 25 percent was tied to secondary sales, meaning actual sell-through from distributor to sub-dealer to end consumer, tracked imperfectly through a combination of distributor-reported data and periodic market checks. The remaining 35 percent covered a mix of new outlet additions, Modern Trade execution, and product mix targets.

The distortion this created was not subtle, and Ananya's own regional managers had, in more candid moments, described it to her directly. A Regional Sales Manager facing a primary sales shortfall in the final week of a quarter had every financial incentive to persuade — or in blunter internal parlance, "push" — a distributor to accept additional billing, even against the distributor's own stated sell-through capacity, because the RSM's bonus was calculated at quarter-close on primary billing, not on whether that inventory subsequently moved. One Regional Sales Manager in Pune, in a conversation Ananya had not been meant to overhear at a channel partner dinner in July, put it to a colleague this way: "By the time the secondary numbers catch up and show the stock is stuck, my bonus is already banked. It's the next guy's problem, or it's my problem next quarter, but it's not my problem tonight."

This was not, Ananya reflected, a case of individually irrational actors. It was a system in which every actor — the RSM protecting quarterly variable pay, the distributor protecting a channel relationship he could not afford to damage by refusing stock, and corporate protecting a global number already committed upward — was behaving in a locally rational way that produced, in aggregate, exactly the outcome Rajiv Mehta had forecast in his message: inventory accumulating faster than the market could clear it, margins too thin to absorb the carrying cost, and credit terms stretching until something gave.

The Sales Force Incentive Scheme was due for its annual revision in January. Ananya had flagged the structural misalignment in her own recommendations' memo the previous cycle. The memo had been acknowledged and not acted upon, on the stated grounds that changing the primary-sales weighting mid-cycle would be "difficult to communicate to the field" during a growth push.

6. The Crossroads

Ananya pulled her laptop closer and opened a blank slide in the deck she was meant to present at Goa. The cursor blinked on an empty title field. Around her the office had emptied out; through the glass she could see the cleaning staff beginning their rounds on the tenth floor below. She had, by her own count, four paths in front of her, and she trusted none of them completely.

She could recommend holding the 45 percent target for the total channel but reallocate the load away from the already-strained National and Regional Distributors and toward Modern Trade and e-commerce, both of which had more balance sheet capacity to absorb short-term inventory — though this risked further hollowing out the offline General Trade network that reached the Tier-2/3 consumers Veloce's own market research identified as its fastest-growing segment, and would very likely draw exactly the kind of channel-conflict complaint from distributors that Rajiv Mehta's message had already threatened.

She could propose a formal price-protection and sale-or-return clause for the Regional

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Distributor tier, effectively extending Modern-Trade-style terms downward through the network — a move that would almost certainly repair channel trust and might even accelerate secondary sell-through if distributors felt safe accepting stock, but one that would compress Veloce's own margins further at exactly the moment corporate was demanding volume growth, and would require a sign-off from the finance organization that Ananya doubted she could secure in eleven days.

She could hold firm on the target as communicated and manage the optics — book the primary sales, hit the Diwali number Amsterdam wanted to see, and address the resulting channel stress in the subsequent quarter through a structured "return and rework" program, accepting that this meant knowingly pushing inventory she had reason to believe several distributors could not sustainably absorb, and betting that the relationships would hold long enough to unwind the position in an orderly way.

Or she could go to Vikram Sood before Goa — not after — and make the case, on the record, that the 45 percent target was not achievable through the existing channel without triggering exactly the defaults Mehta was forecasting, and propose a revised number to take to Amsterdam instead, a conversation that would be read internally, fairly or not, as her failing to deliver on her mandate less than a year into the VP role. Her phone buzzed again. Rajiv Mehta, a second time. “Ananya. Friday.”

She looked at the four options laid out in note form on the slide, none of them reduced to a single clean line of text, all of them carrying a cost she could specify and a benefit she could not fully guarantee. Outside, the last of the cleaning staff moved past the glass and switched off the lights on the floor below. She did not close the laptop.

7. Discussion questions:

1. What is driving the gap between what corporate is asking Veloce's channel to absorb and what the channel can plausibly sell through before the credit and margin structure breaks down?
2. Trace how the 40% primary-sales weighting in the Sales Force Incentive Scheme produces the behavior described in the Pune RSM's remark. What would need to change in the scheme's architecture — not just its weighting — to close that gap?
3. Is the distributor margin compression from 5% to 2% primarily a channel-management problem, a trade-pricing problem, or a competitive-positioning problem relative to e-commerce? Does the answer change what Ananya should recommend?
4. Evaluate each of the four options Ananya is weighing at the end of the case. For each, identify who bears the cost, over what time horizon, and what has to be true for the option to succeed.
5. If you were advising Ananya, what would you recommend she say to Vikram Sood, and would you advise she have that conversation before or after Goa?

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Case Study: LT Foods – Digital Supply Chain Transformation multiplied Revenue Growth

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Abstract

LT Foods is a 70-year-old packaged food company specializing in basmati and other rice-based products, faced significant supply chain inefficiencies that were hampering its growth despite a strong global presence in over 80 countries. Partnering with EY in 2020, the company deployed the AI-powered Asterisk digital supply chain platform to overhaul its planning, inventory, and distribution processes. The transformation, built on five strategic pillars, resulted in nearly 2x revenue growth, a reduction in finished goods inventory from 45 to 20 days, expansion of the distribution network from 6 to 12 depots, and a service level of approximately 95%. This case illustrates how digital transformation combined with cultural change can drive sustainable business growth in the FMCG/food sector.

Keywords:

Digital Transformation, Supply Chain Management, Artificial Intelligence (AI), Asterisk Platform, Inventory Optimization, Demand Planning, Distribution Network, Dynamic Capabilities

Introduction

LT Foods is a well-established player in the packaged food industry, with a strong global footprint supported by a network of over 1,300 distributors. As consumer expectations evolved and markets became more dynamic, the company recognized the need for a more agile and responsive supply chain to sustain its growth ambitions. In 2020, LT Foods began a supply chain transformation journey with EY, selecting EY's Asterisk digital platform to modernize its operations across planning, inventory, and distribution — with the objective of enabling growth across domestic and global markets.

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Conceptual Framework: A Dynamic Capabilities Perspective

To analyze how LT Foods converted a technology deployment into sustained business performance, this case draws on the Dynamic Capabilities framework (Teece, Pisano & Shuen, 1997; Teece, 2007). Dynamic capabilities are an organization's ability to sense opportunities and threats, seize them by mobilizing resources, and continuously transform internal structures and processes to sustain competitive advantage in changing environments. Unlike ordinary (operational) capabilities, which enable a firm to "make a living" by performing existing activities efficiently, dynamic capabilities enable a firm to renew and reconfigure those very activities as conditions change. The framework is well suited to LT Foods because the case is not simply about installing software — it is about an organization systematically re-sensing its market, re-seizing its supply chain design, and re-configuring its processes and culture. The three capabilities map onto the LT Foods journey as follows:

1. Sensing – Identifying the Need for Change

Sensing refers to the capacity to scan the environment, identify shifting customer expectations, and diagnose the root causes of operational underperformance. At LT Foods, this was evident in the recognition that:

- Evolving consumer expectations and increasingly dynamic markets required a more agile, responsive supply chain to sustain growth.
- Manual, Excel-based planning and intuition-based decisions were creating fragmented visibility across sales, manufacturing, procurement, and supply chain functions.
- Persistent stockouts, delivery delays, and high finished-goods inventory (45 days) were symptoms of a deeper structural gap between the existing operating model and the scale of a business already present in 80+ countries.

2. Seizing – Mobilizing Resources to Capture the Opportunity

Seizing involves committing resources, forming the right partnerships, and designing a structured response once an opportunity or threat has been sensed. LT Foods' seizing actions included:

- Partnering with EY in 2020 and selecting the AI-powered Asterisk platform as the technology backbone for transformation, rather than attempting an in-house or piecemeal fix.
- Structuring the response around five strategic pillars — control tower, order management and replenishment, supply planning, demand planning, and network optimization — so that investment was directed at the specific root causes identified during sensing.
- Defining clear KPIs and securing strong leadership sponsorship, which signaled organizational commitment and ensured resources (budget, people, management attention) were aligned to the transformation.

3. Transforming (Reconfiguring) – Embedding Change into the Organization

Transforming is the ongoing reconfiguration of assets, processes, and organizational culture so that gains are sustained rather than one-off. LT Foods' transforming actions included:

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- Redesigning the depot network itself (from 6 to 12 depots) using optimization modeling, rather than layering new technology on an unchanged physical network.
- Replacing static, siloed reporting with a daily analytics-led control tower, institutionalizing a "single version of the truth" as the new way of working.
- Investing in people's capabilities alongside technology and building a culture of data-driven, continuous improvement — ensuring the new processes for replenishment, supply planning, and demand planning became routine practice rather than a temporary project.

Viewed through this lens, LT Foods' nearly 2x revenue growth, reduced inventory, expanded depot network, and improved service levels were not simply the output of a software rollout. They were the observable result of a dynamic capability that allowed the organization to continuously sense market and operational gaps, seize the right technological and structural response, and transform its processes and culture to sustain performance gains — a cycle the company can, in principle, repeat as it scales further.

LT Foods: Transition from Traditional to AI-Powered Distribution Network

1. The Traditional Distribution Approach (Before Transformation)

LT Foods' distribution network originally relied on manual, experience-based processes rather than data or technology:

- **Manual planning on Excel** — Supply and distribution planning was done using spreadsheets, which limited scalability and made real-time adjustments difficult.
- **Intuition-based decision-making** — Order prioritization depended largely on individual judgment rather than systematic, data-backed insights.
- **Limited visibility** — Sales, manufacturing, procurement, and supply chain functions operated with fragmented data, making it hard to see the full picture or identify root causes of problems.
- **Reactive operations** — Because planning wasn't automated or predictive, the network struggled to respond quickly to changing market demand.
- **Smaller depot network** — Only 6 depots served LT Foods' distribution needs, limiting reach and responsiveness.

Resulting problems: frequent stockouts, delivery delays, high finished-goods inventory (45 days), and inconsistent customer service — all of which held back growth despite strong market demand.

2. The Shift: Why LT Foods Moved to AI-Powered Distribution

In 2020, LT Foods partnered with EY to modernize its supply chain using the **Asterisk digital platform**, an AI-powered system, with the specific goal of making the network agile, responsive, and scalable for domestic and global expansion.

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3. What Changed — Traditional vs. AI-Powered Distribution

Sl. No.	Aspect	Traditional Approach	AI-Powered Approach (Post-Transformation)
1	Planning method	Manual, Excel-based	Automated, AI-driven (Asterisk platform)
2	Decision basis	Individual intuition	Data-driven insights and analytics
3	Visibility	Siloed data across functions	Analytics-led control tower with unified dashboards
4	Inventory	High finished-goods inventory (45 days)	Reduced to 20 days via scientific inventory norms
5	Demand forecasting	Reactive, limited forecasting	AI-powered statistical forecasting with bottom-up collaboration
6	Production planning	Static, less responsive	Automated, daily-refreshed plans (frozen/fixed/tentative horizons)
7	Distribution network	6 depots	Expanded and optimized to 12 depots
8	Service level	Inconsistent	~95% service level
9	Revenue impact	Growth constrained by inefficiencies	Nearly 2x revenue growth

Source: LT Foods gets 2x revenue via digital supply chain,ey.com

4. Key Enablers of the AI-Driven Distribution Network

1. **Analytics-led Control Tower** — Replaced fragmented reporting with daily, actionable dashboards spanning sales, supply chain, manufacturing, and procurement, creating a "single version of the truth."
2. **AI-Powered Demand Planning** — Statistical forecasting engines replaced guesswork, supported by collaborative input from sales, marketing, and product teams.
3. **Automated Supply Planning** — Daily-refreshed, automated production plans replaced static planning cycles, enabling faster response to demand shifts.

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4. **Network Optimization Modeling** — AI-based optimization was used to redesign the depot network — resizing, closing, and opening depots strategically (6 → 12) — rather than relying on legacy, unoptimized locations.
5. **End-to-End Replenishment Model** — Scientific inventory norms replaced manual restocking decisions, reducing slow-moving inventory and improving order fulfillment.

5. Outcome of the Transition

- **Revenue** nearly doubled since deployment.
- **Inventory holding** cut from 45 days to 20 days.
- **Distribution network** expanded from 6 to 12 depots.
- **Service level** reached ~95%.
- **Organizational culture** shifted toward data-driven collaboration across sales, plants, and supply chain teams — not just a technology upgrade, but a mindset shift toward agility.

LT Foods' move from a traditional, manual distribution model to an AI-powered one wasn't just about adopting new software — it involved redesigning processes (planning, replenishment, network structure), building analytical capability, and shifting organizational culture toward data-driven decision-making. This holistic approach is what allowed the AI-based system to translate into measurable business outcomes rather than remaining a purely technical upgrade.

Summary of the Transformation Journey: Pre-, During-, and Post-Implementation

For readability, the table below consolidates LT Foods' transformation into three phases — the legacy state before change, the period of active implementation, and the resulting post-implementation operating model — bringing together the process changes and the KPI shifts already described above into a single, at-a-glance view.

Phase	Strategic Focus	Key Actions	Status / Indicators
Pre-Implementation (Before 2020)	Legacy, manual operations	Supply and distribution planning done manually on Excel; Order prioritization based on individual intuition; Fragmented visibility across sales, manufacturing, procurement and supply chain; Reactive, non-predictive network with only 6 depots	45-day finished-goods inventory; frequent stockouts and delivery delays; inconsistent service levels
Implementation (2020 onward)	Technology deployment	Partnered with EY; selected and deployed the AI-powered Asterisk platform; Rolled out	Transition phase: new processes, dashboards, and forecasting

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Phase	Strategic Focus	Key Actions	Status / Indicators
	and capability building	five strategic pillars: control tower, order management & replenishment, supply planning, demand planning, network optimization; Defined clear KPIs, invested in people capability, and secured leadership sponsorship for change management; Ran network optimization modeling to redesign depot footprint	models being embedded alongside legacy practices
Post-Implementation (Current State)	Data-driven, agile operating model	Automated, AI-driven planning replaces manual, Excel-based processes; Analytics-led control tower gives a single version of the truth across functions; Scientific inventory norms and daily-refreshed production plans in routine use; Depot network expanded and optimized from 6 to 12	20-day inventory; ~95% service level; nearly 2x revenue growth; data-driven culture embedded

Challenges

- **Delivery delays and stockouts** — Directly impacted customer satisfaction and hindered business growth.
- **Manual, Excel-based supply planning** — Created inefficiencies and limited the company's ability to respond quickly to market demand.
- **Lack of data-driven order prioritization** — Decisions relied heavily on individual intuition rather than systematic, data-backed insights.
- **Limited supply chain visibility** — Fragmented data across sales, manufacturing, and procurement made root-cause analysis and cross-team collaboration difficult.

Opportunity

- Growing global demand for packaged rice-based food products, with LT Foods already present in 80+ countries.

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- A large, established distributor network (1,300+ distributors) that could be leveraged more efficiently with better planning tools.
- Availability of advanced AI-powered supply chain technology (EY's Asterisk platform) that could bring agility, transparency, and predictive capability to operations.
- Potential to convert operational efficiency gains directly into revenue growth and improved customer service levels.

Strategies

The transformation was built on five strategic pillars:

1. **Analytics-led Control Tower** — Introduced daily dashboards across sales, supply chain, manufacturing, and procurement, enabling a "single version of the truth" and more data-driven cross-team conversations.
2. **Order Management and Replenishment** — Shifted to an end-to-end replenishment model with scientific inventory norms, improving customer service levels and eliminating slow-moving inventory.
3. **Supply Planning** — Implemented automated, daily-refreshed production plans using frozen, fixed, and tentative planning horizons, increasing SKU output and manufacturing flexibility.
4. **Demand Planning** — Deployed AI-powered statistical forecasting and promoted bottom-up collaborative planning involving sales, marketing, and product teams to improve forecast accuracy.
5. **Network Optimization** — Redesigned the depot network (expanding from 6 to 12 depots) through optimization modeling, reducing delivery lead times and costs while improving service levels.

Supporting success factors:

- Clear KPIs and well-defined expectations to sustain agility.
- Investment in people's capabilities alongside technology.
- Building a culture of data-driven, continuous improvement.
- Strong leadership support to drive change management and adoption.

Conclusion

LT Foods' supply chain transformation demonstrates that digital technology alone is not sufficient for sustainable growth — it must be paired with a cultural shift toward agility, collaboration, and data-driven decision-making. Viewed through the Dynamic Capabilities lens, the company's ability to sense operational gaps, seize the right technology and partnership, and transform its processes and culture is what allowed a platform deployment to translate into durable business outcomes. By systematically addressing visibility, planning, and network design through the Asterisk platform, LT Foods not only solved its immediate operational challenges but also built a scalable foundation for long-term growth, achieving nearly double its revenue and a ~95% service level.

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Questions for Discussion

1. What were the root causes of LT Foods' supply chain inefficiencies before the transformation, and how were they interlinked?
2. How did the "Analytics-led Control Tower" pillar help address the lack of data-driven decision-making at LT Foods?
3. In what ways did demand planning and supply planning need to work together for the transformation to succeed?
4. What role did organizational culture and people capability play in the success of this technology-driven transformation?
5. How did network optimization (expanding depots from 6 to 12) contribute to both customer service and cost efficiency?
6. What risks might a company like LT Foods face if it scales such a digital transformation too quickly across new global markets?
7. Can this transformation model (used in the food/FMCG sector) be applied to other industries? What adaptations might be needed?
8. Using the Sensing–Seizing–Transforming framework, identify one action LT Foods took under each capability. Which capability do you think was hardest to sustain, and why?

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Racing Against the Forecast: Postponement and Cross-Docking at Veloura Home Appliances

A Case on Redesigning Supply Chain Flows for a Regionally Fragmented Indian Consumer Durables Market

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Abstract

This instructional case investigates the process by which Veloura Home Appliances, a mid-sized Indian manufacturer of small kitchen and personal-care appliances, redesigned its supply chain to address a persistent tension between regional product variety and forecast accuracy. Veloura encountered simultaneous stockouts in certain regions and aged, discounted inventory in others while operating a make-to-forecast model with fully finished, region-specific SKUs (which varied by plug type, voltage rating, and language of the instruction manual) stored in five regional warehouses. In the case, management evaluates two classical logistics levers: postponement (delaying final product differentiation until closer to actual regional demand) and cross-docking (eliminating regional warehousing in favour of a central hub that sorts and forwards shipments with minimal dwell time). Ultimately, these levers are combined into a single redesigned flow. Typically, postponement and cross-docking are introduced as strategic and operational responses to demand uncertainty and SKU proliferation in Logistics and Supply Chain Management. The case is intended for this scenario. Students are required to assess the trade-offs of each lever independently and collaboratively, and to suggest an implementation sequence that is suitable for a resource-constrained mid-market organization.

Keywords: *postponement, cross-docking, supply chain integration, SKU proliferation, logistics strategy, Indian consumer durables*

1. Background

In 2009, Veloura Home Appliances was founded and has since become a reputable mid-market brand in the small appliance category of India. The company manufactures electric kettles, mixer-grinders, and personal hygiene devices from a single manufacturing facility located near Pune. By the year of the case, Veloura had a presence in all major Indian regions, selling through a network of large-format retail chains, regional distributors, and its own e-commerce shopfront. Its annual revenue firmly placed it in the mid-market segment, requiring multi-regional distribution planning. However, it was still significantly smaller than the scale at which the largest consumer-durables players operate dedicated regional manufacturing or fully automated distribution infrastructure.

The regional fragmentation of India's small appliance market has a direct impact on product specification. The expectations for voltage tolerance vary modestly across states, dependent on

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the stability of the grid. In certain southern and eastern markets, multi-language instruction manuals (Tamil, Telugu, Bengali) are preferred over the Hindi/English default used elsewhere. Packaging design for e-commerce fulfilment is distinct from packaging optimised for retail shelf display. The Veloura product team had, over the course of several years, expanded a single kettle model into eleven finished-goods SKUs and its flagship mixer-grinder into eighteen. Each SKU was fully assembled, packaged, and labelled at the factory before being shipped in bulk to one of five regional warehouses (North, South, East, West, and a dedicated e-commerce fulfilment center) based on a rolling three-month regional demand forecast. This was done in order to accommodate the differences.

Veloura had been reasonably successful with this make-to-forecast, fully-finished-goods model while its SKU count was low. However, the planning team was confronted with a multiplied forecasting task as the SKU count increased to accommodate regional variety. Rather than forecasting demand for a single kettle, planners were now required to forecast demand for eleven regional kettle variants, each with its own historical sales pattern, promotional calendar, and seasonal quirks. The forecast error at the SKU-region level was significantly higher than the forecast error at the aggregate product level, a pattern that the planning team had observed but had not yet addressed.

2. The Problem

Veloura's North region warehouse was unable to supply the Hindi-manual, 5-amp kettle variant for six weeks during the peak wedding-gifting season, which resulted in an estimated ₹1.4 crore in lost sales. Furthermore, the SKU was temporarily delisted by a major retail chain in anticipation of supply reliability verification, which was more detrimental. This transpired two quarters prior to the case. The Bengali-manual kettle variant was in the East region warehouse for eleven weeks during the same quarter, surpassing Veloura's inventory-holding target of four weeks. As a result, a clearance discount was required, which resulted in a margin reduction of approximately eighteen percent for the affected quantity. During the investigation, the Head of Supply Chain identified that the pattern was structural rather than a singular planning error. The forecast error for a specific region-variant combination could not be rectified without either an expensive emergency air-freight transfer between regional warehouses (which Veloura had employed twice in the preceding year, at a landed cost approximately four times the normal transport cost) or accepting the stockout or overstock event, as each regional SKU variant was fully completed at the factory and subsequently committed to a specific regional warehouse based on a forecast made three months in advance. The CEO was not presented with the underlying question by the Head of Supply Chain regarding how to more accurately forecast, as regional demand for small appliances is inherently volatile and promotion-driven. Rather, the question was whether Veloura's supply chain design necessitated the forecast to perform more precise work than any forecast could reasonably accomplish.

The CEO tasked the Head of Supply Chain with the following responsibility: to propose a redesign of Veloura's distribution model that would reduce the company's susceptibility to region-level forecast errors, without the need for the establishment of a second manufacturing facility, in advance of the fiscal year's planning cycle.

3. Two Logistics Levers Under Consideration

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3.1 Postponement

The strategic delay of final product differentiation to the most recent feasible point in the supply chain is known as postponement. This process involves moving the point at which a generic product becomes a specific, committed SKU as close as possible to the instant actual demand is known. The generic, undifferentiated component of a product that is differentiated late is the only component that is affected by forecast error. This component can be pooled across all regional variants, rather than each completely specified regional SKU individually. This principle is sometimes referred to as risk pooling. Postponement, when applied to Veloura, would entail the production of a single generic kettle or mixer-grinder base at the Pune facility, and the postponement of the region-specific steps (such as the installation of the correct plug/voltage component, the inclusion of the correct language manual, and the application of region-appropriate packaging) until a point that is significantly closer to an actual, known order or firm regional demand signal. This is in contrast to the commitment to a specific regional variant three months in advance based solely on forecasts.

3.2 Cross-Docking

Cross-docking is a distribution practice that involves the prompt sorting and consolidation of inbound shipments with other inbound flows for immediate loading onto outbound transport. This minimises the time goods spend at rest inside the facility, as opposed to being placed into storage. Cross-docking directly synchronises inbound and outbound flows by substituting information and scheduling coordination for physical inventory, whereas conventional warehousing decouples inbound and outbound flows by holding stock as a buffer against uncertainty. When applied to Veloura, cross-docking would entail the replacement of some or all of the five regional warehouses, which are currently utilised to store weeks of finished-goods inventory, with a single central cross-dock facility. This facility would facilitate the rapid flow of product to regional and retail destinations, rather than allowing it to remain in regional storage.

3.3 Why the Two Levers Interact

Postponement and cross-docking are frequently more effective when used in conjunction than when used separately, as they address distinct aspects of the same underlying issue. Cross-docking minimises the time any committed, differentiated unit spends in storage before reaching its destination, thereby reducing the inventory-holding exposure of how what is produced then moves through the network. Postponement reduces the forecast-error exposure of what is produced by delaying commitment to a specific regional variant. A company that implements postponement alone still requires a location for the flow of newly differentiated, regionally committed goods. Similarly, a company that implements cross-docking alone still encounters the original forecasting problem for any completely finished goods that enter the cross-dock. When viewed in conjunction, the two levers characterise a redesigned flow: a generic product that is manufactured to a stable, aggregate forecast, differentiated late based on firmer regional signals, and then moved rapidly to its destination through a cross-dock rather than parked in regional storage.

4. Alternatives Considered

The CEO was presented with four redesign options by the Head of Supply Chain's team for evaluation:

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A. **Refined forecasting, status quo**: Maintain the current fully-finished regional-warehouse model, but invest in more granular, AI-assisted demand forecasting at the SKU-region level to directly reduce forecast error.

B. **Postponement exclusively**: Implement a generic-product manufacturing model with late differentiation at the Pune facility (or a newly added postponement line adjacent to it), while maintaining the five existing regional warehouses to store the region-specific, now-differentiated finished goods.

C. **Cross-docking exclusively**: Maintain the current fully-finished, region-specific manufacturing model; however, replace the five regional warehouses with a single central cross-dock facility that receives fully finished regional SKUs from the factory and promptly transports them to regional destinations.

D. **Cross-docking and postponement combined**: Centrally manufacture a generic product, transport it undifferentiated to a central hub, perform final regional differentiation (plug/voltage fitting, manual insertion, packaging) at the hub based on firmer regional order signals, and cross-dock the now-differentiated output directly onto outbound regional transport with minimal dwell time.

5. Evaluation of Alternatives

Criterion	A: Status Quo + Better Forecasting	B: Postponement Only	C: Cross-Docking Only	D: Combined
Addresses forecast-error root cause	Partial - improves precision, but SKU-region granularity problem remains structurally	Strong - risk pooling reduces exposure to regional forecast error	Weak - still commits to regional variant early	Strong - combines risk pooling with fast downstream flow
Capital investment required	Low (forecasting software/analytics)	Moderate (postponement line/workstation)	Moderate (single cross-dock facility vs. five warehouses)	Moderate-high, but overlaps with B and C rather than additive
Inventory holding cost	Unchanged - still holds weeks of finished goods per region	Reduced generic-stock holding, but finished goods still held regionally	Substantially reduced - minimal dwell time at the hub	Most reduced across both differentiation and storage
Coordination/IT demand	Low-moderate (forecasting system upgrade)	Moderate (differentiation scheduling)	High (inbound-outbound	Highest - both differentiation scheduling and

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			synchronization)	dock synchronizatio n must work together
Risk of disruption to current operations	Low	Moderate - factory process change only	High - full warehouse-network restructuring at once	High if attempted simultaneously ; manageable if sequenced

6. Recommendation

The most effective structural solution to Veloura's issue is the combined approach (Alternative D). However, a mid-market organization that lacks prior experience with either practice is at a significant execution risk when attempting to implement postponement and cross-docking simultaneously. Alternative D is the preferred course of action, as it is a deliberate sequencing approach rather than a simultaneous rollout. Initially, postponement is introduced, and the existing five regional warehouses are temporarily retained as a buffer during the transition. Subsequently, the facilities are consolidated into a central cross-dock facility once the postponement process is stable and regional differentiation lead times are predictable. This sequence guarantees that the extant warehouse network will continue to provide a safety margin in the event that the postponement process encounters early difficulties, and cross-dock synchronisation will not be attempted against a still-changing upstream process.

7. Implementation Plan

Phase 1 (Months 1-4): Generic Manufacturing and Postponement Line

Separate the generic base assembly from the region-specific components (plug/voltage module, language manual, region-appropriate packaging) by redesigning the kettle and mixer-grinder bill of materials. Establish a postponement workstation that is dedicated and located adjacent to the primary assembly line. This workstation is responsible for the final differentiation process, which is based on confirmed regional orders rather than forecasts. During this phase, the existing five regional facilities will continue to receive differentiated output.

Phase 2 (Months 5-7): Lead-Time Measurement and Stabilisation

Under the new postponement process, monitor the accuracy of regional order fulfilment and the lead time for differentiation. Utilise this timeframe to determine the advance time from order confirmation to dispatch that the inbound-outbound synchronisation of the future cross-dock facility must account for.

Phase 3 (Months 8-12): Cross-Dock Consolidation

Establish a single central cross-dock facility that is strategically located to ensure that all four regions have balanced transport access. Subsequently, transition regional order fulfilment from the five regional warehouses to direct cross-dock flow. To enable the transport and dock-

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scheduling team to address the synchronisation requirements of one region before introducing the next, regional warehouses are decommissioned sequentially, rather than simultaneously.

Risk Management During the Rollout

- Maintain the North and East regional warehouses, which are the two regions most affected by the stockout/overstock incidents, as the last to be migrated after the cross-dock procedure has been proven in lower-risk regions.
- Maintain a contingency air-freight protocol during the transition period in the event that early cross-dock synchronisation failures reintroduce the short-term stockout risk.
- Develop an internal business case for the rollout's completion by monitoring the monthly inventory-holding cost and stockout/overstock incidence against the pre-redesign baseline.

8. Discussion Questions

1. Using the concept of risk pooling, explain why forecasting at the level of eleven regional kettle SKUs produces higher aggregate forecast error than forecasting demand for one generic kettle base. Would risk pooling benefits be larger or smaller if Veloura's regional variants differed only in packaging colour rather than in functional components like voltage rating?
2. Alternative A (better forecasting alone) was evaluated as addressing the problem only partially. Under what circumstances might improved forecasting alone be a sufficient response, without requiring postponement or cross-docking at all?
3. Why does the case recommend sequencing postponement before cross-docking, rather than the reverse order or a simultaneous rollout? Construct the argument for reversing the sequence instead, and evaluate whether it is equally defensible.
4. Cross-docking substitutes coordination and information flow for physical inventory. What specific information-system and scheduling capabilities would Veloura need to build before its cross-dock facility could function reliably, and what happens to regional service levels if that coordination fails?
5. Veloura is a mid-market firm. Identify one element of this case's recommended approach that might not be feasible for a much smaller firm, and one element that might be unnecessary for a much larger firm with dedicated regional manufacturing. What does this suggest about the relationship between firm scale and the choice between postponement and cross-docking?

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Eraaya Lifespaces Limited: Growth, Acquisition Financing and Financial Sustainability

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1. Background of the Case

Eraaya Lifespaces Limited (formerly known as Justride Enterprises Limited) is a listed company incorporated in 1967. During FY 2024–25, the Company went through a significant strategic transformation. Its business profile expanded substantially, particularly following its acquisition of 97.58% equity interest in Ebix Inc. through a consortium-led transaction under the U.S. Chapter 11 restructuring process.

For the purpose of this case, however, students are required to look at the transformation only from the perspective of Eraaya Lifespaces Limited's standalone financial position and performance. The financial performance of Ebix Inc. and its subsidiaries is deliberately excluded. The Annual Report identifies digital marketing as accounting for approximately 98% of the Company's turnover on the standalone reporting boundary, while the Company also describes its broader strategic interests in hospitality, QSRs, digital marketing and technology-enabled businesses. The year 2024–25 therefore represents an interesting financial decision-making situation. On the one hand, Eraaya demonstrated a dramatic increase in standalone revenue and mobilised substantial financial resources. On the other hand, the Company reported a significant standalone loss, negative operating cash flow and substantially higher financial liabilities. The central question for management and financial decision-makers is:

Can rapid strategic expansion and acquisition-led growth create sustainable shareholder value when the standalone company is simultaneously experiencing substantial cash outflows, higher leverage and a significant accounting loss?

2. Standalone Financial Performance: The First Signal

The standalone Statement of Profit and Loss provide an immediate indication of the scale of change during FY 2024–25.

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Exhibit 1: Selected Standalone Financial Performance

₹ Million

Particulars	FY 2023–24	FY 2024–25
Revenue from Operations	12.65	213.85
Other Income	3.73	4.36
Total Income	16.39	218.20
Employee Benefit Expenses	1.94	29.78
Finance Costs	0.38	24.73
Depreciation & Amortisation	0.35	2.99
Other Expenses	9.46	504.45
Total Expenses	12.14	561.95
Profit/(Loss) Before Tax	4.25	(343.75)
Tax Expense/(Credit)	0.86	(85.10)
Profit/(Loss) After Tax	3.39	(258.65)
Basic/Diluted EPS (₹)	0.22	(1.48)

Source: Standalone Statement of Profit and Loss, Annual Report 2024–25

The figures reveal a striking financial transition. Revenue from operations increased from ₹12.65 million to ₹213.85 million—an increase of approximately 1,591%. However, the substantial increase in revenue did not translate into profitability. Instead, the Company moved from a profit after tax of ₹3.39 million in FY 2023–24 to a loss of ₹258.65 million in FY 2024–25. The Company itself attributed the standalone decline primarily to higher input costs, expansion-related expenses and strategic investments undertaken to strengthen its long-term positioning. This creates the first financial-management dilemma:

Revenue growth is impressive—but is it economically meaningful if the additional revenue is accompanied by substantially greater expenditure and negative cash generation**?**

3. The Cost Structure: Where Did the Money Go?

The most striking feature of the standalone income statement is the increase in Other Expenses, which reached ₹504.45 million compared with ₹9.46 million in the preceding year. Several components deserve particular attention:

- Legal and professional charges: ₹188.71 million
- Exchange-rate fluctuation: ₹192.25 million
- Business promotion expenses: ₹98.65 million
- Tour and travelling expenses: ₹11.09 million
- Advertisement: ₹3.13 million

Thus, three categories—legal/professional charges, foreign exchange fluctuation and business promotion—together account for a very substantial proportion of Other Expenses. Finance costs also increased to ₹24.73 million, including ₹20.89 million of interest on loans and ₹0.43

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million of interest on lease liabilities. For an MBA Finance student, this raises an important distinction between:

- growth expenditure,
- strategic investment,
- transaction-related expenditure,
- financing cost, and
- recurring operating expenditure.

Management may view certain expenditures as necessary for long-term expansion. However, the finance function must determine whether such expenditure is generating or is reasonably expected to generate sufficient future cash flows.

4. Standalone Balance Sheet: A Completely Transformed Financial Structure

The balance sheet presents another important dimension of the case.

Exhibit 2: Selected Standalone Balance Sheet

₹ Million

Particulars	March 31, 2024	March 31, 2025
Total Non-Current Assets	65.81	12,004.83
Investments	—	11,679.03
Loans	—	158.62
Current Assets	72.18	3,758.80
Cash & Cash Equivalents	65.56	7.93
Total Assets	137.98	15,763.63
Share Capital	151.23	190.69
Other Equity	(17.80)	3,207.39
Total Equity	133.43	3,398.08
Non-Current Borrowings	—	9,967.41
Current Liabilities	4.55	2,386.09
Total Equity & Liabilities	137.98	15,763.63

Source: Standalone Balance Sheet

The most important change is the investment portfolio. Standalone investments increased to ₹11,679.03 million, of which ₹11,639.03 million represented the investment in Ebix Inc. The Annual Report states that Eraaya held 97.58% of Ebix Inc. Consequently, approximately 74% of total standalone assets were represented by investments. This concentration creates a classic corporate-finance question:

Has the Company created financial value by deploying capital into a strategic investment, or has it created concentration and financing risk that must now be supported by future cash flows? Students should also notice that cash and cash equivalents fell from ₹65.56 million to only ₹7.93 million.

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5. Financing the Strategic Transformation

The acquisition and broader expansion required substantial financing. As at March 31, 2025, standalone non-current borrowings were ₹9,967.41 million. Of this, ₹9,778.51 million related to secured borrowings and ₹188.90 million to unsecured borrowings. The Company issued US$120 million of 9.50% Senior Secured Foreign Currency Convertible Bonds (FCCBs) in two tranches. The bonds were convertible into equity shares at an initial price of ₹801 per share, subject to stated adjustments. The investment in Ebix Inc. was intended to serve as security; however, the pledge had not been created as at the reporting date.

A particularly important issue was that US$40 million of the second FCCB tranche had not been received, and the Company had initiated legal proceedings for recovery. In the standalone balance sheet, the amount was reflected as a receivable considered good.

In addition, approximately ₹2,338.68 million was included in Other Financial Liabilities, representing USD 27.327 million of acquisition consideration pending remittance. Therefore, the finance manager faces several simultaneous questions:

1. How much debt can the Company prudently carry?
2. What is the appropriate debt-equity mix?
3. Should further funding be through debt, equity or convertible instruments?
4. What are the implications of foreign-currency borrowing?
5. How should the Company manage refinancing and liquidity risk?

6. Cash Flow: The Most Important Reality Check

The Statement of Standalone Cash Flows provides perhaps the strongest basis for classroom discussion.

Exhibit 3: Standalone Cash Flow Highlights

₹ Million

Particulars	FY 2024–25
Net Cash from Operating Activities	(606.02)
Net Cash Used in Investing Activities	(9,496.90)
Net Cash from Financing Activities	10,045.27
Net Decrease in Cash	(57.64)
Opening Cash & Cash Equivalents	65.56
Closing Cash & Cash Equivalents	7.93

The investing cash outflow included ₹9,340.34 million towards purchase of investments. Financing inflows included ₹6,544.15 million from borrowings, ₹2,965.85 million of share premium and ₹557.86 million from issue of shares.

This produces a particularly important finance lesson:

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Accounting revenue growth does not necessarily mean cash-flow growth. The Company generated negative operating cash flow of ₹606.02 million despite reporting ₹213.85 million of revenue from operations. The operating cash flow was therefore approximately ₹2.83 for every ₹1 of standalone operating revenue in the opposite direction—an extremely important warning signal for students to investigate. At the same time, the Company financed its strategic transformation largely through financing inflows. This raises the question of whether the Company was, during FY 2024–25, in a phase of investment-led transformation or whether it was developing an unsustainable dependence on external financing.

7. Capital Raising and Shareholders' Funds

The Company also substantially increased its equity base.

During FY 2024–25, equity shares were issued through QIP, FCCB conversion and preferential allotment. The number of shares increased from 151.23 million shares to 190.69 million shares, while Other Equity increased to ₹3,207.39 million. The Annual Report records a QIP allocation of 32,61,200 shares at ₹762 per share and subsequent FCCB-related and preferential issuances.

For students, this introduces the issue of financial leverage versus ownership dilution.

Debt financing can preserve ownership but increases fixed financial commitments. Equity financing reduces financial risk but can dilute existing shareholders. Convertible instruments may provide a hybrid solution but can create future dilution and complex accounting and governance issues.

8. Risk, Governance and Financial Decision-Making

The case becomes particularly relevant from a corporate-finance and governance perspective because the standalone financial statements contain several significant disclosures. The Auditor's Report drew attention to the acquisition, FCCB issuance and related legal proceedings. The Company had acknowledged contingent liabilities of ₹557.50 million relating to unrecognised FCCB interest, while the annual report also disclosed a contingent liability of ₹1,112.60 million relating to interest obligations connected with Vikas Lifecare Limited, subject to the outcome of the relevant proceedings. The Company also disclosed that the investment in Ebix was subject to a proposed pledge in connection with FCCBs, that the pledge had not yet been created, and that certain FEMA-related compliance processes concerning the overseas investment and FCCBs were still in process. At the same time, the auditors reported that they did not identify a material uncertainty indicating that the Company was incapable of meeting liabilities falling due within one year, although they expressly noted that this did not constitute an assurance regarding future viability.

This distinction is extremely valuable for MBA students:

An absence of a reported material uncertainty regarding immediate solvency does not mean that the Company has no financial risk.

9. The Management Decision

It is now March 2025. You are part of the senior financial-management team of Eraaya Lifespaces Limited. The Company has:

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- substantially increased its revenue;
- made a transformational strategic investment;
- significantly expanded its asset base;
- raised debt and equity;
- experienced negative operating cash flow;
- reported a substantial standalone loss;
- reduced its cash balance significantly;
- assumed foreign-currency financing obligations;
- and faces legal, regulatory and execution-related uncertainties.

Management nevertheless believes that the strategic investments can generate significant future value. The Board therefore needs to determine the appropriate financial strategy for FY 2025–26. The CFO asks the finance team:

"How should Eraaya balance growth, liquidity, leverage, shareholder dilution and financial sustainability during the next phase of its transformation?"

You have been asked to prepare a financial recommendation.

10. Questions for Classroom Discussion

Question 1 – Profitability and Quality of Growth

Revenue from operations increased dramatically from ₹12.65 million to ₹213.85 million, yet the Company reported a standalone loss of ₹258.65 million. Analyse the profitability position and determine whether the revenue growth represents financially healthy growth. Identify the major cost drivers responsible for the loss.

Question 2 – Liquidity and Working Capital

The Company reported current assets of ₹3,758.80 million, current liabilities of ₹2,386.09 million and cash of only ₹7.93 million. Calculate the current ratio and critically assess the Company's short-term liquidity position. Why might the current ratio alone provide an incomplete picture of liquidity?

Question 3 – Capital Structure and Financial Leverage

Standalone non-current borrowings amounted to ₹9,967.41 million against total equity of ₹3,398.08 million. Calculate the debt-equity ratio and debt-to-total-assets ratio. Discuss whether the Company's capital structure appears aggressive, moderate or conservative. What are the advantages and risks of the financing strategy?

Question 4 – Acquisition Financing Decision

The Company's standalone investment in Ebix Inc. amounted to ₹11,639.03 million, while significant borrowing and convertible bonds were used as part of the financing structure. As a corporate-finance manager, would you recommend debt financing, equity financing or a combination of both for such a strategic acquisition? Justify your answer using the concepts of cost of capital, financial leverage, risk and shareholder dilution.

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Question 5 – Cash Flow versus Accounting Profit

The Company generated negative operating cash flow of ₹606.02 million, while investing activities used ₹9,496.90 million and financing activities generated ₹10,045.27 million. What does this cash-flow pattern tell you about the Company's financial strategy? Is the Company currently financing growth internally or externally? What risks arise if negative operating cash flows continue?

Question 6 – Board-Level Financial Recommendation

Assume that you are advising the Board for FY 2025–26. Prepare a three-part financial strategy for Eraaya Lifespaces Limited covering:

1. Liquidity management
2. Capital structure and financing
3. Investment and cash-flow discipline

Identify at least five financial KPIs that the Board should monitor quarterly to determine whether the transformation is creating sustainable shareholder value.

Important Source Note

This case has been prepared strictly from the FY 2024–25 Annual Report of Eraaya Lifespaces Limited, with the financial analysis based on the standalone financial statements only. The Annual Report itself separately identifies the standalone financial section beginning with the Balance Sheet, Statement of Profit and Loss, Cash Flow Statement and Notes, before the consolidated financial section. Accordingly, consolidated revenue, consolidated profit/loss, consolidated assets, consolidated cash flows and consolidated ratios have not been used in this case. References to the Ebix acquisition are used only insofar as they explain transactions, investments, financing and risks appearing in Eraaya Lifespaces Limited's standalone accounts.

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The Quick-Commerce Dilemma: Can Zomato's Blinkit Deliver Speed and Sustainable Profits?

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Abstract

This case study examines the strategic and operational dilemma facing Blinkit, the quick-commerce subsidiary of Zomato's parent company Eternal Limited, as it seeks to reconcile the competing imperatives of ultra-fast delivery, aggressive market expansion, and sustainable profitability. Since its acquisition by Zomato in 2022, Blinkit has grown into the largest contributor to Eternal's business-to-consumer order value, but this growth has been accompanied by heavy cash burn, intense competitive pressure from Zepto, Swiggy Instamart, BigBasket Now, Flipkart Minutes and Amazon Now, and a fundamental accounting and operational shift from an asset-light marketplace model toward an inventory-led (first-party) model. Drawing on recent financial disclosures, industry reports and academic frameworks in supply chain management and competitive strategy, the case traces the evolution of India's quick-commerce sector, Blinkit's hyperlocal dark-store operating model, and the six strategic challenges confronting its management: balancing speed with profitability, managing unit economics, optimising inventory, choosing between expansion and consolidation, responding to competitive pressure, and addressing sustainability and regulatory concerns. The case is structured for classroom use and includes a SWOT analysis, a Porter's Five Forces analysis, a management dilemma, key decisions for discussion, and seven discussion questions with guidance for instructors. It is intended to help postgraduate management students critically evaluate the trade-offs between growth-led and profitability-led strategies in a technology-enabled, capital-intensive digital business.

Keywords: *quick commerce; Blinkit; Zomato; Eternal Limited; dark stores; unit economics; hyperlocal logistics; competitive strategy; supply chain management*

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1. Introduction

India's digital economy has transformed consumer expectations. Urban customers increasingly value convenience over store visits and are willing to pay for products delivered within minutes. This behavioural shift gave rise to quick commerce, an evolution of e-commerce focused on delivering groceries and daily essentials in 10–20 minutes. Zomato, already a leader in online food delivery, entered this space by acquiring Blinkit in 2022. The acquisition promised growth beyond restaurant delivery but also exposed the company to inventory management, warehousing and last-mile logistics challenges that differed significantly from its asset-light marketplace model (Zomato Limited, 2024).

Quick commerce combines technology, hyperlocal fulfilment and data analytics to minimise delivery time. However, the model demands heavy investment in dark stores, inventory, riders and technology. The strategic question facing management is whether customers' desire for speed can generate sustainable profits or whether rapid expansion will continue to consume cash (Chopra & Meindl, 2023; Christopher, 2022).

By early FY27, this tension had begun to resolve in Blinkit's favour on paper: Eternal Limited reported that its quick-commerce net order value overtook Zomato's food-delivery net order value for the first time in Q1 FY26, and by the first quarter of FY27 Blinkit's adjusted EBITDA had risen 223 per cent year-on-year to a record ₹555 crore, even as consolidated net profit fell on a sequential basis because of a sharply higher tax expense (Business Standard, 2026a; Quash, 2026). At the same time, the underlying comparability of Blinkit's results was complicated by its transition from a marketplace (commission-based) accounting model to a first-party, inventory-owning model, a change that inflated headline revenue growth far beyond the growth in actual consumer demand (Quash, 2026). This case uses that tension — rapid, headline-grabbing growth set against a genuinely difficult profitability story — as the lens through which students examine Blinkit's strategic choices.

2. Literature Review and Conceptual Background

Quick commerce (Q-commerce) is generally defined as a retail model that promises delivery of groceries, medicines, personal care products and household essentials within 10 to 30 minutes, typically fulfilled from small, hyperlocal micro-fulfilment centres known as dark stores (Bain & Company, 2024; Deloitte India, 2024). It represents a further compression of the last-mile logistics timeline established by earlier same-day and next-day e-commerce models, and it draws on classical supply chain concepts of network design, inventory positioning and demand forecasting (Chopra & Meindl, 2023; Christopher, 2022).

Two conceptual streams are particularly relevant to this case. The first is the economics of hyperlocal fulfilment networks. Because dark stores are deliberately located close to the end consumer, they reduce the distance-related cost and time of last-mile delivery, but they also fragment inventory across many small nodes, which raises holding costs, increases the risk of stock-outs at any single node, and requires sophisticated, data-driven demand forecasting to keep each store adequately — but not excessively — stocked (Chopra & Meindl, 2023). The second is competitive strategy, most notably Porter's (1980) framework of five competitive

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forces and generic strategies, which helps explain why quick-commerce operators compete simultaneously on cost (through scale and automation), differentiation (through speed, assortment and brand trust) and, increasingly, sustainability and regulatory compliance.

Industry research on India's quick-commerce sector has tracked its transition from a venture-capital-funded, growth-at-any-cost phase toward a phase in which investors and boards demand credible paths to profitability. Analysts note that the sector, valued at roughly US$5.5–6.8 billion in 2025–26 depending on the estimation methodology used, has grown at a compound annual rate well above 20 per cent and is forecast to continue growing at double-digit rates through the end of the decade, even as growth rates moderate from the exceptional levels recorded between 2020 and 2024 (Mordor Intelligence, 2026; ResearchAndMarkets, 2026; Statista, 2026). This literature frames the present case: Blinkit is not simply choosing between "growth" and "profit" in the abstract, but is navigating a maturing industry in which unit economics, dark-store density and inventory strategy increasingly determine which competitors survive.

3. The Indian Quick-Commerce Market

The Indian retail industry has undergone a remarkable transformation over the last decade, driven by rapid urbanisation, increasing internet penetration, widespread adoption of smartphones, and the growing popularity of digital payment systems. Traditionally, consumers relied on neighbourhood kirana stores and supermarkets for purchasing groceries and daily essentials. While the emergence of e-commerce platforms such as Amazon, Flipkart, and BigBasket revolutionised online shopping by offering home delivery, the delivery timelines of one or two days were often inadequate for customers with immediate needs. This gap in the market led to the emergence of Quick Commerce (Q-Commerce), a retail model that promises delivery of groceries, medicines, personal care products, and household essentials within 10 to 20 minutes. The concept has fundamentally changed consumer expectations by making convenience and speed the primary drivers of purchase decisions (Bain & Company, 2024; Deloitte India, 2024).

The rapid growth of India's quick-commerce market has been fuelled by several socio-economic and technological factors. Urban consumers, particularly in metropolitan cities such as Delhi, Mumbai, Bengaluru, Hyderabad, Chennai, and Pune, lead increasingly busy lifestyles and seek convenient solutions for their everyday shopping requirements. The widespread adoption of the Unified Payments Interface (UPI), affordable mobile internet, and app-based shopping platforms has further accelerated the adoption of quick-commerce services. In addition, the COVID-19 pandemic significantly changed shopping behaviour, with consumers becoming more comfortable purchasing essential products online, encouraging companies to invest aggressively in hyperlocal logistics networks and technology-enabled supply chains.

By 2026, industry estimates of the size of India's quick-commerce market varied considerably depending on methodology, but converged on a picture of continued rapid growth. One estimate placed the market at roughly US$3.65 billion in 2026, forecast to reach US$6.64 billion by 2031 at a compound annual growth rate of approximately 12.7 per cent, with West

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India accounting for the largest regional share (Mordor Intelligence, 2026). A separate data book update projected the market reaching US$6.78 billion by 2025 and roughly US$13 billion by 2029, following a period of extraordinary growth (a compound annual growth rate above 70 per cent between 2020 and 2024) and a subsequent moderation to a still-substantial forecast growth rate of around 17–18 per cent between 2025 and 2029 (Research And Markets, 2026). Domestic brokerage research estimated that India's quick-commerce segment would touch approximately ₹1.08 lakh crore in calendar year 2026, growing about 40 per cent year-on-year and expanding more than twice as fast as India's broader digital commerce market, with the combined dark-store network of Blinkit, Swiggy Instamart and Zepto expanding from 3,405 stores in May 2025 to 5,026 stores in May 2026 (Apparel Resources, 2026).

The Indian quick-commerce industry has attracted substantial investment from venture capital firms and major technology companies because of this growth potential. Leading companies such as Blinkit (owned by Eternal Limited, formerly Zomato Limited), Zepto, Swiggy Instamart, BigBasket Now, Flipkart Minutes and, more recently, Amazon Now are competing intensely to capture market share. Each company differentiates itself through delivery speed, product assortment, pricing strategy, customer experience and technological capability. Despite this impressive growth, the industry faces significant operational and financial challenges: maintaining hundreds of strategically located dark stores, large delivery fleets and continuously optimised technology platforms increases operating costs, while profit margins on grocery products remain relatively thin, so companies must achieve high order volumes and strong customer retention to improve operational efficiency (RedSeer Strategy Consultants, 2024; Deloitte India, 2024).

Technology has become the backbone of the quick-commerce ecosystem (Deloitte India, 2024; RedSeer Strategy Consultants, 2024). Artificial Intelligence (AI), Machine Learning (ML), data analytics, and predictive demand forecasting enable companies to optimise inventory placement, reduce stock-outs, and improve delivery efficiency. Looking ahead, industry experts anticipate continued growth due to increasing urbanisation, rising disposable incomes, changing consumer lifestyles, and ongoing technological innovation, but note that investors are shifting their focus from rapid customer acquisition towards positive unit economics and long-term profitability (Bain & Company, 2024; EY India, 2024).

4. Business Model of Blinkit

Blinkit operates an inventory-led hyperlocal quick-commerce business model that is fundamentally different from traditional marketplace-based e-commerce platforms (Blinkit, 2024; Zomato Limited, 2024). Unlike companies that merely connect buyers with third-party sellers, Blinkit owns or manages inventory through a network of strategically located dark stores — small fulfilment centres situated within residential neighbourhoods and designed exclusively for processing online orders rather than serving walk-in customers. The company's primary objective is to deliver groceries, personal care products, medicines, dairy products, snacks, beverages, and other daily essentials within 10 to 20 minutes, thereby creating significant value for customers through speed and convenience.

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The company's value proposition rests on three promises: ultra-fast delivery, wide product availability, and a seamless digital shopping experience. Customers can browse thousands of products using the Blinkit mobile application, place orders within seconds, make secure digital payments, and receive their purchases at their doorstep within minutes. This convenience is particularly attractive to working professionals, nuclear families, students, elderly individuals, and urban households who prefer saving time rather than visiting physical retail stores.

Blinkit's operational model begins with the procurement of products from manufacturers, distributors, and Fast-Moving Consumer Goods (FMCG) companies. These products are initially received at regional distribution centres before being allocated to dark stores based on sophisticated demand forecasting algorithms. The company employs Artificial Intelligence and Machine Learning techniques to analyse historical sales data, customer buying patterns, weather conditions, festivals, seasonal trends, and local events to determine optimal inventory levels at each dark store. Once a customer places an order, the technology platform automatically identifies the nearest dark store with sufficient inventory; store associates pick and pack the order while the system simultaneously assigns it to the nearest available delivery partner using route optimisation software.

4.1 Recent Financial and Operational Performance

Blinkit's scale expanded rapidly through FY25 and FY26. In the fourth quarter of FY25, Blinkit's revenue rose 122.2 per cent year-on-year to ₹1,709 crore, then representing 29.3 per cent of Eternal's total revenue, as the company added 294 net new dark stores during the quarter to reach a total of 1,301 (IndMoney, 2025). Growth continued to accelerate in FY26: in the first quarter of FY26, Blinkit's gross order value rose to ₹11,821 crore and its net order value rose 126.6 per cent year-on-year to ₹9,203 crore, with average monthly transacting customers increasing from 13.7 million to 16.9 million quarter-on-quarter and the store count reaching 1,544 after the addition of 243 net new stores (Business Standard, 2025). By this point Eternal's combined business-to-consumer annualised net order value across food delivery and quick commerce approached US$10 billion, with quick commerce contributing almost half of that figure and, for the first time, exceeding food delivery's net order value (Business Standard, 2025).

By the fourth quarter of FY26, Blinkit had reached ₹14,386 crore in net order value, operated 2,243 dark stores, recorded 27.2 million monthly transacting users and roughly 274 million quarterly orders, with a net average order value of approximately ₹525, and posted its first positive adjusted EBITDA of ₹37 crore (Quash, 2026). During FY26, Eternal also began transitioning Blinkit from a marketplace (commission-based) model to a first-party, inventory-owning model, under which Blinkit records the full selling value of goods as revenue rather than only a commission. Because of this accounting transition, headline year-on-year revenue growth figures exceeding 500 per cent substantially overstate the underlying growth in consumer demand; on a like-for-like basis, Eternal reported that Blinkit's revenue growth was closer to 117 per cent year-on-year in the first quarter of FY27 (Business Standard, 2026b; Quash, 2026).

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In the first quarter of FY27, Blinkit's reported adjusted revenue rose to ₹15,664 crore and its adjusted EBITDA reached a record ₹555 crore, up 223 per cent year-on-year and 29 per cent quarter-on-quarter, although contribution margin eased slightly from 5.4 per cent to 5.3 per cent, suggesting that a portion of the gross-margin gains from the inventory-led model was absorbed by continued store expansion and fulfilment costs (Business Standard, 2026a, 2026b). Eternal's group chief executive officer stated that the company would continue to focus on assortment expansion in its top eight cities, geographic expansion into the next thirty cities, demand densification, and premiumisation through new "gourmet" store formats (Business Standard, 2026b). These figures illustrate the central tension of the case: Blinkit's unit economics were visibly improving, but the business remained capital-intensive, competitively contested, and only recently and narrowly profitable at the adjusted EBITDA level.

Blinkit's revenue model consists of multiple income streams that enhance business sustainability: product sales (purchasing goods at wholesale prices and selling at retail margins), delivery charges, platform convenience fees, advertising and promotional partnerships with consumer brands, and subscription-based membership programmes that encourage customer loyalty. A major strength of this model lies in its integration with Eternal's broader digital ecosystem: the acquisition enabled Blinkit to leverage Zomato's extensive customer base, technology platform, delivery network and brand recognition, and cross-selling opportunities between food delivery and grocery delivery have further enhanced customer engagement. However, achieving long-term success requires Blinkit to continuously optimise its supply chain, improve unit economics, reduce delivery costs, and enhance customer satisfaction while responding to increasing competition.

5. Strategic Challenges Faced by Blinkit

As Blinkit continues to strengthen its position in India's rapidly expanding quick-commerce industry, the company faces several strategic and operational challenges that directly influence its long-term sustainability. While customer demand for ultra-fast delivery continues to rise, maintaining this promise requires substantial investment in technology, infrastructure, inventory, and human resources. The management of Eternal Limited must therefore strike a careful balance between aggressive expansion and financial discipline. The following strategic issues represent the key challenges confronting Blinkit.

5.1 Balancing Speed with Profitability

Blinkit's biggest competitive advantage is its ability to deliver products within 10–20 minutes. However, achieving this level of service requires maintaining a dense network of dark stores and ensuring sufficient delivery personnel are available throughout the day. Although customers highly value speed, the operational cost of maintaining such infrastructure is extremely high, and the recent, still-narrow adjusted EBITDA profitability described above shows how thin the margin for error remains (Quash, 2026). The management must determine whether every delivery needs to be completed within ten minutes or whether slightly longer delivery windows could significantly reduce costs without materially affecting customer satisfaction.

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5.2 Managing Unit Economics

Quick-commerce businesses operate on relatively low profit margins because grocery and FMCG products generally provide limited gross margins. Every order incurs multiple expenses, including procurement, inventory storage, packaging, delivery partner incentives, fuel, technology costs, and promotional discounts. Blinkit's own contribution margin — which eased marginally from 5.4 per cent to 5.3 per cent even as adjusted EBITDA grew strongly — illustrates how narrow this margin remains even after a shift to an inventory-owning model (Business Standard, 2026a). Unless average order values increase and delivery costs decrease further, achieving sustainable, durable profitability remains difficult; improving unit economics has therefore become one of Blinkit's highest strategic priorities.

5.3 Inventory Optimisation

Blinkit stocks thousands of products across more than two thousand dark stores located in metropolitan cities. Maintaining the right inventory levels is a complex challenge because customer demand changes continuously depending on weather conditions, festivals, weekends, local events, and consumer preferences. Overstocking increases inventory carrying costs and product wastage, whereas understocking leads to stock-outs, cancelled orders, and dissatisfied customers. Accurate demand forecasting has therefore become essential for operational efficiency (Chopra & Meindl, 2023), and the shift to a first-party inventory model makes Blinkit directly responsible for inventory risk that it previously shared with marketplace sellers.

5.4 Expansion versus Market Consolidation

The company faces an important strategic dilemma regarding geographical expansion. Eternal's own commentary points to continued expansion in India's next thirty cities alongside deeper densification of its existing top eight metropolitan markets (Business Standard, 2026b), reflecting the underlying trade-off: expanding into Tier-2 and Tier-3 cities offers opportunities for future growth, but these markets may not yet have sufficient order density to justify investment in dark stores, whereas concentrating resources on existing metropolitan markets could improve operational efficiency and profitability. Determining the appropriate pace and geographic sequencing of expansion remains a crucial strategic decision.

5.5 Competitive Pressure

Competition within India's quick-commerce industry has intensified considerably. Companies such as Zepto, Swiggy Instamart, BigBasket Now, Flipkart Minutes and Amazon Now continue to invest heavily in technology, customer acquisition, and infrastructure; the combined dark-store count of just Blinkit, Instamart and Zepto grew from 3,405 to 5,026 stores in the twelve months to May 2026 (Apparel Resources, 2026). Aggressive promotional campaigns and frequent price discounts increase customer expectations while simultaneously reducing industry profitability. Blinkit must continuously innovate to maintain its competitive advantage.

5.6 Sustainability and Regulatory Concerns

Increasing concerns regarding packaging waste, carbon emissions, rider welfare, and labour regulations have introduced new challenges for quick-commerce companies. Consumers,

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investors, and government authorities increasingly expect businesses to adopt environmentally sustainable and socially responsible practices. Blinkit must therefore incorporate sustainability into its long-term business strategy while maintaining operational efficiency.

6. Competitive Landscape

India's quick-commerce industry has evolved into one of the country's most competitive digital business sectors. The market is characterised by rapid innovation, aggressive expansion strategies, and significant investment in logistics infrastructure. Rather than competing solely on price, companies differentiate themselves through delivery speed, technology integration, product assortment, and customer experience. Blinkit currently operates in an environment where several well-funded competitors are continuously striving to increase their market share.

6.1 Major Competitors

Blinkit (owned by Eternal Limited)

Blinkit has established itself as a market leader by leveraging Zomato's extensive customer base, sophisticated technology platform, and strong logistics capabilities. Its dense network of more than 2,200 dark stores enables deliveries within 10–15 minutes across major metropolitan cities, and it became Eternal's largest business-to-consumer segment by net order value during FY26 (Quash, 2026).

Zepto

Zepto emerged as one of Blinkit's strongest competitors by introducing the concept of 10-minute grocery delivery. The company relies heavily on artificial intelligence, demand forecasting, and strategically located dark stores to maximise operational efficiency. Its rapid expansion and substantial funding have made it a formidable competitor.

Swiggy Instamart

Swiggy Instamart benefits significantly from Swiggy's established food-delivery infrastructure. By utilising its existing delivery fleet and customer base, the company has successfully expanded into grocery delivery while reducing customer acquisition costs.

BigBasket Now

Supported by the Tata Group, BigBasket combines extensive grocery retail experience with strong supplier relationships and a wide product assortment. Although its delivery times may occasionally exceed those of some competitors, customers value its product quality and reliability.

Flipkart Minutes

Flipkart Minutes represents Flipkart's strategic entry into the quick-commerce segment, seeking to leverage its existing e-commerce infrastructure, technology capabilities, and large customer base to compete effectively in the rapidly growing market.

Amazon Now

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Amazon has entered India's quick-commerce market through Amazon Now, leveraging its strong logistics network, AI-driven supply chain, and Prime customer base. The company aims to deliver groceries and daily essentials rapidly while maintaining operational efficiency and customer trust.

6.2 Key Areas of Competition

The major players compete across several dimensions:

- Delivery speed (10–20 minutes)
- Product assortment and availability
- Pricing and promotional offers
- Customer experience and app usability
- Dark-store network expansion and density
- Technology-driven inventory management
- Delivery partner efficiency
- Brand reputation and customer trust

6.3 Competitive Advantage of Blinkit

Blinkit's competitive strength lies in its integration with Eternal's wider ecosystem (Porter, 1980; Zomato Limited, 2024). The acquisition has enabled the company to leverage Zomato's technology platform, customer database, and operational expertise. Furthermore, Blinkit's sophisticated AI-driven demand forecasting, efficient last-mile logistics, and expanding, increasingly profitable network of dark stores contribute significantly to its market leadership. However, sustaining this advantage requires continuous innovation and operational excellence as competitors continue investing aggressively.

7. SWOT Analysis of Blinkit

The following analysis synthesises the strategic position described above into a standard SWOT framework for classroom discussion.

Dimension	Details
Strengths	Integration with Eternal's technology, customer base and brand; AI-driven demand forecasting; dense, expanding dark-store network (2,243 stores by Q4 FY26); first-mover scale advantage; diversified revenue streams (product sales, delivery fees, advertising, subscriptions).
Weaknesses	Thin contribution margins (around 5.3–5.4 per cent); recent and still-narrow adjusted EBITDA profitability; high fixed costs from warehousing, staffing and technology; complex, hard-to-compare

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	financial reporting following the shift to an inventory-led model; heavy dependence on continued external capital and reinvestment.
Opportunities	Large, fast-growing addressable market (forecast to reach US$6.6–13 billion by the early 2030s); expansion into Tier-2/3 cities; assortment expansion and premiumisation (e.g., "gourmet" store formats); advertising and brand-partnership revenue; cross-selling with Zomato's food-delivery base; rising UPI and smartphone penetration.
Threats	Intense, well-funded competition from Zepto, Swiggy Instamart, BigBasket Now, Flipkart Minutes and Amazon Now; combined competitor dark-store count more than doubling in a year; aggressive discounting eroding industry-wide margins; regulatory and labour-welfare scrutiny; sensitivity to macro shocks such as rainfall deficits and food inflation affecting FMCG volumes.

8. Porter's Five Forces Analysis

Porter's (1980) five-forces framework offers a complementary lens on the intensity and structure of competition in India's quick-commerce industry.

Force	Assessment
Threat of new entrants	Moderate to high. Capital requirements for dark stores and technology are substantial, but well-capitalised diversified players (e.g., Amazon Now, Flipkart Minutes) can enter quickly by redeploying existing logistics and customer assets.
Bargaining power of suppliers	Moderate. Large FMCG manufacturers retain some leverage, but the scale of platforms such as Blinkit and their shift to first-party inventory ownership increases platforms' negotiating power and enables direct sourcing relationships.
Bargaining power of buyers	High. Low switching costs, multiple competing apps, and heavy promotional discounting give urban consumers significant power to shift between platforms based on price and delivery speed.
Threat of substitutes	Moderate. Traditional kirana stores, supermarkets, and slower e-commerce grocery platforms remain viable substitutes.

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	particularly for planned, non-urgent purchases and for price-sensitive consumers.
Competitive rivalry	Very high. Numerous well-funded competitors (Zepto, Swiggy Instamart, BigBasket Now, Flipkart Minutes, Amazon Now) are simultaneously expanding dark-store networks and competing on speed, assortment and price, compressing industry-wide margins.

9. Management Dilemma

By 2026, Blinkit had become one of the fastest-growing businesses within Eternal's portfolio, and its net order value had overtaken that of Zomato's core food-delivery business (Business Standard, 2025). Customer demand continued to increase, order volumes reached record levels, and the company's presence across metropolitan cities expanded rapidly. Despite these achievements — including the company's first positive adjusted EBITDA quarters — senior management remained concerned about the long-term financial sustainability of the business. Maintaining the promise of ultra-fast delivery required substantial and continuing investment in dark stores, inventory, technology infrastructure, and delivery personnel, and investors continued to question whether the company's rapid growth strategy would translate into durable, GAAP-comparable profitability once the effects of the marketplace-to-inventory accounting transition were fully absorbed (Zomato Limited, 2024; Bain & Company, 2024; Quash, 2026).

During the annual strategic review meeting, Eternal's Board of Directors and senior executives debated the future direction of Blinkit. One group believed that the company should continue expanding aggressively, arguing that capturing market share at an early stage would create long-term competitive advantages through economies of scale, stronger supplier relationships, and increased customer loyalty. They emphasised that delaying expansion could allow competitors such as Zepto, Swiggy Instamart, and Flipkart Minutes to strengthen their positions in high-potential markets, particularly as the combined dark-store network of the sector's top players had already grown by nearly 50 per cent in a single year (Apparel Resources, 2026).

Another group of executives advocated a more cautious strategy. They argued that Blinkit should consolidate the recent gains in contribution margin and adjusted EBITDA by focusing on improving unit economics — increasing average order values, reducing delivery costs, optimising inventory, and improving operational efficiency — before committing further capital to new markets. According to this perspective, sustainable, comparable profitability should take precedence over rapid expansion because investors were becoming increasingly concerned about cash burn, reporting complexity, and long-term shareholder value.

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The Chief Executive Officer recognised that both perspectives had merit. On one hand, expanding aggressively could strengthen Blinkit's leadership position in India's growing quick-commerce market. On the other hand, uncontrolled expansion could increase operational costs and delay durable profitability. The CEO therefore requested the senior management team to develop a strategic plan that would enable Blinkit to balance customer satisfaction, operational efficiency, competitive positioning, and financial sustainability.

10. Key Decisions Before Management

The management team must decide:

- Should Blinkit continue expanding aggressively into new cities or strengthen its presence in existing metropolitan markets?
- How can the company improve unit economics without compromising its promise of ultra-fast delivery?
- Should Blinkit reduce customer discounts and promotional offers to improve profitability, even if it risks losing market share?
- What role should Artificial Intelligence, automation, and data analytics play in improving inventory management and delivery efficiency?
- How can Blinkit build a sustainable competitive advantage while responding to increasing competition from Zepto, Swiggy Instamart, BigBasket Now, Flipkart Minutes, and Amazon Now?
- What strategic initiatives should Eternal Limited prioritise over the next five years to ensure that Blinkit achieves both market leadership and long-term profitability?

11. Conclusion

Blinkit's trajectory illustrates a broader pattern in India's digital economy: businesses built on speed and convenience must eventually demonstrate that their unit economics can support sustainable profitability without relying indefinitely on external capital. The company's recent progress — rising net order value, an expanding dark-store network, and its first positive adjusted EBITDA quarters — suggests that disciplined execution can coexist with rapid growth. At the same time, thin contribution margins, an unresolved accounting transition, and intensifying competition mean that Blinkit's long-term success is not guaranteed. For students of strategy and operations, the case offers a timely, data-grounded opportunity to weigh the competing logics of growth and profitability in a capital-intensive, technology-enabled business.

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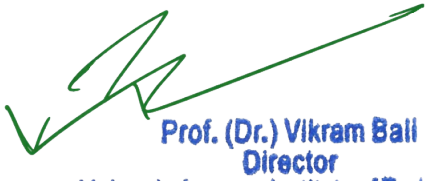
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