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INFLUENCE OF PRODUCT PRICE ON CONSUMER PERCEPTIONS OF THE AUTHENTICITY OF SUSTAINABILITY LABELS

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ABSTRACT

In the German-speaking food market, a significant gap exists between consumer preference for sustainable options and purchasing behavior, primarily due to skepticism about the authenticity of sustainability claims. In a study involving 368 participants from Germany, Austria, and Switzerland, the influence of price on the perceived authenticity of sustainability labels was examined. Participants were surveyed on their explicit attitudes, while their implicit attitudes were assessed using the implicit association test (IAT). Results show that a higher price significantly improves the perception of a product's authenticity. Socioeconomic factors, such as nationality and gender, are significant, with Swiss nationality and female gender showing strong correlations with higher perceived authenticity. This study uniquely examines initial attitudes and reactions to reflect heuristic consumption decisions. Insights can be used to develop pricing and marketing strategies tailored to different markets and target groups, effectively addressing consumer skepticism through targeted communication and pricing.

KEY WORDS

sustainability, labelling, communication

JEL CODES

M30, M31, M37

1 INTRODUCTION

In 2022, organic food generated a turnover of €15.87 billion in Germany, constituting 7% of the food industry's total turnover (Nielsen et al., 2023; BÖLW, 2023). Despite this, there exists an untapped potential for sustainable products due to consumer skepticism arising from untrustworthy labels indicating a potential market value of up to €181 million (Capgemini Research Institute, 2020; Edelman, 2022). This study explores how enhancing con-

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sumer trust can be harnessed, particularly for sustainable items categorized as credence goods (Vega-Zamora et al., 2018). This classification means consumers cannot inspect the product or its properties at purchase or post-purchase, relying on the supplier for verification (Darby and Karni, 1973). In the pursuit of trust establishment, labels play a crucial role in confirming factors that remain unverifiable by consumers, effectively mitigating the information gap (Caswell and Mojduszka, 1996).

To address the challenge of consumer distrust, this study investigates the impact of price on perceived authenticity. Notably, 55.6% of Germans are familiar with the term greenwashing, indicating a heightened sensitivity to deceptive sustainability claims (Vaude et al., 2023). This refers to the declaration of sustainability factors in a product that are not fulfilled to achieve a higher sales price (Schmuck et al., 2018; Arouri et al., 2021). Trust issues are further underscored by the fact that 44% of German consumers lack confidence in product sustainability claims (Capgemini Research Institute, 2020), with skepticism directed towards labels identified as a primary reason (Hughner et al., 2007; Vega-Zamora et al., 2018).

As far as sustainability is concerned, there is a link between sustainability and health as well as between price and value. Consumers consider sustainable products to be healthier and more valuable and therefore expect a higher price (Garcez de Oliveira Padilha et al., 2021; Rivera-Toapanta et al., 2022). On the other hand, 54% of consumers in Germany do not buy sustainable products as they are too expensive (Deloitte, 2023). This situation engenders a conflict of objectives in pricing strategy. On one hand, there is the imperative to establish competitive prices that resonate with cost-conscious consumers. Conversely, there exists the countermanding necessity to avoid pricing structures that might convey a perception of inferiority, subsequently undermining the sustainability of the product. Consequently, the inquiry arises regarding the optimal organization of pricing (Bastounis et al., 2021). Considering this, the ensuing section scrutinizes how consumers implicitly align themselves with lower or higher price points and whether such alignment exerts an influence on their perception of authenticity of sustainability attributes.

Regarding trust in a product proposition, Vega-Zamora et al. (2018) name two major factors:

- Functionality refers to whether the claimed product specification meets the customer's needs.
- Authenticity indicates whether the offer matches the advertised product.

The study introduces the Implicit Association Test (IAT) to measure implicit attitudes towards sustainable consumption, aiming to predict consumer behavior related to trust in sustainability labels while mitigating self-image biases (Greenwald et al., 2003; Jahn, 2018). In the following study, the added value lies in the measurement of implicit association. It is investigated whether the IAT can also be used in this setting to measure implicit attitudes towards sustainable consumption to develop an instrument that can predict consumer behavior regarding trust in sustainability labels.

This study examines how product price influences perceptions of the authenticity of sustainability labels in the German-speaking food market. Given the gap between consumer interest in sustainable products and actual purchasing behavior, it is crucial to address factors such as skepticism toward sustainability claims. The study hypothesizes that price—often perceived as a signal of quality—could play a key role in shaping perceptions of authenticity in terms of sustainability.

In addition to analyzing price as a variable, this research considers socioeconomic factors, such as nationality, education, age, to understand their impact on the relationship between price and authenticity. Another focus lies on the explicit attitudes of consumers toward sustainability, referring to their conscious beliefs and opinions. The objective is to understand how explicit attitudes influence authenticity perceptions in relation to pricing. By examining these dimensions, this study seeks to provide a comprehensive understanding of the factors shaping consumer trust in sustainability claims related to pricing, offering valuable insights

for businesses and policymakers on how sustainability labels can promote more consistent, sustainable purchasing behavior.

The comprehensive analysis that follows delves into the multifaceted dimensions of the subject matter from technological, business, and political perspectives. This approach is adopted to holistically examine the intricate interplay of factors contributing to a nuanced understanding.

From a business perspective, successful marketing strategies for sustainable products must balance communicating their value with justifying their higher costs (Bastounis et al., 2021; Li and Kallas, 2021). While most studies rely on choice experiments to gather explicit consumer opinions (Cook et al., 2023), this research uses reaction tests to assess implicit responses, focusing on whether higher prices deter or reinforce perceptions of sustainability's value. The deliberate exclusion of greenwashing practices emphasizes the study's commitment to genuine sustainability discourse.

From a political perspective, the findings highlight policy levers to promote sustainable consumption. While pricing is largely determined by businesses, political education and subsidies can influence consumer behavior indirectly (Ammann et al., 2023). This research provides insights into subsidizing sustainable products and achieving price parity with conventional options, identifying policies and governance mechanisms critical for fostering widespread adoption of sustainable practices.

2 THEORETICAL FRAMEWORK

The initial stage of this research examines factors influencing trust in sustainability labels, aiming to identify dependencies that, along with price, affect the perception of authenticity. Fig. 1 classifies these influencing factors. Based on a comprehensive literature review, the key factors are outlined.

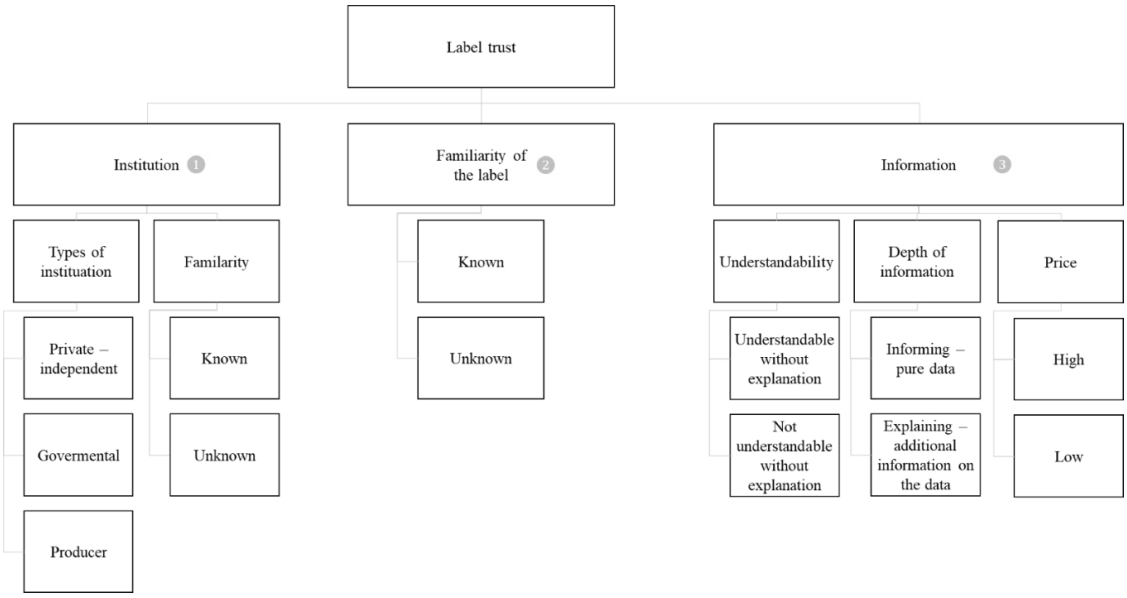

Fig. 1: Trust in credence good sustainability impacting factors. Legend: 1 = Gorton et al. (2021); 2 = Bickart and Ruth (2012); 3 = Schoenheit (2014), Van Loo et al. (2014), Marette et al. (2012), Gutierrez et al. (2020), Garcez de Oliveira Padilha et al. (2021), Rivera-Toapanta et al. (2022), Carmela Aprile and Punzo (2022)

Institution. Consumer trust in a label is significantly influenced by the credibility of the awarding institution. Labels associated with public or reputable institutions are perceived as more reliable and trustworthy, with consumer trust positively correlating with institutional reputation (Gorton et al., 2021).

Familiarity of the label. The extent to which consumers recognize and understand a label strongly impacts trust in its claims. Familiarity, encompassing both recognition and comprehension of the label's meaning, enhances the perceived reliability of the provided attributes (Bickart and Ruth, 2012).

Information. Consumer comprehension of a label is positively correlated with perceptions of sustainability. Detailed explanations and supplementary information accompanying labels enhance understanding, thereby increasing the perceived credibility of the product's attributes (Van Loo et al., 2014; Schoenheit, 2014; Gutierrez et al., 2020). Supplementary details alongside labels enhance consumer understanding of product attributes, increasing overall comprehensibility (Carmela Aprile and Punzo, 2022).

Price. Sustainable products are often associated with health benefits and intrinsic value, leading consumers to anticipate higher prices. This perceived correlation between sustainability, health, and value reinforces expectations of premium pricing (Garcez de Oliveira Padilha et al., 2021; Rivera-Toapanta et al., 2022).

As mentioned, the effectiveness of labelling and information depends on the consumer's interpretation of the sustainability attributes and their trust in the labelling. In this context, a distinction must be made between two forms of trust as shown in Fig. 2. Trust in the offer and authenticity of the offer. Trust in the offer signifies the ability of the offer to fulfil consumer requirements, regardless of its authenticity. This increases the perceived sustainability value, especially among the LOHAS (Lifestyle of Health and Sustainability) target group or consumers who are inclined towards sustainable consumption (Choi and Feinberg, 2018). The authenticity of the sustainability attribute ensures that consumers believe that the product is consistent with its claims. If it is perceived as authentic, the perception of sustainability increases (Vega-Zamora et al., 2018).

At this juncture, the author conducts an empirical analysis to assess the direct correlation between perceived authenticity of sustainability and price level, positing the following hypothesis.

H_1: *There is a positive correlation between the price associated with a label and the perceived authenticity.*

3 METHODOLOGY AND DATA

To test Hypothesis 1, the implicit attitudes of the subjects are assessed using an Implicit Association Test (IAT).

3.1 Design of the IAT

Attitude is defined as the evaluation of a concept, distinguishing between explicit (conscious, system 2) and implicit (automatic, system 1) attitudes (Jahn, 2018). Fig. 2 illustrates the connection between "Label/Information" and "Authenticity of offer" through explicit (system 2) and implicit (system 1) processing.

This study investigates whether increased price influences perceived authenticity, independent of processing or understanding. An Implicit Association Test (IAT) is used to measure implicit attitudes, reducing self-image biases through both surveys and IAT results (Tab. 1). The study examines whether higher-priced labels generate greater trust and authenticity perceptions than lower-priced ones.

Participants pair target concepts with associative attributes, using labels linked to high/low price synonyms and authentic/inauthentic synonyms. Reaction times measure implicit attitudes, with results

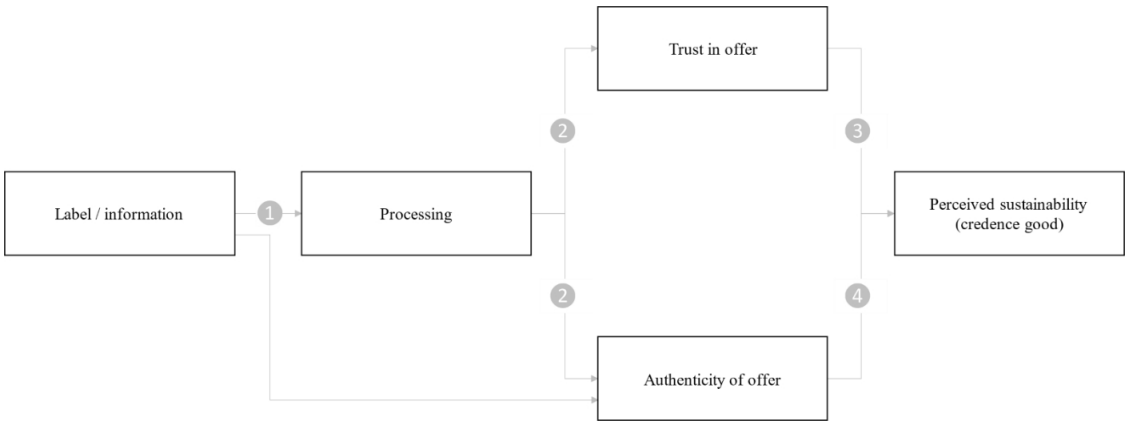

Fig. 2: Dependency of authenticity and price. Legend: 1 = Carmela Aprile and Puzzo (2022); 2 = Van Loo et al. (2014), Gutierrez et al. (2020), Schoenheit (2014), Marette et al. (2012); 3 = Gorton et al. (2021); 4 = Vega-Zamora et al. (2018)

evaluated using Greenwald's improved *d*-score (Greenwald et al., 1998), which adjusts reaction times for accuracy, training effects, and learning. Values from blocks 3, 4, 6, and 7 calculate associations for A-C and B-D versus reverse assignments, ensuring robust analysis of implicit attitudes (Greenwald et al., 2003).

Exclusion Criteria

- Exclude response times below 300 ms if they exceed 10% of responses.
- Exclude answers over 10 seconds.

Standard Deviation

- Calculate for practice blocks 3 and 6, and test blocks 4 and 7.

Incorrect Answers

- Add 600 ms to the average block response time for incorrect answers (excluding standard deviation).

Average Response Time

- Calculate for each test block.

Normalization and Index

- Compute the difference between average response times of blocks 6 and 3, and 7 and 4.
- Normalize by dividing differences by their standard deviations.
- The index value is the average of these two quotients, indicating the strength of implicit association.

Tab. 1: Procedure of the IAT

#	Category	Function	Left	Right	Trials
1	Initial target-concept	Practise	A: Label with a high price	B: Label with a low price	20
2	Associated attribute trust	Practise	C: Synonyms (trust)	D: Synonyms (fraud)	20
3	Initial combined task	Practise	C: Synonyms (trust) A: Label with a high price	D: Synonyms (fraud) B: Label with a low price	20
4	Initial combined task	Test	C: Synonyms (trust) A: Label with a high price	B: Synonyms (fraud) B: Label with a low price	40
5	Reversed target-concept	Practise	B: Label with a low price	A: Label with a high price	20
6	Reversed combined task	Practise	C: Synonyms (trust) B: Label with a low price	D: Synonyms (fraud) A: Label with a high price	20
7	Reversed combined task	Test	C: Synonyms (trust) B: Label with a low price	D: Synonyms (fraud) A: Label with a high price	40

Tab. 2: Associated Attributes used in IAT

#	Authentic/Trustable German	English	Inauthentic/Fraud German	English
1	Vertrauen	Trust	Misstrauen	Mistrust
2	Authentisch	Authentic	Fassade	Facade
3	Kontrolliert	Controlled	Inzenierung	Staging
4	Vertrauenswürdig	Trustworthy	Lüge	Lie
5	Wahrheit	Truthful	Manipulation	Manipulation
6	Transparenz	Transparent	Skandal	Scandal
7	Gewissheit	Certainty	Skeptisch	Sceptical
8	Verifiziert	Verified	Zweifeln	Doubt

Note: The associated attributes are based on synonyms from Duden (2022)

Tab. 3: Initial Target-Concept

#	Content	Name	Label
1	Fairtrade	Regional und fair (En: regional and fair)	
2	Regionality	Bio – aus der Region (En: Organic – from the region)	
3	Environmental protection	Rainforest Aliance	
4	Child labor	Fair for Life	
5	Regionality	Regional	
6	Environmental protection	Dolphin safe	
7	Minimum wage	Ethiquable	
8	Faitrade	Faitrade	

Source: Bundesverband (2022)

The Duden dictionary, adhering to official spelling regulations (Bibliographisches Institut, 2017), was used to identify associative attributes. Words were selected for their comprehensibility and current usage in German, resulting in eight terms as shown in Tab. 2 reflecting authentic/trustworthy and inauthentic/fraudulent attributes.

To minimize influencing factors, this study uses self-explanatory "word labels" easily understood without prior knowledge (Van Loo et al., 2014). The EU organic label, for example, was excluded for lacking direct reference to organic attributes. Participants are challenged to quickly classify information as "high price" or "low price" without interpretation. To avoid biases related to awarding institutions or manufacturers, only standalone labels were used (GIM, 2020; Gorton et al., 2021). Labels with the highest reach and recognition were selected from the Association of Consumers in Germany's database (Bundesverband, 2022). The eight selected labels are listed in Tab. 3. In the Implicit Association Test (IAT), label images were paired with synonyms for valuable/expensive ("high price") and affordable/inexpensive ("low price") as shown in Tab. 18 in the Annex.

3.2 Executing the IAT

The study was created using SoSci (2022) Survey software (version 3.5.00), chosen for its capability to conduct the IAT and set association parameters, allowing accurate time measurement given a sufficient internet con-

nection. SoSci Survey also facilitates direct evaluation of the Greenwald improved *d*-score.

Participants were classified through preliminary questions to rank socioeconomic status and sustainability ambitions (see Tab. 17 in the Annex). The survey link was shared across various groups to ensure a diverse socioeconomic sample. The survey was conducted from December 2023 to January 2024 and from July to August 2024. Distribution included:

- Emden/Leer University of Applied Sciences (Master's program in Consulting)
- Rowing club in Cologne
- Regional Facebook groups in Haren (Ems), Bielefeld, Emden, Stuttgart, and Cologne
- A racing bike club in Vienna
- Regional Facebook groups in Pöls, Salzburg, and Tyrol
- WZU in Zurich (Master's program Economics)
- Regional Facebook groups in Zurich, Bern, and Lucerne

3.3 Sample

In this pilot study, 748 people participated in the IAT, with 368 completing the test fully, resulting in a completion rate of 49.3%. The socioeconomic distribution is shown in Tab. 4, and its representativeness will be analyzed subsequently.

This structure must be compared with the population structure in the target countries, as presented in Tab. 5, to assess the representativeness of the data.

3.3.1 Sample Size

The sample size of 368 respondents in this study is robust and adheres to methodological standards in comparable studies utilizing the Implicit Association Test (IAT) (Pennington et al., 2023). After expanding the sample to 368 participants, results demonstrated consistency, with a minimal adjustment in the *d*-score from 0.24 (SD = 0.5) to 0.21 (SD = 0.55), thus confirming the stability and reliability of the initial findings. This slight variation reflects an increased distribution in age and education.

In correlational IAT research, standard practice recommends sample sizes between 200 and 400 participants to achieve adequate statistical power (typically around 0.80) for detecting medium effect sizes (Cohen's $d \approx 0.5$), while accounting for the moderate test-retest reliability of the IAT, generally averaging 0.50. With 368 participants, this study meets and exceeds these benchmarks, ensuring reliable detection of moderate effects and sufficient statistical robustness (Pennington et al., 2023).

For further comparison, a detailed list of studies using similar or smaller sample sizes is provided in Tab. 19 in the Annex. These include research across healthcare, socio-cognitive psychology, and consumer behavior, where sample sizes within this range have consistently yielded valid and reproducible results. This alignment with established sample size standards supports the validity of our findings and underscores the reliability of the insights into sustainable consumption behaviors across Germany, Austria, and Switzerland.

3.3.2 Sample Distribution

The sample's socioeconomic structure closely aligns with the general populations of Germany, Austria, and Switzerland across gender, age, education, and nationality. Gender distribution includes 52% male and 48% female participants, reflecting national distributions but excluding non-binary individuals, limiting correlations for these groups. The age distribution is concentrated in the 25–34 range, with 93% of participants within the 15–64 demographic, moderately aligning with national averages (64.7–67.5%). However, older adults (65+) are underrepresented (3% vs. 17.7–21.7%), restricting conclusions for this group. Despite this, the focus on younger participants is relevant, as they are key drivers of sustainability trends due to their environmental consciousness, digital literacy, and preference for values-driven brands (Ziesemer et al., 2021; United Nations, 2023; Hong et al., 2024).

Educational attainment is representative, with primary education at 11%, secondary at 51%, and tertiary at 38%, comparable to national averages. Although tertiary education in Switzerland is slightly underrepresented, the overall profile is reflective of the population. Nationality distribution includes 36%

Tab. 4: Summary statistics of sample's socio-demographic characteristics

Characteristics	***N* (abs.)**	***N* (rel.)**
Gender		
Male	192	52%
Female	176	48%
Divers	0	0%
Age group (years)		
15–19	24	7%
20–24	40	10%
25–29	68	18%
30–34	77	21%
35–39	45	12%
40–44	36	10%
45–49	23	6%
50–54	22	6%
55–59	17	5%
60–64	15	4%
65 or older	11	3%
Education		
Partial Skilled Worker Qualification	1	0%
Completed Vocational or Agricultural Apprenticeship	42	11%
Completed Commercial Apprenticeship	40	11%
Vocational School Certificate	43	12%
Technical School Certificate	66	18%
Master Craftsman, Technician, or Equivalent Technical School Certificate	35	10%
University of Applied Sciences Degree	69	19%
University Degree	48	13%
Student	4	1%
In professional apprenticeship	20	5%
Origin		
Germany	131	36%
Austria	128	35%
Switzerland	109	30%

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 5: Socioeconomic structure DACH

Country	**Male (%)**	**Female (%)**	**Age 0–14 (%)**	**Age 15–64 (%)**	**Age 65+ (%)**	**No Education (%)**	**Primary Education (%)**	**Secondary Education (%)**	**Tertiary Education (%)**
Germany	49.3	50.7	13.60	64.70	21.70	0.50	9.00	56.40	34.1
Austria	49.5	50.5	14.10	65.10	20.80	0.40	7.50	55.80	36.3
Switzerland	49.4	50.6	14.80	67.50	17.70	0.30	6.70	49.10	43.9

Source: Bundesamt (2024a, 2024b), Statistics Austria (2024), Bundesamt für Statistik (2023)

Germans, 35% Austrians, and 30% Swiss, offering balanced cross-national comparability despite minor deviations from actual population distributions.

In summary, the sample effectively represents key socioeconomic dimensions but underrepresents older adults, a limitation to consider when interpreting findings, especially if age significantly impacts the variables studied. Insights remain relevant, particularly given the influence of younger consumers on sustainable market dynamics.

4 RESULTS

The results are given in the form of the *d*-score, but these must also be analyzed in the context of socioeconomic factors and explicit attitudes.

4.1 Result

The *d*-score of 0.2110 indicates a moderate implicit bias towards the 'high price' category, with a standard deviation of 0.5575 reflecting variability in reaction times as shown in Tab. 6. These results support H_1, showing a positive correlation between price and perceived authenticity, influenced by socio-economic factors.

Tab. 6: Resulting *d*-score of IAT

Description	Values
Average of improved *d*-score	0.2110
StdDev of improved *d*-score	0.5575
Count of Interviews	369

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

4.2 Correlations

There is a strong positive correlation between DACH nationality and *d*-score ($r = 0.47$, $p < 0.0001$). Trust in sustainable products also shows a strong correlation with *d*-score ($r = 0.53$, $p < 0.0001$). Moderate correlations are observed between *d*-score and gender ($r = 0.17$, $p = 0.0014$), increasing professional qualification ($r = 0.15$, $p = 0.0033$) and with higher sustainability values and behaviors. No significant correlation is found between age and *d*-score ($r = 0.00$, $p = 0.9688$).

A significant positive correlation ($r = 0.47$, $p = 0.0014$) between DACH nationality and *d*-score highlighting a nuanced relationship between nationality and authenticity perceptions. This indicates that Germans have a negative perception of sustainability at higher prices, whereas Austrians and Swiss have a positive perception as shown in Tab. 8.

A correlation coefficientbetween gender and *d*-score ($r = 0.17$, $p = 0.0014$) shows a low positive relationship, indicating statistical significance. Mean *d*-scores for males and females were 0.122 and 0.308, respectively, with standard deviations of 0.580 and 0.515. This indicates variability within genders and suggests a weak but significant link between gender and *d*-score, with females showing a higher sustainability perception with higher prices than males as shown in Tab. 9.

The analysis shows a weak positive correlation ($r = 0.12$, $p = 0.0255$) between the importance placed on sustainability in shopping and the *d*-score. *D*-scores decrease from strong disagreement to strong agreement with the sustainability statement, indicating lower authenticity perceptions at higher prices with greater sustainability emphasis. Standard deviations showing more homogeneous perceptions among those somewhat disagreeing and more diverse perceptions among those agreeing. The distribution shows that over 83% of participants strive for sustainability as shown in Tab. 10.

The analysis shows a moderate positive correlation ($r = 0.37$, $p < 0.001$) between the importance of choosing sustainable products and the *d*-score. *D*-scores decline from strong disagreement (0.839) to strong agreement (-0.142) with the sustainability statement, reflecting lower authenticity perceptions with greater sustainability emphasis. Standard deviations range from 0.002 (disagreement) to 0.555 (agreement), indicating more consistent perceptions among those disagreeing. Tab. 11 highlights a trend towards sustainable shopping

Tab. 7: Correlations of socioeconomic factors and explicit

Correlation of *d*-score to:	***r***	***n***	***t***	***p***
Gender	0.17	368	3.22	0.0014
Age (categories, 5 years)	0.00	368	0.04	0.9688
DACH Nationality	0.47	368	10.06	0.0000
Professional qualification	0.15	368	2.96	0.0033
Importance of sustainability: Sustainability is important to me	0.07	368	1.27	0.2037
Importance of sustainability: I strive for a sustainable lifestyle	0.12	368	2.24	0.0255
Importance of sustainability: I make sure to choose sustainable products when shopping	0.37	368	7.61	0.0000
Value: I expect sustainable products to be more expensive	0.28	368	5.56	0.0000
Value: I would buy more sustainable products if they were cheaper	0.26	368	5.14	0.0000
Value: I consider sustainable products to be trustworthy	0.53	368	12.04	0.0000
Value: I would like sustainable products to be cheaper	0.26	368	5.10	0.0000
Sustainability categories: Social	0.16	368	3.18	0.0016
Sustainability categories: Economic	0.07	368	1.30	0.1945
Sustainability categories: Ecological	0.16	368	3.13	0.0019

Note: r = correlation coefficient, n = sample size, t = number of degrees of freedom, p = p-value – significance.
Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 8: *d*-score after Country of origin

Country of origin	**Germany**	**Austria**	**Switzerland**	**Total**
Average of improved *d*-score	−0.141	0.330	0.494	0.211
StdDev of improved *d*-score	0.323	0.556	0.562	0.558
Count of Interviews	131	128	109	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 9: *d*-score after Gender

Gender	**Male**	**Female**	**Total**
Average of improved *d*-score	0.122	0.308	0.211
StdDev of improved *d*-score	0.580	0.515	0.558
Count of Interviews	192	176	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 10: *d*-score after Importance of sustainability: I strive for a sustainable lifestyle

Importance of sustainability: I strive for a sustainable lifestyle	**Somewhat disagree**	**Neutral**	**Somewhat agree**	**Strongly agree**	**Total**
Average of improved *d*-score	0.839	0.042	−0.175	0.537	0.211
StdDev of improved *d*-score	0.002	0.666	0.256	0.504	0.558
Count of Interviews	27	33	157	151	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 11: *d*-score after Importance of sustainability: I make sure to choose sustainable products when shopping

Importance of sustainability: I make sure to choose sustainable products when shopping	**Strongly disagree**	**Rather disagree**	**Neutral**	**Rather agree**	**Strongly agree**	**Total**
Average of improved *d*-score	0.839	0.492	−0.341	0.465	−0.142	0.211
StdDev of improved *d*-score	0.002	0.532	0.225	0.555	0.261	0.558
Count of Interviews	27	19	35	162	125	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 12: *d*-score after Value: I expect sustainable products to be more expensive

Value: I expect sustainable products to be more expensive	**Neutral**	**Rather agree**	**Strongly agree**	**Total**
Average of improved *d*-score	−0.250	0.368	−0.049	0.211
StdDev of improved *d*-score	0.005	0.469	0.609	0.558
Count of Interviews	8	233	127	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

behavior and its impact on authenticity perceptions.

The analysis reveals a moderate positive correlation ($r = 0.28$, $p < 0.001$) between the expectation that sustainable products will be more expensive and the *d*-score. Those expecting higher prices for sustainable products have slightly more positive authenticity perceptions. The average *d*-score generally increases with agreement on expected higher prices, except for those who strongly agree, where it decreases. Most participants agree with the expectation of higher prices for sustainable products (233 and 127 interviews, respectively), indicating a common perception among participants as shown in Tab. 12.

The analysis shows a moderate positive correlation ($r = 0.26$, $p < 0.001$) between willingness to buy more sustainable products at lower prices and *d*-score. Those open to cheaper sustainable products view their authenticity more positively as prices rise, with *d*-scores peaking for those strongly agreeing. Perception variability is most homogeneous among those rather disagreeing (0.008) and most diverse among those strongly agreeing (0.596). Most participants agree (23) or strongly agree (273) with buying cheaper sustainable products, indicating a common preference. This paradox shows a preference for lower prices contrasts with increased trust in authenticity at higher prices, reflecting consumer uncertainty as shown in Tab. 13.

The analysis reveals a strong positive correlation ($r = 0.53$, $p = 0.00$) between seeing sustainable products as trustworthy and higher *d*-scores, indicating that those who trust in sustainability tend to perceive higher authenticity in products with increased prices. *D*-scores rise with growing trust, peaking for strong believers in sustainability's trustworthiness (highest average *d*-score: 0.696). Variability within groups is noted, with those strongly disagreeing showing the most homogeneity (lowest standard deviation: 0.107) and those somewhat agreeing to show the most diversity (highest standard

Tab. 13: *d*-score after Value: I would buy more sustainable products if they were cheaper

Value: I would buy more sustainable products if they were cheaper	**Rather disagree**	**Neutral**	**Rather agree**	**Strongly agree**	**Total**
Average of improved *d*-score	0.030	−0.247	−0.379	0.326	0.211
StdDev of improved *d*-score	0.008	0.110	0.125	0.596	0.558
Count of Interviews	55	17	23	273	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 14: *d*-score after Value: I consider sustainable products to be trustworthy

Value: I consider sustainable products to be trustworthy	**Rather disagree**	**Neutral**	**Rather agree**	**Strongly agree**	**Total**
Average of improved *d*-score	−0.022	−0.208	−0.326	0.696	0.211
StdDev of improved *d*-score	0.107	0.136	0.437	0.275	0.558
Count of Interviews	68	18	111	171	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

Tab. 15: *d*-score after Value: I would like sustainable products to be cheaper

Value: I would like sustainable products to be cheaper	**Rather disagree**	**Neutral**	**Rather agree**	**Strongly agree**	**Total**
Average of improved *d*-score	−0.012	−0.167	−0.290	0.316	0.211
StdDev of improved *d*-score	0.126	0.027	0.077	0.605	0.558
Count of Interviews	61	11	22	274	368

Source: Questionnaire survey, November 2023 and July 2024, $n = 368$

deviation: 0.437). Most participants agree or strongly agree that sustainable products are trustworthy (111 and 171 interviews, respectively), highlighting a widespread positive perception of sustainability. This suggests that trust in sustainability correlates with more positive authenticity perceptions at higher prices as shown in Tab. 14.

The analysis shows a moderate positive correlation ($r = 0.26$, $p < 0.001$) between the desire for more affordable sustainable products and *d*-scores. Those who wish for cheaper sustainable options tend to perceive them as more authentic. Disagreement with the need for lower prices correlates with less positive authenticity perceptions, improving as agreement increases. Most participants agree or strongly agree with the need for cheaper sustainable products (274 and 22 interviews, respectively), suggesting affordability concerns positively impact authenticity perceptions with higher price as shown in Tab. 15.

5 DISCUSSION

In the following, the results of the study are contextualized within the current state of research, and open and further research questions are defined. Additionally, the study's limitations are discussed, and potential improvements in the study design are highlighted.

5.1 Context in the State of Research

Research shows consumers are willing to pay a premium for sustainable products due to perceived health benefits and intrinsic value (Rivera-Toapanta et al., 2022; Garcez de Oliveira Padilha et al., 2021). Our findings align, indicating participants perceive sustainable products as more expensive, with implicitly perceived authenticity increasing accordingly. This suggests a need for strategies to maintain the perception of sustainability at lower or comparable prices, possibly through additional labeling or information.

German consumers show lower *d*-scores, reflecting limited trust in higher-priced products, likely due to their significant price sensitivity. Discount supermarkets accounted for over 37% of food purchases in 2023, while organic products held only a 6.3% market share in 2022 (GfK, 2024). Austrian consumers demonstrate moderate price sensitivity, with discount stores representing 29% of food purchases and organic food 11% in 2022. Swiss consumers, with higher incomes and living costs, are least price-sensitive, as shown by a 22% share of discount stores and 11.6% organic food market share in 2023. German consumers may trust lower-priced sustainable products more than others,

emphasizing the importance of tailored pricing strategies for each country.

Results indicate that expensive products are perceived as more authentically sustainable, aligning with findings that women and educated individuals are more willing to pay premiums for eco-labeled foods (Bastounis et al., 2021). However, discrepancies between willingness-to-pay (WTP) and trust suggest social and environmental influences, particularly among older and higher-educated individuals, warrant further study.

A moderate correlation ($r = 0.26$, $p < 0.001$) was found between affordability preferences and trust in higher prices, highlighting a paradox: consumers trust expensive sustainable products but prefer affordability. This underscores high price sensitivity, suggesting strategies like taxing unsustainable products or subsidizing sustainable options to maintain perceived authenticity without compromising affordability (Parker et al., 2021; Schütz et al., 2021). Policies ensuring price parity could further motivate less environmentally conscious consumers toward sustainable choices.

5.2 Representativeness

Concerning the selected experimental design, it is imperative to acknowledge that inaccuracies may arise due to the following factors:

Socioeconomic structure. The study cohort reflects reasonable diversity across gender, age, education, and origin. However, the overrepresentation of individuals with higher education levels and specific age groups introduces potential biases, particularly toward perspectives linked to greater educational attainment. Regional variations may also influence viewpoints. These demographic patterns may limit the broader applicability of the findings, and researchers should exercise caution in generalizing results. Future studies with more diverse samples are needed to enhance the robustness of generalizability.

Inaccuracies in the IAT. Furthermore, it is imperative to note at this juncture that inaccuracies may occur in the IAT test. One factor is, that it also depends on the subjects' reaction time, which can result in inaccuracies. In the further course, the figures presented in the IAT can be further investigated to see how the results affect the analysis. The reaction time can also be influenced by the device used and the internet speed. The following results must be considered on this basis.

The findings presented in this study provide insights into the intricate dynamics of consumers' authenticity perceptions within the nexus of sustainability and pricing. Utilizing the Implicit Association Test (IAT) to gauge participants' implicit biases, the results reveal a moderate implicit association, indicating a discernible preference for concepts aligned with the 'high price' category.

5.3 Limitation

While this study provides valuable insights into sustainable consumption behaviors, its validity cannot be fully guaranteed due to several limitations. The sample size of 368 respondents aligns with IAT research recommendations (200–400 participants for correlational studies) and exceeds the minimum required to detect medium effect sizes (Cohen's $d \approx 0.5$). However, it remains modest for representing Germany, Austria, and Switzerland, potentially limiting generalizability across diverse demographics. Older adults (65+), comprising only 3% of the sample, are significantly underrepresented, and the exclusion of non-binary individuals further narrows gender-based insights. Differences in tertiary education levels, particularly in Switzerland, may also skew cross-country comparisons. The use of the IAT, while effective for measuring implicit attitudes, is constrained by moderate test-retest reliability (~ 0.50), which could affect individual-level results. Similar limitations are noted in studies such as Pennington et al. (2023), where comparable sample sizes produced reliable but context-sensitive findings. Furthermore, the study's focus on the German-speaking food market restricts the applicability of results to broader contexts. Despite these limitations, the methodology aligns with best practices in the field, and the study contributes meaningful insights when interpreted within its methodological constraints.

6 CONCLUSIONS

This study aimed to determine whether an increased price directly influences the perceived authenticity of sustainable products, regardless of processing and understanding. The results confirm Hypothesis 1, showing a positive correlation between the price of a sustainable product and its perceived authenticity, as measured by the Implicit Association Test (IAT). An average *d*-score of 0.24 indicates a moderate level of implicit association, with considerable variability (standard deviation of 0.506) in participants' responses.

Higher prices enhance the perceived authenticity of sustainable products, which is significant for marketers and producers aiming to improve consumer perceptions of authenticity. Analysis across DACH nationalities, sex, and attitudes highlights the importance of understanding regional and demographic differences in price sensitivity and authenticity perception.

Future research should explore the price point at which perceived authenticity declines and leads to a loss of trust, differences in price perception and authenticity among DACH countries, and gender-specific differences in willingness to pay for sustainable products. Additionally, examining the impact of educational attainment on perceptions and purchasing behavior, conducting longitudinal studies, and assessing the effectiveness of different marketing strategies are recommended.

The study also emphasizes the need to address the paradox where trust in sustainable products increases with price, yet consumers desire lower prices. Investigating optimal pricing for various consumer groups is essential. Technological, business, and political perspectives highlight the importance of aligning product value with consumer-perceived worth and implementing nuanced, context-specific approaches.

Despite certain limitations, such as the overrepresentation of higher-educated individuals, this study provides valuable insights into the complex interplay between price, authenticity, and consumer behavior. These findings pave the way for future research and strategic considerations for businesses navigating consumer attitudes towards sustainability and authenticity. The identified paradoxes need to be further defined through dedicated research, and the pricing factor quantified, to develop economically viable strategies.

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8 ANNEX

Tab. 16: IAT Attributes

#	A: Label with low price	B: Label with high price	#	A: Label with low price	B: Label with high price
1	günstig	hochpreisig	5	kosteneffizient	wertvoll
2	preiswert	kostspielig	6	rabattiert	kostbar
3	einfach	kostenintensiv	7	kosteneffizient	aufwändig
4	erschwinglich	wertig	8	preisbewusst	preisintensiv

Tab. 17: Preliminary Questions

#	**Assessment statement (English)**	**Response Options (English)**	**Intent**
1	Sex	Male, female, divers	Socio-demographic classification and inferences
2	Age	15–19, 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65 or older	Socio-demographic classification and inferences
3	Nationality	Germany, Austria, Switzerland	Socio-demographic classification and inferences
4	Professional qualification	No professional training qualification Completed industrial or agricultural apprenticeship Completed commercial apprenticeship Vocational school diploma Master craftsman's, technicians, or equivalent technical college qualification Degree from a university of applied sciences University degree	Socio-demographic classification and inferences
5	Importance of sustainability: Sustainability is important to me	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance sustainability
6	Importance sustainability: I strive for a sustainable lifestyle	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance sustainability
7	Importance of sustainability: I make sure to choose sustainable products when shopping	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance sustainability
8	Value: I expect sustainable products to be more expensive	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance sustainability
9	Value: I would buy more sustainable products if they were cheaper	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance sustainability
10	Value: I consider sustainable products to be trustworthy	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception dealing with sustainability
11	Value: I would like sustainable products to be cheaper	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception dealing with sustainability
12	Sustainability categories: Social	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance social sustainability
13	Sustainability categories: Economic	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance economic sustainability
14	Sustainability categories: Ecological	Strongly disagree, disagree, neither disagree nor agree, agree, strongly agree	Explicit perception importance ecologic sustainability

Note: In the survey, response options were provided in German. At this point, for better understanding, they are presented in English for demonstration purposes.

Tab. 18: IAT-View in SoSci

Tab. 19: List of correlational IAT research

Year	Field	Sample Size	Content	Paper Name	Source
2022	Socio-Cognitive Psychology	235 participants	Examined how the race-IAT correlates with other implicit socio-cognitive measures like empathy, emotion recognition, and perspective-taking.	Implicit Bias and Socio-Cognitive Measures of Empathy	Frontiers in Psychology, 2022
2022	Youth Well-Being	Children and adolescents	Developed the WB-IAT-Y to assess implicit well-being among youth, revealing new potential for mental health assessments.	Youth Well-Being through Implicit Measures: WB-IAT-Y	Springer, 2022
2021	Healthcare	Various healthcare providers	Used the IAT to examine racial and weight-based biases in healthcare providers and their impact on patient care.	Implicit Bias in Healthcare: A Global Review	BMC Public Health, 2021
2021	Political Science	Undisclosed	Studied the impact of implicit biases on political preferences and decisions in politically polarized environments.	Political Preferences and Implicit Biases in Polarized Environments	MIT Press, 2021
2021	Gender Studies	300 participants	Explored implicit gender biases, particularly the backlash against women who exhibit stereotypically male traits.	Implicit Gender Bias and Backlash toward Agentic Women	Journal of Social Issues, 2021
2021	Political Psychology	400 participants	Measured implicit political biases and their influence on decision-making in politically polarized environments.	Affect, Not Ideology: Implicit Bias in Political Polarization	Public Opinion Quarterly, 2020
2020	Healthcare	1,150 physicians	Examined implicit racial biases among healthcare professionals and their impact on patient care.	Physicians Implicit and Explicit Attitudes about Race by MD Race, Ethnicity, and Gender	Journal of Health Care for the Poor and Underserved, 2021
2020	Consumer Behavior	Undisclosed (brand studies)	Used the IAT to assess implicit attitudes towards brands, showing a correlation with consumer behavior.	Predictive Validity of the Implicit Association Test in Studies of Brands	Journal of Consumer Psychology, 2020
2020	Education	200–300 students	Investigated implicit biases in educational settings, particularly regarding stereotype threats in STEM fields.	Stereotype Threat and Implicit Bias in STEM Education	Personality and Social Psychology Bulletin, 2020

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GAM MODELLING OF DAILY NUMBER OF TRAFFIC ACCIDENTS AS A FUNCTION OF METEOROLOGICAL VARIABLES IN THE CZECH REPUBLIC

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ABSTRACT

Meteorological conditions exert a considerable influence on traffic patterns. This paper examines the influence of meteorological variables on the daily number of traffic accidents requiring fire brigade intervention. The influence of meteorological variables, including maximum temperature, wind speed, air pressure, precipitation, snow cover and sunshine, was examined. A Generalized Additive Model for variables with a Poisson distribution was employed for modelling purposes, as this allows for the representation of non-linear dependencies. The analysis demonstrates that the lowest incidence of accidents occurs at temperatures approximating 10 °C. The average daily number of accidents increases with windy weather, the minimum number of accidents occurs at zero precipitation, and the accident rate rises with higher levels of sunshine. In the Czech Republic, the period of greatest risk in terms of road traffic accidents is the summer and winter months. The findings may have several practical applications, for example, in the improvement of meteorological warnings in traffic.

KEY WORDS

traffic accidents, integrated rescue system, weather, Poisson distribution, generalised additive model

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1 INTRODUCTION

The utilisation of personal vehicles for the purpose of transportation is an integral aspect of contemporary society. On the one hand, contemporary automobiles are equipped with an array of sophisticated technology and are manufactured with a heightened emphasis on safety compared to previous eras. Conversely, however, automobiles are becoming increasingly affordable, traffic congestion is intensifying, and drivers are often encouraged to utilise the full potential of their vehicles, which can have adverse consequences and potentially contribute to accidents.

KOLÍSKOVÁ, Petra, and NEUBAUER, Jiří. 2025. GAM Modelling of Daily Number of Traffic Accidents as a Function of Meteorological Variables in the Czech Republic. *European Journal of Business Science and Technology,* 11 (1): 23–38. ISSN 2694-7161, DOI 10.11118/ejobsat.2024.014.

The occurrence of traffic accidents can be attributed to a multitude of factors. Police records indicate that such causes include driver inattention, driving under the influence of addictive substances, and failure to comply with regulations. It appears that the influence of human personality can be negated by operating a vehicle with the assistance of artificial intelligence, as autonomous vehicles represent the future of transportation. However, it should be noted that there are also numerous external factors that can influence the vehicle, some of which are challenging to anticipate, while others can be predicted based on external conditions, such as the impact of weather. Even autonomous vehicles are susceptible to adverse weather conditions and require various sensors to monitor external factors such as temperature, pressure, and humidity. Consequently, there is a potential for unexpected hazards on the road.

The relationship between meteorological parameters and traffic is dependent on the specific characteristics of the local climate and the particularities of regional traffic patterns. The more densely populated regions of the country are distinguished by a more extensive and frequent transportation infrastructure, including long-distance highways. Conversely, mountainous border regions, which are sparsely populated, are also highly attractive to tourists during peak tourist seasons. Furthermore, traffic volume is indicative of the prevailing meteorological conditions. It is generally accepted that higher temperatures encourage people to engage in outdoor activities. However, research indicates that temperatures above 25–30 °C may have a deterring effect (Thorsson et al., 2004; Aultman-Hall et al., 2009). In the context of low temperatures, a reduction in vehicle traffic is observed. However, commercial traffic remains operational. Wind speeds may also present a challenge, particularly in regions with elevated altitudes or along stretches of highways where forestland gives way to open countryside. Extreme weather conditions represent a significant challenge to the uninterrupted flow of traffic, although such occurrences are not a common feature of the Czech Republic. In Brázdil et al. (2021), an analysis of traffic accidents in the Czech Republic is conducted, examining the impact of various meteorological conditions, including windstorms, convective storms, rain, snow, ice, frost, heat, fog and floods. The greatest influence was found to be that of frost (31%), followed by that of ice, rain and snow. High wind speeds present a significant hazard, particularly for trucks, and also for the collision of any vehicle with a flying object (Becker et al., 2022a). The transportation of goods and passengers over longer distances is frequently constrained by precipitation, particularly in the form of rain and snow (Roh, 2020). The occurrence of severe weather in conjunction with drivers' risky driving behaviour frequently results in an elevated incidence of traffic accidents (Brázdil et al., 2022). In urban areas, precipitation has been observed to increase vehicular traffic, which does not necessarily imply an elevated risk of accidents. A 21-year observation of daily traffic accidents in Athens (Yannis and Karlaftis, 2010) revealed that precipitation is associated with a reduction in accidents. This phenomenon can be attributed, at least in part, to drivers demonstrating heightened levels of attention and adherence to safety regulations. In general, the most recent findings indicate a declining trend in the impact of weather on fatal road accidents in the country (Brázdil et al., 2023).

The objective is to provide a quantitative description of the manner in which meteorological parameters can enhance the predictive capacity of models designed to anticipate traffic accidents. Such applications can be found in areas where accurate estimation of traffic flow is of importance, for example, in road traffic accident models, where traffic flow represents the dominant factor in the assessment of risk, and in the field of traffic management, as well as in the planning of routes for navigation systems (Becker, 2022b). The findings may have implications for real-time traffic management and the implementation of crash warning systems. Furthermore, based on these findings, weather-dependent driving restrictions could be issued with the aim of enhancing road safety (Becker et al., 2022a).

2 THEORETICAL BACKGROUND

The relationship between the number of traffic accidents and meteorological conditions and other explanatory variables can be examined through the application of diverse investigative techniques. The GAM (Generalized Additive Model) method is frequently contrasted with machine learning-based methods (Anderson et al., 2015). Both methods have been employed to describe non-linear relationships between variables in the tsunami generation area, and both have yielded comprehensive models. Despite achieving relatively low mean errors, the machine learning-based methods did not demonstrate a superior ability to describe the risk event model in comparison to GAM. However, the interpretation of smoothing splines may present a potential challenge with GAM. Despite the fact that machine learning methods did not yield optimal predictions (Cerna et al., 2020; Guyeux et al., 2020), they demonstrated superior performance in accommodating unanticipated surges in rescue operations due to difficult-to-forecast natural disasters in comparison to classical models. The effectiveness of GAMs has been demonstrated in the context of lightning-induced forest fires (Rodríguez-Pérez et al., 2020). The application of GAM models to traffic accident data is a common occurrence (Li et al., 2011; Zhang et al., 2012). When compared to GLM models, GAM displays greater flexibility in describing the effect of changes in independent variables and produces superior results. The relationship between hourly vehicle departures and weather conditions has been investigated by Lepage and Morency (2020), who employed GAM and ARIMA to model this variable. In comparing the models, it was found that ARIMA performed better in short-term forecasts, while GAM proved to be more suitable for long-term forecasts, where ARIMA exhibited a significant mean error. In light of the aforementioned literature and further study, it can be posited that GAM is an appropriate method for describing a sparse phenomenon such as the daily number of traffic accidents involving firefighter call-outs and its dependence on weather.

In the literature, a number of significant probability distributions for traffic accident data are identified. The impact of meteorological data, including precipitation, temperature, cloud cover, and wind speed, on the number of vehicles passing per hour was investigated by Becker et al. (2022b). The probability distribution was analysed as a Poisson distribution. The Poisson, Negative Binomial (NB), Zero Inflated Poisson (ZIP), and Zero Inflated Negative Binomial (ZINB) distributions are frequently employed for the description of traffic accidents (Lord et al., 2005). In Pop (2018), the Poisson and quasi-Poisson GLM model was employed for the analysis of fatal traffic accidents. It appears that overdispersion has a significant impact on the data distribution. In Basu and Saha (2017), it was demonstrated that a model based on a negative binomial distribution yielded superior results for real data exhibiting overdispersion in comparison to Poisson regression.

The objective of this paper is to investigate the influence of meteorological variables on the daily number of accidents. It is assumed that the variable follows a Poisson distribution, and a GAM approach is used for modelling. The quality of the prediction result is contingent upon the character of the data and the modelling method employed. The temporal and spatial relationships between traffic and meteorological data are not exact. It is challenging to establish such a link, as the meteorological measuring station is frequently situated at a distance from the location of the traffic accident. This is particularly evident in the case of precipitation, which varies significantly from place to place (Thorsson et al., 2004). Other potential limitations include the assumption that meteorological variables are equally significant across all regions, the use of data with outliers, and the overparameterisation of the model due to the smoothing.

3 METHODOLOGY AND DATA

3.1 Traffic Accident Data

In accordance with Czech legislation, a traffic accident is defined as an incident occurring on a road that endangers or threatens the life or health of individuals or causes damage to property, and which is subject to notification.

In the event of a traffic accident, the integrated rescue system is typically mobilised, with the fire brigade assuming a prominent role. In the event of vehicles obstructing traffic or liquids leaking, firefighters are equipped with the necessary apparatus to resolve the situation or assist an injured individual in extricating themselves from the wreckage.

The data on traffic accidents has been sourced from the database of the Czech Republic's Fire Rescue Service. It comprises information on accidents, primarily concerning the time and location of the incident. A concise overview of incidents involving firefighter call-outs in the 2012–2021 period is presented for each region in the form of boxplots in Fig. 1. The Czech Republic is comprised of 14 regions. The regions in question are Kralovehradecky (HKK), Jihocesky (JHC), Jihomoravsky (JHM), Karlovarsky (KVK), Liberecky (LBK), Moravskoslezsky (MSK), Olomoucky (OLK), Pardubicky (PAK), Hlavni mesto Praha (PHA), Plzensky (PLK), Stredocesky (STC), Ustecky (ULK), Vysocina (VYS), Zlinsky (ZLK).

From 1 January 2012 to 31 December 2021, a total of 198,773 traffic accidents occurred in the Czech Republic, which were attended to by fire rescue service units. The accident data were initially subjected to a series of adjustments. For instance, coordinates that were deemed to be meaningless were removed. Additionally, the redistribution of territory within municipalities due to administrative changes in the Czech Republic over the 10-year period for which the measurements were taken was taken into account. The dataset revealed 1,730 instances of exceptionally high daily accident counts across various regions. In the initial modelling stage, the outlier cases were included to the model of the average daily accident count. It is plausible that these outliers may represent the true data, rather than being the result of measurement error. Furthermore, they align with the inherent characteristics of the data.

The data were arranged in chronological order, with each day from 1 January 2012 to 31 December 2021 assigned the daily number of accidents and the categorical variables, including day of the week, month, region of the country, public holidays and state of emergency during a pandemic caused by the SARS-CoV-2 virus.

The data set was expanded with the inclusion of information pertaining to whether the day in question was a public holiday or a state of emergency. The following dates are observed as public holidays in the Czech Republic: 1 January (Day of the Independent Czech Republic), Good Friday and Easter Monday, 1 May (Labour Day), 8 May (Victory Day), 5 July (Cyril and Methodius Day), 6 July (Burnt Day of Master Jan Hus), 28 September (Day of Czech Statehood), 28 October (Day of the Establishment of Czechoslovakia), 17 November (Day of the Fight for Freedom and Democracy), 24–26 December (Christmas Day and the 1st and 2nd Christmas Holidays). The following dates were marked by the declaration of a state of emergency in response to the ongoing pandemic: The period between 12 March 2020 and 17 May 2020, between 5 October 2020 and 11 April 2021, and between 26 November 2021 and 25 December 2021 was characterised by the declaration of a state of emergency.

3.2 Meteorological Data

Furthermore, meteorological variables were incorporated into the data set, including maximum daily temperature, average daily wind speed, average daily air pressure, total daily precipitation, total daily snow height, and total daily sunshine.

The meteorological data is derived from a selection of weather stations located within each region. The Czech Meteorological Office

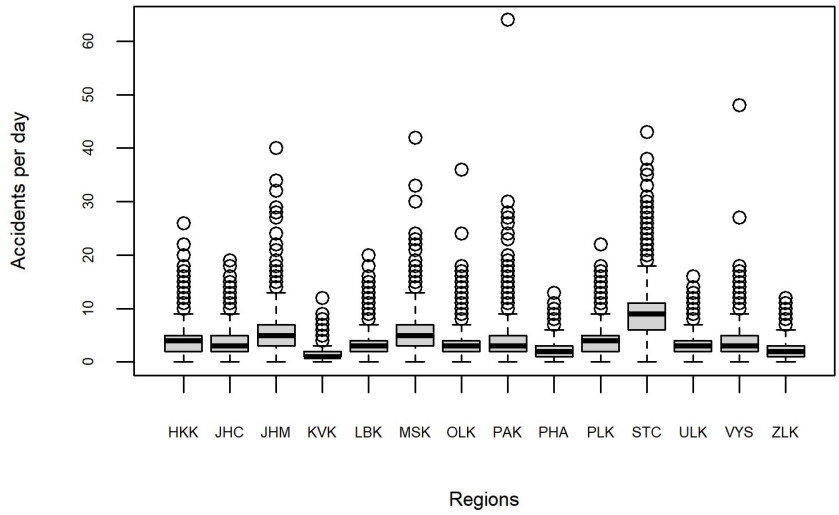

Fig. 1: Boxplots showing median, minimum, maximum and outliers of the daily number of accidents with the deployment of the Fire Rescue Service in the regions of the Czech Republic

(CHMI) oversees the monitoring of climatic and meteorological phenomena in the Czech Republic through a network of various types of stations. The most significant of these are those with a professional meteorologist and an automated measuring system. The meteorological parameters on which the dependence of the explained variable was studied in this paper are as follows:

- *temperature.max* – The maximum daily air temperature in °C – is recorded at the hourly interval between 9 p.m. on the previous day and 9 p.m. on the current day.
- *wind.speed* – The average daily wind speed in m/s – is determined by calculating the mean of the measurements taken at 7 a.m., 2 p.m., and 9 p.m. hours local mean solar time.
- *air.pressure* – The average daily air pressure in hPa – is calculated as the mean of the pressures observed at 7 a.m., 2 p.m., and 9 p.m. local mean solar time.
- *precipitation* – The daily rainfall in mm – is measured at 7 a.m. for the previous 24 hours and recorded as of the previous day.
- *snow.height* – The total height of the snow cover in cm – measured at 7 a.m.
- *sunshine* – The daily total sunshine in hours – represents the time interval in whole hours between sunrise and sunset when the sun was not obscured by clouds or other obstructions, i.e., the intensity of the flow of direct solar radiation greater than 120 W/m^2.

The Czech Meteorological Office measured a number of variables, and those that contribute to the predictive ability of the model were selected. It was not possible to include all variables due to the resulting multicollinearity. The statistical characteristics of the meteorological variables during the period of interest are presented in Tab. 1, and the data are presented graphically in Fig. 2.

3.3 Methods

The linear regression model (LRM) is a well-established technique for expressing the explained variable Y_i as a linear combination of the independent variables X_{ij}, where $i = 1, \ldots, n$, $j = 1, \ldots, k$, and the corresponding parameters. In this context, n represents the number of observations and k denotes the number of parameters. The regressors may be either continuous or categorical. In the event that the explanatory variable is discrete, a Poisson regression model may be employed. This falls within the GLM family, with a logarithmic function serving as the link function.

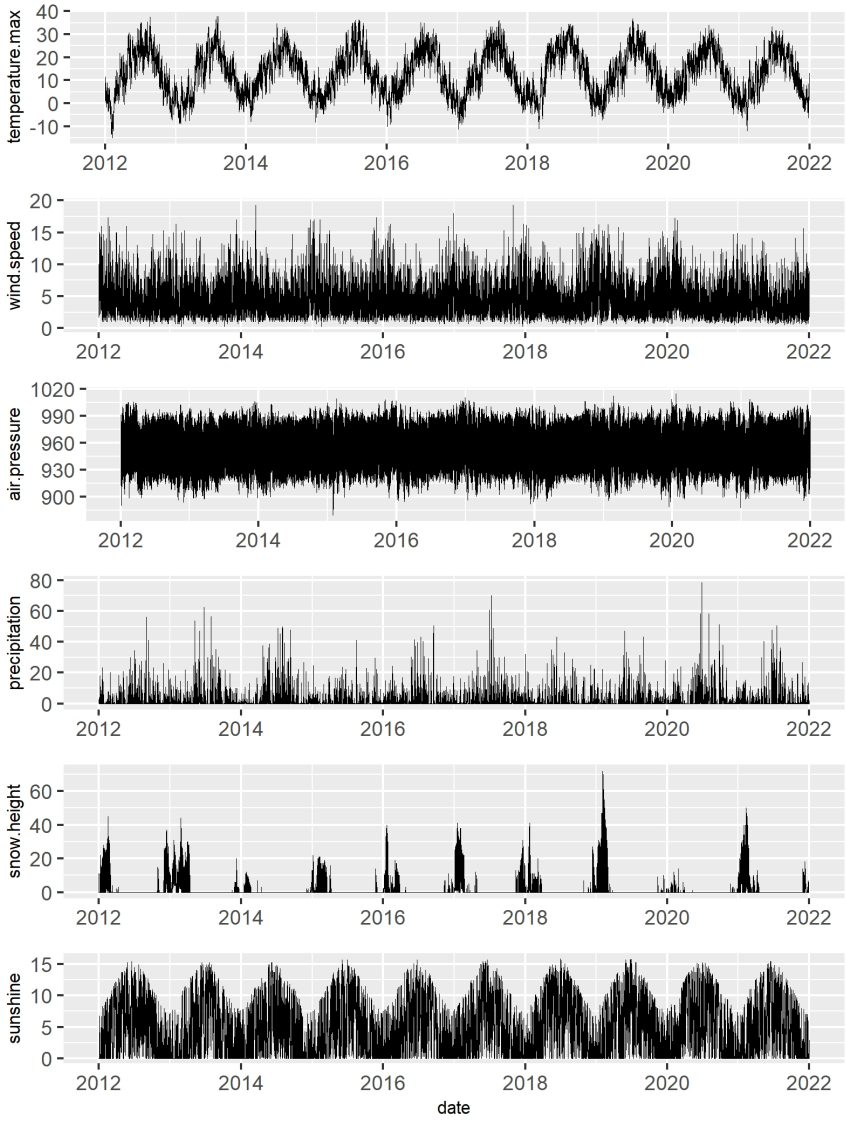

Fig. 2: Graphs of meteorological variables used for the period 2012–2021

Tab. 1: Statistical characteristics of meteorological variables for the period 2012–2021

	temperature.max	**wind.speed**	**air.pressure**	**precipitation**	**snow.height**	**sunshine**
Minimum	−14.90	0.300	879.6	0.000	0.000	0.000
1st Quartile	5.60	2.300	947.1	0.000	0.000	0.200
Median	13.40	3.300	966.8	0.000	0.000	3.600
Mean	13.39	3.857	962.3	1.747	1.268	4.697
3rd Quartile	21.00	4.800	981.3	1.300	0.000	8.300
Maximum	37.80	19.300	1015.0	78.700	72.000	15.900
Standard deviation	9.50	2.078	23.5	4.380	4.681	4.476

The generalised additive model (GAM) represents an extension of the generalised linear model (GLM), wherein the linear terms are substituted with non-parametric smooth functions (Anderson et al., 2015). The fundamental tenets of both models remain consistent: the quantity under investigation belongs to the exponential family of distributions, in this case the Poisson distribution, and its mean can be expressed in terms of regressors via a link function.

$$E(y) = \mu$$
$$g(\mu) = b_0 + f(x_1) + f(x_2) + \ldots + f(x_l)$$

The principal distinction is that it incorporates smooth functions $f(x)$ of one or more regressors into the linear model. Smooth functions are typically nonlinear, thereby enabling the modelling of nonlinear relationships between regressors and the explained variable (Clark, 2024). The smooth function f can be written as

$$f(x) = \sum_{j=1}^{J} b_j(x)\beta_j,$$

where $b_j(x)$ is the j-th of some basis functions and β_j are some unknown parameters, which must be estimated (Becker et al., 2022a; Wood, 2017). The number of parameters affects the degree of change in the shape of the resulting dependent variable, or its "wiggliness". A function with a greater number of parameters is better able to capture finer patterns and has a more complex shape. However, when building a model, it is undesirable for the function to be over-fitting and to reproduce noise rather than the principal trend. A smoothing parameter λ is therefore introduced in order to achieve a balance between the degree of wiggliness and the likelihood of the model, which characterises its ability to describe the data accurately:

$$\text{Fit} = \text{Likelihood} - \lambda \cdot \text{Wiggliness}$$

Thus, GAMs are generalised linear models that are formed by the sum of smooth functions of variables instead of a linear combination of variables. The advantage of GAM over GLM is that they permit the description of nonlinear relationships between variables and the generation of accurate predictions. Like GLM, GAM models are capable of statistical inference and the explanation of the underlying structure of the models, as well as the justification of their predictions. Nevertheless, the process of smoothing variables can result in an increased number of degrees of freedom in the model, necessitating the use of more extensive data for GAM modelling. The use of a large number of parameters to generate spline functions in GAM models can result in estimated coefficients that are challenging to interpret (Li et al., 2011). The results of the GLM and GAM models are comparable when the regressors are genuinely independent and the variable being explained is a linear variable. In this context, GAM does not offer a notable advantage over GLM; instead, it can lead to overfitting of the data (Li et al., 2011).

The proportion (or percentage) of explained deviance serves as a measure of model quality. For both GAM and GLM models, the proportion of explained deviance can be determined using the expression

$$1 - \frac{D}{D_{\text{null}}},$$

where the deviance D_{null} corresponds to the model containing only the intercept (worst fit) and the residual deviation D is for the model containing the independent variables. An higher value of D indicates a greater discrepancy between the estimated and observed values, thereby signifying that the model is less capable of accurately representing the observed dependence. The proportion of explained deviance is an indicator of the accuracy of the model, with values ranging from 0 to 1. A value approaching 1 indicates a superior model that more closely aligns with the actual data. The statistical software typically expresses this in percentage terms.

In the event that a variable is modelled as a function of multiple variables, the graphical output of the GAM is then constituted by a set of graphs, each representing the partial contribution of a given variable to the overall prediction. The modelled smooth curve for a specific variable represents the predicted mean value of the explained variable, assuming that

the other dependent variables reach their mean. It is accompanied by a 95% confidence interval.

The data were initially subjected to a series of tests to ascertain their suitability for analysis. These tests included the Cramer-von Mises and Anderson-Darling goodness-of-fit tests, which indicated that the data exhibited the best fit with a Poisson distribution. Prior to investigating the impact of meteorological variables on traffic accidents, the potential for multicollinearity among the meteorological regressors was evaluated. This analysis revealed that there was no evidence of collinearity between the selected variables. The calculations were conducted using the R statistical software, version 4.3.1.

4 RESULTS

The initial model employed for the analysis of the dependence of daily accident rates on meteorological variables was a GLM model for Poisson distribution data with a logarithmic link function. All variables were found to be statistically significant, with a p-value of less than 0.01. In this case, the percentage of explained deviance was 34.6%. A negative binomial model is frequently employed for risk event count data (Basu and Saha, 2017; Pop, 2018), thus a GLM model was also conducted to assess the assumption of a negative binomial distribution of the data for comparison. However, this model did not yield any improvement, resulting in a lower percentage of explained variance, namely 33.3%.

The data demonstrate a clear non-linear relationship between meteorological variables and the number of traffic accidents resulting in firefighter deployments. In such cases, the GAM model is an advantageous statistical tool for analysis. The GAM model was estimated for the case of the same variables as the GLM model. Initially, the model was estimated without the use of splines, which resulted in a model that was almost indistinguishable from the GLM, as anticipated. Subsequently, the meteorological variables were smoothed, as illustrated in Tab. 2. The variables region, month, day, holiday and Covid emergency are categorical variables and are represented as parametric coefficients in the model. A treatment contrast (dummy coding) was employed, with the variables region (HKK), month (January), and day (Monday) serving as the reference category. The results of the model demonstrated that all variables were statistically significant, with the exception of month2 February and day Thursday, which exhibited a daily number of accidents that was nearly identical to the reference value. The table illustrates which regions, days and months exhibit a lower or higher number of accidents per day in comparison to the reference variables. The variables representing holidays and the state of the pandemic have a negative coefficient, indicating that they serve to reduce the number of accidents. The GAM model with a Poisson distribution and outliers included exhibited an explained deviance of 36.1%. The percentage of explained deviance for the GAM model assuming a negative binomial distribution is once again lower, at 34.8%.

The output of the GAM model is also a table of the smoothed functions, which are visualised by a series of graphs. The value edf represents the effective degrees of freedom and characterises the degree of wiggliness of the curve. A value of edf 1 represents a straight line, edf 2 a parabola, and so on. The remaining columns pertain to the results of the significance testing, which indicate that all variables are statistically significant. The plots for the meteorological parameters in Fig. 3 show the smoothed terms plots expressing the contribution of a given variable to the value of the modelled variable – daily number of accidents. The horizontal axis depicts the observed values of the variable, while the vertical axis illustrates the partial effect of the smoothed variable at the estimated number of degrees of freedom relative to the overall mean of the explained variable. The 95% confidence interval is indicated in grey. The wider confidence interval is attributable to the paucity of accident data for these values of the independent variable.

Tab. 2: R output for GAM with Poisson distribution, model for complete data and data without outliers

	Complete data				Without outliers			
Parametric coefficients	**Estim.**	**Std. error**	***p*-value**		**Estim.**	**Std. error**	***p*-value**	
(Intercept)	1.363	0.015	< 0.001	***	1.297	0.016	< 0.001	***
regionJHC	−0.136	0.014	< 0.001	***	−0.087	0.014	< 0.001	***
regionJHM	0.353	0.014	< 0.001	***	0.337	0.014	< 0.001	***
regionKVK	−1.087	0.026	< 0.001	***	−1.097	0.029	< 0.001	***
regionLBK	−0.262	0.013	< 0.001	***	−0.289	0.013	< 0.001	***
regionMSK	0.301	0.014	< 0.001	***	0.301	0.014	< 0.001	***
regionOLK	−0.151	0.015	< 0.001	***	−0.206	0.015	< 0.001	***
regionPAK	−0.160	0.014	< 0.001	***	−0.119	0.015	< 0.001	***
regionPHA	−0.454	0.014	< 0.001	***	−0.474	0.014	< 0.001	***
regionPLK	−0.215	0.024	< 0.001	***	−0.041	0.026	0.112	
regionSTC	0.853	0.010	< 0.001	***	0.845	0.011	< 0.001	***
regionULK	−0.489	0.028	< 0.001	***	−0.284	0.030	< 0.001	***
regionVYS	−0.195	0.014	< 0.001	***	−0.159	0.015	< 0.001	***
regionZLK	−0.492	0.016	< 0.001	***	−0.516	0.016	< 0.001	***
month2	−0.020	0.012	0.094	.	−0.046	0.013	< 0.001	***
month3	−0.081	0.013	< 0.001	***	−0.093	0.014	< 0.001	***
month4	−0.028	0.014	0.050	*	−0.042	0.015	0.006	**
month5	0.049	0.015	0.001	**	0.032	0.016	< 0.001	*
month6	0.197	0.016	< 0.001	***	0.144	0.017	< 0.001	***
month7	0.140	0.017	< 0.001	***	0.096	0.018	< 0.001	***
month8	0.187	0.017	< 0.001	***	0.118	0.017	< 0.001	***
month9	0.246	0.015	< 0.001	***	0.180	0.016	< 0.001	***
month10	0.252	0.014	< 0.001	***	0.207	0.015	< 0.001	***
month11	0.152	0.012	< 0.001	***	0.136	0.013	< 0.001	***
month12	0.196	0.011	< 0.001	***	0.175	0.012	< 0.001	***
dayTuesday	−0.062	0.008	< 0.001	***	−0.060	0.009	< 0.001	***
dayWednesday	−0.044	0.008	< 0.001	***	−0.039	0.009	< 0.001	***
dayThursday	−0.020	0.008	0.015	*	−0.024	0.009	0.006	**
dayFriday	0.117	0.008	< 0.001	***	0.103	0.008	< 0.001	***
daySaturday	−0.071	0.008	< 0.001	***	−0.066	0.009	< 0.001	***
daySunday	−0.232	0.009	< 0.001	***	−0.208	0.009	< 0.001	***
holiday1	−0.243	0.014	< 0.001	***	−0.231	0.015	< 0.001	***
COVIDemergency1	−0.141	0.009	< 0.001	***	−0.123	0.010	< 0.001	***
Approximate significance of smooth terms:	**Edf**	**Ref. df**	***p*-value**		**Edf**	**Ref. df**	***p*-value**	
s(temperature.max)	8.911	8.997	< 0.001	***	8.439	8.887	< 0.001	***
s(wind.speed)	6.035	6.929	< 0.001	***	2.753	3.483	< 0.001	***
s(air.pressure)	8.307	8.831	< 0.001	***	6.970	7.975	0.011	*
s(precipitation)	8.652	8.956	< 0.001	***	8.324	8.837	< 0.001	***
s(snow.height)	8.325	8.780	< 0.001	***	3.929	4.774	< 0.001	***
s(sunshine)	5.251	6.332	< 0.001	***	4.216	5.172	< 0.001	***
	$R^2_{\text{adj}} = 0.379$				$R^2_{\text{adj}} = 0.439$			
	Deviance explained = 36.1%				Deviance explained = 39.3%			
	$n = 51141$				$n = 49408$			

Note: Significant levels: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, . $p < 0.1$

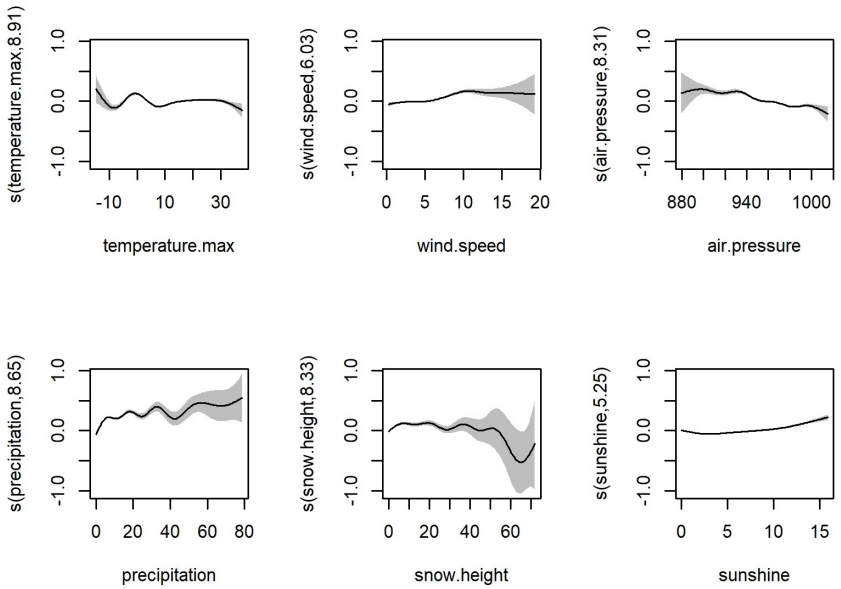

Fig. 3: Graphical output from R for GAM with Poisson distribution (partial effect plots show the component effect of each of the smooth terms in the model)

Fig. 3 illustrates the impact of specific meteorological variables on the incidence of accidents. A negative effect on the number of accidents is observed in temperatures between −5 and 0. The lowest incidence of accidents occurs at temperatures close to −10, which is likely to be a period with minimal traffic. Conversely, temperatures close to 10, which probably correspond to the spring season, are associated with a low number of accidents.

The occurrence of windy weather has been observed to result in an increase in the number of accidents. In our geographical conditions at the ground surface, the average wind speed is typically between 2 and 8 m/s, with rare instances of speeds exceeding 15 m/s (ČHMÚ, 2024).

The observed increase in air pressure is indicative of a corresponding decline in the number of accidents. In general, lower pressure is associated with the presence of precipitation, whereas higher pressure is associated with conditions of dry and sunny weather.

There are notable fluctuations in precipitation and snow depth. The period between 2014 and 2017 was one of the driest on record, with a number of concurrent hydrometeorological events, including the occurrence of weak winters, heat waves and rainless periods (ČHMÚ, 2018). Given the relatively dry conditions that have prevailed in recent years, inclement weather is an uncommon occurrence, and drivers are discouraged or more cautious. A lack of precipitation is associated with a reduction in the incidence of accidents.

The incidence of accidents tends to rise in line with an increase in levels of sunshine. The greatest number of accidents occurs outside of the winter months, specifically in the summer (Brázdil et al., 2021). This is attributable to a greater number of inexperienced drivers, an increase in the number of motorcyclists, cyclists and pedestrians on the roads, and the negative effects of high temperatures on the body, including fatigue and a decline in cognitive function, particularly in older vehicles lacking air conditioning (PČR, 2024).

A diagnosis of deviance residuals was made, as illustrated in Fig. 4. The results of the analyses demonstrated that the residuals did not exhibit the assumed properties. The issue was identified in the potential outliers, and thus a process of identification and exclusion was initiated. An outlier was considered to be any observation that exceeded $x_{0.75}+1.5\cdot\text{IQR}$ ($x_{0.75}$ is the upper quartile, IQR is the interquartile

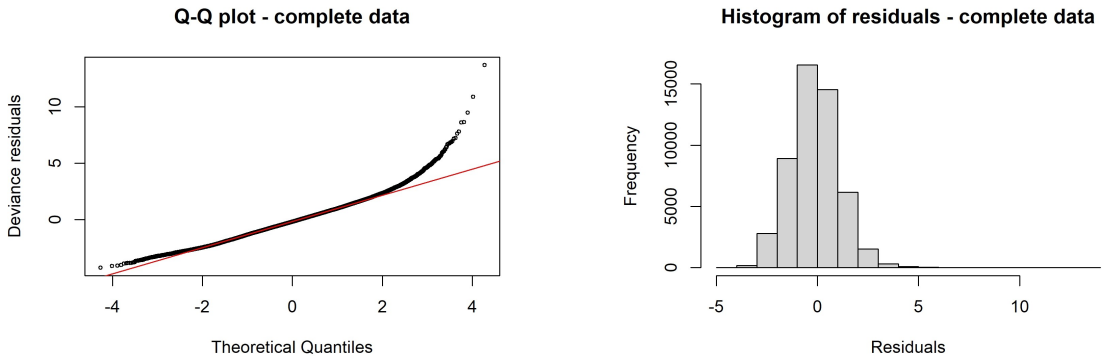

Fig. 4: Diagnostic graphs – model for complete data (the Q-Q plot of the residuals is displayed on the left, while the corresponding histogram is shown on the right)

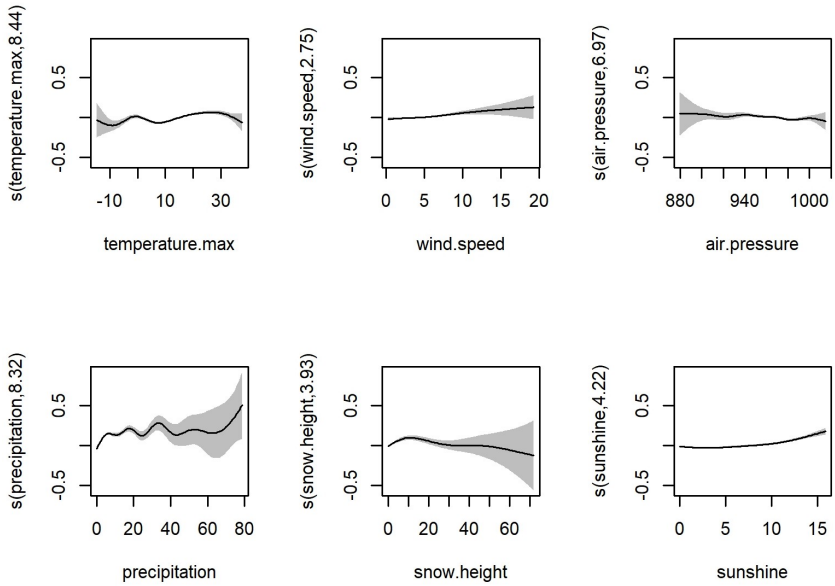

Fig. 5: Graphical output from R for GAM with Poisson distribution and outliers omitted (partial effect plots add up to the overall prediction)

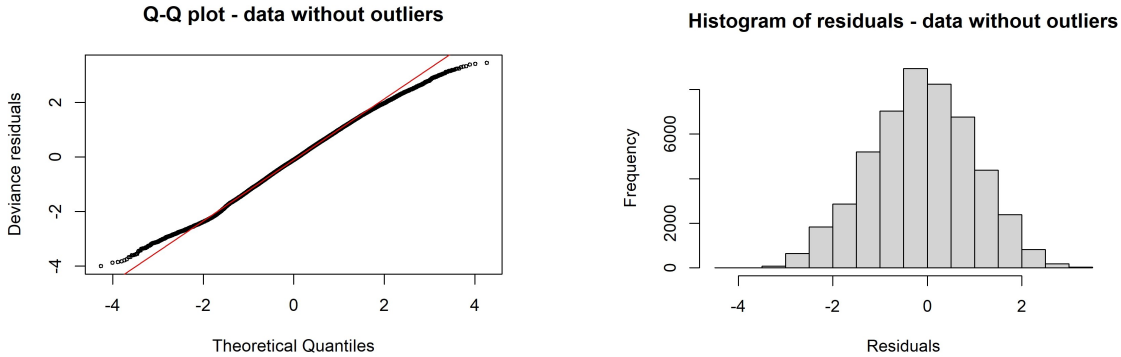

Fig. 6: Diagnostic graphs – model without outliers (the Q-Q plot of the residuals is displayed on the left, while the corresponding histogram is shown on the right)

range). The detection of outliers was performed in each region separately, resulting in a total of 1730 potential outliers being identified.

Additionally, the data were modelled after the exclusion of outliers. The principal distinction is the decline in the mean daily number of accidents by day, month, region, holiday and state of emergency. The model without outliers is better described by the probability distribution, with the GAM giving better results. The percentage of explained deviance increased to 39.3%. A comparison of the graphs in Fig. 3 and 5 shows that the number of accidents decreased during adverse weather conditions, including high maximum temperature, high wind speed, high or low air pressure, heavy precipitation and snow. It can therefore be hypothesised that these meteorological influences lead to the extreme daily number of accidents. A comparison of the plots of the smooth terms (Fig. 3 and 5) reveals that the influence of the air pressure variable diminished after the outliers were excluded. Nevertheless, the F-test continues to indicate statistical significance.

At last, the GAM model was validated. Tests of the GAM model for data with outliers included did not yield optimal results. This may be attributed to the fact that the data only approximately fit the theoretical probability distribution. For the model with outliers omitted, please refer to Fig. 6, which depicts a Q-Q plot comparing the model residuals to a normal distribution. Additionally, the histogram of the residuals exhibits a symmetric bell shape.

5 SUMMARY AND DISCUSSION

The objective of this study was to examine the relationship between the daily number of traffic accidents involving firefighter call-outs and meteorological measurements. The data from the period between 2012 and 2021 were subjected to analysis, with the objective of determining the dependence of the daily number of accidents in the country on meteorological variables, including temperature, pressure, wind, precipitation and sunshine. The present paper is loosely related to a study (Kolísková and Neubauer, 2024) in which the authors employ a GLM model to analyse the relationship between the number of accidents and the day of the week and month. In this paper, the GAM method was employed for modelling purposes. This entailed estimating the relationship between the number of accidents and meteorological variables, as well as the influence of additional factors such as the day of the week, month, region, holiday and the impact of the Coronavirus (Covid-19) emergency. Furthermore, the non-linear relationship between meteorological regressors and accidents was examined using smoothing splines.

The model output verifies that the observed variables are statistically significant. The JHM, MSK and STC regions have a higher incidence of accidents than the reference region, HKK. Nevertheless, comparisons between the regions are challenging due to the discrepancies in their sizes, populations, traffic network densities, geographical characteristics, and other factors. However, the regions exhibit a similar pattern of fluctuations in accident rates throughout the year, as evidenced by the findings of Brázdil et al. (2021, 2023). The number of accidents per day is below average during the spring months, particularly in March. The number of accidents per day is more pronounced from November to February, with the highest number of accidents occurring in summer and early autumn, particularly in September and October. This trend is undoubtedly influenced by the variability of traffic and climatic characteristics typical of the season. During the summer months, there is a notable increase in travel, whereas the winter season is characterised by the occurrence of sudden and unforeseen circumstances, such as the formation of ice and the melting of snow, which can lead to adverse road conditions. The lowest number of accidents per day is recorded on Sundays. Conversely, Monday and Thursday are associated with a higher incidence

of accidents. Friday is identified as the riskiest day of the week in terms of accidents, which can be attributed to fluctuations in traffic volume throughout the week. The variables associated with holidays and the impact of the pandemic have an attenuating effect on the value of the daily number of accidents.

The models demonstrate that a maximum daily temperature of −5 to 0 exerts a negative influence on the number of accidents. The lowest incidence of accidents is observed at temperatures approaching −10, when traffic levels appear to be minimal, and at temperatures close to 10, which correlates with the spring period when the number of accidents is relatively low. The occurrence of accidents is found to increase in the presence of windy weather conditions. An increase in pressure, which is typically associated with dry and sunny conditions, is associated with a reduction in the number of accidents. The most pronounced fluctuations are observed in average daily precipitation and total daily snow depth, which are related to historical climatic circumstances and driver habits. The 2014–2017 period was one of the driest on record, and drivers are more likely to be deterred from travel or to exercise greater caution when the weather is significantly adverse. The absence of collisions is indicative of minimal accident occurrence. Conversely, the incidence of accidents is higher in areas with greater levels of sunshine. The effects of rain, drizzle, snow, ice, fog and wind were examined by Brázdil et al. (2022), and the findings yielded comparable results. The highest number of accidents occurs outside of the winter months, with the summer period seeing the greatest number of accidents. This is likely due to the increased fatigue experienced by drivers in high temperatures, as well as other risk factors associated with extreme weather.

In line with the findings of several recent studies, we employed the use of generalised additive models, which have been specifically designed for the analysis of non-linear relationships between meteorological regressors and the number of traffic accidents (Anderson et al., 2015; Lepage and Morency, 2020). The non-parametric GAM method was employed for modelling a variable with a Poisson probability distribution. The methodology employed was contrasted with that of the Poisson GLM approach. The two methods were compared on the basis of the percentage of explained deviance, which was found to be 36.1% for GAM and 34.6% for GLM. The potential benefits of a negative binomial distribution were also considered, but this did not result in an improvement to the model. This distribution is typically recommended for models with real (overdispersed) data (Basu and Saha, 2017). However, in this case, the predictive ability of the model deteriorated by 1–2%. In light of the aforementioned findings, it can be concluded that the Poisson model is an appropriate choice for these data. Ultimately, a model that excluded outliers was estimated, which demonstrated an enhancement in the percentage of explained variance, reaching 39.3%. The proportion of outliers in the analysed data is approximately 3%, which equates to approximately 10 outliers per region per year. It is evident that some cases are directly attributable to sudden changes in meteorological conditions. For instance, the formation of ice on the road or the occurrence of snow calamities in regions with higher elevations can be attributed to such changes.

A comparison of GLM and GAM methods revealed that GAM may result in over-parameterisation of the model. However, the computational software can be optimally adjusted if sufficient data is available. For the more extreme values of the meteorological variables, the confidence intervals of the smooth functions exhibited considerable width at their upper and lower limits. This was a direct consequence of the low occurrence of outliers in the data. The GAM model is likely to be unsuitable for use over a large area with disparate conditions due to the extent of the generalisation involved. In future work, it may be possible to carry out an analysis using GAM modelling for individual regions of the country, where it will also be possible to examine outliers in greater detail. The model incorporates a considerable number of variables, yet the interactions between meteorological variables

remain unexplored. For instance, the impact of current rain and wind, which are associated with an increased risk of accidents, has not been investigated. Similarly, the influence of sunshine and snow cover, which can result in glare from reflection, has not been considered. These factors represent promising avenues for future research.

6 CONCLUSIONS

It has been demonstrated that substituting the GLM model with the GAM model markedly enhances the model's capacity to forecast the daily number of traffic accidents with firefighter call-outs. The GAM employs smooth functions to identify the optimal functional relationships between the explanatory variable and the regressors, a strategy that has been demonstrated to be advantageous for this data set. The extent of the improvement is contingent upon the data distribution employed. The models that demonstrated the greatest efficacy were those based on the Poisson distribution. The GAM model with a Poisson distribution and outliers omitted exhibited a percentage of explained deviance of 39.3%.

The paper's conclusion is that weather exerts a significant influence on the number of accidents, and that the relationship between weather and accidents is non-linear. The number of accidents is found to depend significantly on the maximum daily temperature, to decrease slightly with increasing air pressure, and to increase with increasing sunshine. In the context of the relatively arid climate of the Czech Republic, precipitation appears to exert its influence on the number of accidents primarily through its impact on driver behaviour.

The analysis of the impact of meteorological conditions on accident rates reveals a number of potential applications for such models. Such models may also be applied to road traffic accident models, for example, to enhance accident warning systems. The integration of meteorological data into traffic forecasts can facilitate enhanced navigation systems, improved traffic management, the identification of regions experiencing a high frequency of accidents contingent on weather conditions, and the distribution of heavy traffic. Moreover, the introduction of weather-related driving restrictions is anticipated to contribute to enhanced road safety. The potential for innovative solutions arises from its application in real-time traffic management systems and predictive modelling for accident prevention. This could result in the implementation of more intelligent, data-driven decisions regarding the deployment of rescue services and the implementation of traffic safety measures. It is of significant importance to increase awareness of traffic issues, particularly among those who are most vulnerable. This encompasses the implementation of preventative programmes for groups such as inexperienced drivers, which address the challenges posed by adverse driving conditions. Such factors may include, for instance, road slipperiness, driver visibility, reaction time and braking distance. Such factors may be more accurately estimated by an AI system than by a human operator in an autonomous vehicle. Such precautions may prove effective in reducing both the frequency of accidents and their associated economic and human costs.

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THE ROLE OF REIT DIVIDEND POLICY ON EX-ANTE PORTFOLIO ALLOCATION

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ABSTRACT

To test the diversification benefits of REIT sub-groups formed based on dividend payout ratios, we forecast ex-ante variance-covariance matrices using a rolling window correlation and a DCC model. Regression-based mean-variance spanning tests, mean-variance efficient frontiers, and a minimum variance portfolio allocation approach using ex-ante optimization frameworks are considered. A major finding of the current study is the dividend payout ratios of REITs affect REIT market diversification benefits. Apart from extending stock market index investors' investment universe and providing more efficient (higher profitability and/or lower risk) portfolios, REITs offer diversification benefits directly related to dividend policies. A unique level of diversification is attained by classifying REITs based on their dividend payout ratios. As well, these REIT sub-groups are capable of left-shifting the efficient frontier of a market portfolio with either of the REIT sub-groups.

KEY WORDS

DCC, REITs, correlation, dividend policy, portfolio optimization, estimation, forecasting

JEL CODES

G14, G18, G32, H12

1 INTRODUCTION

The real estate market has proven to be an asset class with high diversification potential for the stock market investors (Lu et al., 2013; Yang et al., 2012; Case et al., 2012; Fugazza et al., 2007; Clayton and MacKinnon, 2001; Bley and Olson, 2005; Cotter and Stevenson, 2006; Chong et al., 2009; Liow et al., 2009; Niskanen and Falkenbach, 2010; Akinlana et al., 2019). A specific area of literature examines whether diversification benefits of real estate to equity market investors are related real estate investment trusts' (REITs) dividend policies

(Allen and Rachim, 1996; Hussainey et al., 2011; İlbasmış et al., 2025). For example, İlbasmış et al. (2025) report that the REIT dividend payout ratio is negatively correlated with the time-varying correlation when REITs face restrictions on their dividend payout policies. This suggests that the REIT dividend policy has the potential to reduce REITs' correlation with the stock market. The modern portfolio theory posits that it means that the diversification benefits assigned to each asset class are different if two asset classes have different levels of correlation with the general stock market.

Whilst the literature on mixed-asset portfolios including REIT has demonstrated the contribution of REIT in enhancing portfolio performance, most studies rely on ex-post and in-sample results. In the absence of a solid grounding in asset pricing theory, portfolio allocations using ex-post models with in-sample data may be unrealistic for active portfolio managers in real world scenarios. For a more convincing portfolio allocation practice, we use an out-of-sample portfolio allocation with ex-ante variance-covariance matrix forecasts. Taking the stock market index portfolio as an optimal portfolio that comprises the efficient frontier, we investigate whether portfolios including REITs with different dividend payout policies in this portfolio further expands the investment opportunity set and improves the efficient frontier differently.

This study aims to document the differential diversification power of REIT sub-groups formed based on their dividend payout ratios and to test the extent to which they can diversify a stock market portfolio. Thus, our attention focuses on the differences in the efficient frontier obtained when a different subgroup of REITs is added to the stock market portfolio.

Companies that own or finance income-producing real estate across a variety of property sectors are known as REITs. They are required to distribute a considerable share of their earnings as dividends in order to keep their REIT status and continue to enjoy the tax advantages provided by governments around the world. For instance, according to the Securities and Exchange Commission (SEC), "To qualify as a REIT, a company must have the bulk of its assets and income connected to real estate investment and must distribute at least 90 percent of its taxable income to shareholders annually in the form of dividends.[1]" Any non-distributed income over the threshold is taxed at the corporate level of 35%.

Our sample comprises weekly returns on the stock market index and REITs spanning from January 2000 to December 2022, covering two significant global economic crises: the 2008 Global Financial Crisis and the recent Covid-19 pandemic crisis. After creating groups of REITs with high- and low-dividend-payments, we first use a mean- variance spanning test to examine whether these sub-groups of REITs can lead to a statistically significant improvement in the efficient frontier. Second, to assess the economic significance of these improvements, we optimize global minimum variance portfolios consisting of the stock market index and a subgroup of REITs using both ex-post and ex-ante covariance matrices. In doing so, we use two forecasting models, the Dynamic Conditional Correlation (DCC) and rolling window correlation (RWC), to acquire the covariance matrix.

Various contributions have been made to the literature on REITs' dividend policy and diversification power. We first document that the efficient frontier of the market portfolio is influenced by the dividend policies of REITs in the portfolio. In other words, as well as expanding investment opportunities for stock market index investors and providing more profitable or less risky portfolios, REIT dividend policies contribute directly to their diversification benefits. Investing in REITs that are categorized based on dividend payout ratios offers varying levels of diversification. To our knowledge, this study is the first to document improvements in the efficient frontier of the market portfolio due to differential dividend policies. Second, our study contributes to the forecasting literature by using a DCC and a rolling window correlation model in ex-ante

[1]The minimum dividend requirement was 95% prior to 2001.

portfolio allocation. Each model employed in this study has its own advantages and disadvantages. For instance, although both models produce similar levels of expected returns for a portfolio of the stock market index and a REIT sub-group, the DCC model out-performs the rolling window correlation model in mitigating the risk of the portfolio. What is more, the rolling window correlation model produces portfolios with better risk-return combinations, while the DCC model allows investors to form portfolios with higher risk and higher return. These outcomes hold both at the index level and the firm level portfolio allocation.

Several interesting findings come out of this study. First, we find that the two sub-groups of REITs formed based on the dividend payout ratio cannot be spanned by a market portfolio consisting of the stock market index. Furthermore, the sub-groups are not a substitute for each other in portfolio allocation. Analyses are conducted at both index and firm levels and our findings are confirmed with multiple methods, including Huberman and Kandel (1987)'s spanning test, and global minimum variance portfolio expected returns and standard deviations. The main finding is that REITs, when divided into sub-groups, continue to offer diversification opportunities to stock market investors, regardless of their investment in other REIT sub-groups. This implies that REITs provide diversification benefits both within and across asset allocations. Our sub-period analysis further reveals that the diversification potential of REITs and their sub-groups evolves over time. Notably, the diversification benefits of REITs were prominent before and during the 2008 global financial crisis. However, while REIT sub-groups still offer diversification benefits to stock market index investors post-crisis, their ability to diversify among different REIT sub-groups significantly diminishes. Additionally, our investigation of REITs' diversification power during the recent Covid-19 pandemic shows that REITs continue to offer diversification benefits to stock market investors.

The rest of the paper is organized as follows. Section 2 provides a brief overview of the relevant literature. Section 3 describes the data and outlines the mean-variance spanning test and the methodologies used to predict the correlation forecasts along with the global minimum variance problem. Section 4 presents the results from the spanning test, portfolio allocations, and time varying diversification benefits of sub-grouped REITs. Finally, section 5 offers some concluding remarks and discusses our overall findings.

2 LITERATURE REVIEW

Owing to the low correlations of real estate with traditional asset classes, the literature has documented ample evidence on the diversification benefits of the real estate market in mixed-asset portfolios. Thus, after providing the literature on the overall role of the real estate market, this section focuses on the role of different real estate categories in mixed-asset portfolios.

Hudson-Wilson et al. (2003, 2005) addressed the question of "Why Real Estate?" providing central explanations for the inclusion of real estate in a mixed-asset portfolio. The authors rationalize that investors benefit by adding real estate to their portfolios in the following ways: i) reduction in risk or enlargement of returns, ii) hedging against inflation, iii) stable and high cash flows, and iv) expansion of the investment universe. Addressing a similar question, Garay and ter Horst (2009) review the literature on the diversification benefits of real estate investments and find that the real estate market improves mean-variance efficiency.

One of the early studies examining the diversification of the stock market via securitized real estate is Burns and Epley (1982). Using quarterly data from 1970 to 1979, they compared the location of the efficient frontier of portfolios consisting of REITs only, stocks only, and both. The combined portfolio of REITs and stocks was found to be superior to both single-asset portfolios. Thus, the authors conclude that the inclusion of REITs in the stock market

portfolio improves risk-return opportunities for investors. On the other hand, a study by Mull and Soenen (1997) shows conflicting evidence that the diversification potential of REITs is dependent on the time period under examination. They report that the diversification potential of REITs were not attractive in the 1985–1990 period, while the 1990–1994 period was a good period to invest in REITs. Both of these papers study the ex-post diversification benefits of REITs.

Building on these foundational studies, more recent research has expanded the examination of REIT diversification benefits beyond the U.S. context. For instance, Badji et al. (2021) extended the analysis to European markets, showing that European REITs contribute to diversification in mixed portfolios, even if the risk reduction is limited. Similarly, Marzuki and Newell (2021) highlighted the significance of Mexico REITs, particularly in emerging markets, where they demonstrated strong risk-adjusted performance and diversification potential despite higher volatility.

Fugazza et al. (2007) used Bayesian estimators to account for parameter uncertainty when including U.S. REITs in optimal portfolios of stocks, bonds, and cash. Their findings indicate that ex-post gains from portfolios containing REITs are large, despite higher realized portfolio volatility. This work laid the foundation for understanding the significant ex-post benefits of including REITs in portfolios, even when considering the added volatility.

Sa-Aadu et al. (2010) addressed how real estate helps investors of stocks and bonds improve the performance of their portfolios using monthly data from January 1972 to December 2008. They investigate whether adding REITs to the portfolio in a regime-switching economy (the good times and the bad times) would decrease the lower bound of volatility, equivalent to increasing the Sharpe ratio of the portfolio. Their results indicate that gains from the inclusion of equity REITs lead to a considerable increase in portfolio performance across different economic states.

Further, Lin et al. (2020) focused on Industrial and Logistics REITs (I&L REITs) in the Pacific Rim region, examining their performance against other asset classes in mixed-asset portfolios. Their study revealed that I&L REITs offered superior average annual returns and provided significant portfolio diversification benefits. This is particularly relevant in the context of the growing importance of logistics properties driven by the e-commerce boom. Their findings underscore the added value of sector-specific REITs in enhancing portfolio performance, especially in regions heavily influenced by modern economic trends.

Huang and Zhong (2013), an important paper in this line of literature, examined in-sample and out-of-sample diversification opportunities by including REITs, commodities, and Treasury Inflation-Protected Securities (TIPS) into portfolios of U.S. equity, U.S. bonds, international equity, and international bonds. The study's sample period from 1970 to 2010 showed that none of these asset classes could substitute each other before the 2008 global financial crisis, although all had diversification potential. However, the 2008 crisis significantly altered their diversification roles, showing how economic crises can impact the effectiveness of REITs and other assets in a portfolio.

Additionally, Pacholec (2022) revisited the diversification potential of REITs by examining the impact of individual REIT sectors on mixed portfolios. His findings contrast earlier studies by showing that certain REIT sectors, such as Apartments and Industrials, consistently provided diversification benefits across different decades. His study demonstrated that replacing even small portions of traditional assets with sector-specific REITs could significantly enhance portfolio performance, particularly during specific market conditions.

Another area of literature examines the diversification benefits within real estate sub-classes. Hudson-Wilson and Elbaum (1995) conducted an early study on asset allocation within real estate, providing evidence for the diversification benefits of including public equity, public debt, and private debt securities in a real estate portfolio dominated by private equity. Their findings suggest that a diversified real estate portfolio can offer significant risk reduction

and return enhancement by combining different types of real estate securities.

Building on this, Seiler et al. (1999) focused on the diversification potential of real estate in a mean-variance context. They reviewed literature concerning the optimal allocation of real estate within both real estate-only portfolios and mixed-asset portfolios that include real estate. Seiler et al. (1999) highlighted the varying approaches in the literature regarding the appropriate amount of real estate to include in a diversified portfolio. Their key conclusion was that while real estate significantly expands the investment universe, effective diversification often requires investing in different types of real estate, given the variations in property type, geographic location, and economic conditions. Importantly, they distinguished between unsecuritized and securitized real estate: unsecuritized real estate tends to have low correlations with other asset classes, making it a strong hedge against inflation, while securitized real estate (such as REITs) exhibits higher correlations with other asset classes, reducing its effectiveness as an inflation hedge.

Taking a different approach, Boudry et al. (2020) used a utility-based framework to assess the diversification benefits of REIT preferred and common stocks. Their findings emphasized that while REIT common stocks are beneficial for low-risk aversion investors seeking higher returns, REIT preferred stocks provide a venue for risk reduction. This distinction is crucial as it highlights the varying roles that different types of REIT securities can play in portfolio optimization.

Chen et al. (2005) investigated the characteristics of REITs that play a role in the diversification benefits. Their empirical results demonstrate that REITs did not provide diversification benefits prior to 1985. However, from 1986 to 2002, adding REITs to a portfolio did offer diversification benefits. In particular, mortgage REITs were found not to provide meaningful diversification, whereas equity REITs did. This study aligns with the broader literature that differentiates between the diversification potential of different REIT subtypes.

Further, recent research by Ervin and Smolira (2023) extends the discussion to the role of REITs in retirement portfolios. Their Monte Carlo simulations show that portfolios including REITs are more likely to sustain withdrawals over time, which is crucial for retirement planning. Lastly, Li et al. (2023) investigated the relationship between sector-specific Australian REITs and their underlying property assets, finding that property features like occupancy rates and portfolio market value significantly influence REIT dividend outcomes.

The real estate literature has mostly focused on private (un-securitized) versus public (securitized) real estate asset classes. Size, property type, geographic and economic regions, urban versus suburban, mortgage versus equity, and common versus preferred stock types in real estate are some of the main groupings for which the literature evaluates their diversification power. This study proposes a new way to categorize within securitized real estates in the form of REITs for the purpose of differential diversification benefits. REITs in the current study are classified according to their dividend payout ratios.

3 DATA AND EMPIRICAL METHODOLOGY

3.1 Data

We use weekly returns on US stock market index (S&P500), FTSE Nareit all REIT index, and REIT firms from January 4, 2000 to December 31, 2022. Both firm and index level data are collected from Refinitiv ESG database. Relying on the ex-post dividend decisions of REITs, we place REITs into two groups of low and high dividend paying firms, using the annual dividend payout ratios. If the dividend payout ratio of a REIT is lower (higher) than the average of all REITs in that year, then we

mark that REIT as a candidate for the group with low (high) dividend payments.[2]

We construct a value weighted REIT index for each sub-group based on their dividend payouts; low and high REITs. As there is a 90% minimum dividend requirement for REITs in the US, they can choose to pay around this threshold or they can choose to pay all of their earnings in the form of dividends.[3]

Tab. 1 presents the descriptive statistics of the equity market index, a REIT market index and weighted REIT indices. Our categorization of low and high REITs is meaningful since we create two categories with distinct dividend payout ratios. The table shows that, between the REIT groups, the high REITs group has the higher return and the higher standard deviation, the low REITs group has the lower return and lower standard deviation, which means that the risk-return trade-off concept is in play. Higher standard deviation of the high REITs group is supported by higher returns and lower standard deviation of the low REITs group is supported by lower returns. In terms of the combination of risk and return, the low REITs group has a better performance; return per unit of risk is slightly larger for the low REITs group.

One consideration is the overall correlations between our sub-groups of REITs. If the diversification benefits do change with their dividend payout ratios, then we would expect these sub-groups of REITs to have low or negative correlations with each other and similar correlations with the equity market index. Panel B of Tab. 1 reports the pairwise correlation between the stock market index and the value-weighted indices of REITs. The table shows that both REIT indices have low correlations with the stock market index and negative correlation with each other, which implies that each REIT sub-group has the potential to further diversify the stock market portfolio and the other REIT sub-group.

Between the REIT indices, the high REITs group has the lower pairwise correlation with the stock market index and the higher diversification potential for the stock market investors. One can argue that if a REIT's dividend payout decision is unrelated to its correlation with the stock market index, then we should expect to see no difference in correlations of our REIT sub-groups with the stock market index. However, a two-sample t-test strongly rejects (p-value: 0.000) the null hypothesis of zero difference in correlations of the sub-groups of REITs with the stock market. This is evident for that these sub-groups of REITs are not just randomly selected into their groups. They provide a different and a unique level of diversification.

Further, having negative correlations between the REIT sub-group indices confirms that our way of grouping REITs based on their dividend payout ratios can be used to form REIT subclasses that give unshared diversification benefits. The negative correlations of REIT indices with each other as well as the low correlation with the stock market index signal the possibility of the diversification power of

[2]When REITs that do not consistently classify as low- or high-dividend firms throughout the sample period are excluded due to significant changes in their dividend policies, the unreported results are similar and more robust.

[3]For US REITs, a minimum dividend payout ratio of 90% is applied to taxable income, which is not disclosed. Financial statements are often used to estimate taxable income by increasing net income to its pre-tax value using the statutory tax rate. For example, if a firm has net income of USD 6.5 million and the statutory tax rate is 35% the taxable income would be calculated at USD 10 million (USD 6.5 million/0.65). This example assumes that the firm paid USD 3.5 million in current tax; however, how much tax this firm actually paid is impossible to determine. Several reasons are suggested for why taxable income cannot be estimated using financial statements. Ample evidence in the literature suggests that reported earnings in financial statements can be manipulated upwards or downwards as needed. In addition, financial statements are prepared under business objectives, whereas the tax payable to the Internal Revenue Service is calculated under tax accounting systems. Thus, a firm's reported tax and the actual tax paid to the authorities can be different. Not surprisingly, different sets of rules in different accounting systems with different objectives are expected to produce different incomes. To overcome this problem, the literature suggests multiple methods to estimate taxable income, all of which are prone to errors. Our assumption is that the dividend decision is either unaffected or affected in the same way by the tax rate since all REITs in the US are subject to the same tax rates. Thus, we expect the dividend payout ratio to reflect the firm's dividend policy decisions.

Tab. 1: Descriptive Statistics & Pairwise Correlations
This table presents the descriptive statistics of returns on equity and weighted REIT indices that are created based on their dividend distribution ratios. Weights are chosen based on market capitalization of REITs when indices are formed. Low REITs and High REITs represent REIT indices consisting low-dividend-paying, and high-dividend-paying, respectively. Equity is annualized return on S&P 500 Composite Price Index (S&PCOMP(PI)) and REIT is annualized return on FTSE Nareit All REITs Index (FTFNAR) for the period from Jan 2000 to Dec 2022.

	Equity	**REIT**	**Low REITs**	**High REITs**	**Cash**
Panel A: Descriptive Statistics					
Mean	0.0497	0.0277	0.0729	0.0847	0.0166
Median	0.1236	0.1332	0.1558	0.1858	0.0101
Maximum	5.9403	11.6974	26.2385	64.8078	0.0620
Minimum	−10.4436	−15.8319	−29.6469	−72.3770	−0.0000
Std. Dev.	1.3071	1.9525	2.4572	3.9758	0.0184
Skewness	−0.8678	−0.6589	−0.8779	−0.9450	0.9593
Kurtosis	10.1293	14.4118	46.0878	4.2967	2.5981
Jarque-Bera Test Statistic (10^4)	0.2806	0.5520	9.6934	0.0137	0.0199
N	1248	1004	1248	1248	1248
Div. Payout Ratio			66%	336%	
Panel B: Pairwise Correlations					
Equity	1	0.7522	0.5338	0.2494	−0.0052
REIT		1	0.6542	0.3636	−0.0073
Low REITs			1	−0.3014	−0.0064
High REITs				1	−0.0086

REIT sub-groups to one another as well as to the stock market index investors.

3.2 Mean-Variance Spanning Test

In the first part of our analysis, we test the diversification potential of the overall REIT index as well as the weighted REIT indices to the stock market index portfolio by performing a regression-based spanning test. We use the mean-variance spanning test introduced by Huberman and Kandel (1987), hereafter HK. The main idea behind the mean-variance spanning test is simple. Spanning is the coinciding of the mean-variance efficient frontier of the benchmark assets (a set of K assets) and that of the benchmark assets plus the test assets (a set of $N+K$ assets), in which case test assets do not provide significant diversification benefits over benchmark assets.[4] We assume that the risk-free rate does not exist, or equivalently, risk-free lending and borrowing rates are different. Hence, we investigate the spanning of the minimum variance portfolios rather than a tangency portfolio since investors will be interested in the minimum variance portfolios when they cannot short the risk-free rate.[5]

The assumption is that the stock market portfolio (K) spans a larger portfolio of the stock market plus REITs ($N+K$) if the frontier of the stock market portfolio coincides with the frontier of the stock market plus REITs. If the two frontiers of both smaller and larger portfolios span, then REITs do not provide significant diversification benefits to the stock market.

[4]For a discussion on mean-variance spanning tests, the reader is referred to Kan and Zhou (2012) and Lee and Lee (2010).

[5]When shorting risk-free rate is allowed, the objective of investors is to maximize the Sharpe ratio. In that case they will be interested in the tangency portfolio of risky assets and investigate whether the tangency portfolio from using a set of K benchmark risky assets is identical to the one from using a set $N+K$ test plus benchmark risky assets.

As a first step in formalizing the statistical test of spanning, we define the expected returns (μ) of both asset classes as:[6]

$$\mu = E[r_t] = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix} \tag{1}$$

and the covariance matrix (V) of the $N + K$ risky assets as:

$$V = \text{Var}[r_t] = \begin{bmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{bmatrix}, \tag{2}$$

where V is assumed to be non-singular. By projecting r_{2t} on r_{1t}, we estimate the following equation:

$$r_{2t} = \alpha + \beta r_{1t} + \epsilon_t, \quad t = 1, 2, \ldots, T, \tag{3}$$

with $E[\epsilon_t] = 0_N$ and $E[\epsilon_t r_{1t}'] = 0_{N\times K}$, where 0_N is defined as N-by-1 vector of zeros and $0_{N\times K}$ is an N-by-K matrix of zeros; r_{1t} and r_{2t} are assumed to be normally distributed.[7] Borrowing the necessary and sufficient conditions for spanning from HK, the null hypothesis of spanning is as follows:

$$H_0: \quad \alpha = 0_N, \quad \theta = 1_N - \beta 1_K = 0_N, \tag{4}$$

where 1_N is defined as an N-by-1 vector of ones. If the null hypothesis is not rejected, then benchmark risky assets are identical to benchmark plus test risky assets, so there is spanning. Benchmark risky assets span benchmark plus test risky assets. However, if the null hypothesis is rejected, then adding the test risky assets to the benchmark risky assets expands the investment universe for the benchmark risky asset investors. In other words, by adding test risky assets investors can shift the minimum variance frontier outward, resulting in portfolios with a reduced risk for similar returns.

To test the null hypothesis given in Eq. 4 for our benchmark asset of the stock market index and test assets of REIT indices, we denote by r_{1t} as the returns on the stock market portfolio (the benchmark risky asset), and by r_{2t} as the returns on REIT indices (the test risky assets). Let r_t represent returns on benchmark plus test risky assets ($N + K$). We run the regression in Eq. 3 under the common assumption that α and β are constant over time. Rewrite Eq. 3 in matrix form for notational convenience as follows:

$$Y = XB + E, \quad E \sim \mathcal{N}(0, \Sigma), \tag{5}$$

where a T-by-N matrix of Y is equal to r_{2t}, a T-by-$(K + 1)$ matrix of X is equal to $[1, r_{1t}']$ with 1 being a size T vector of ones, and a T-by-N matrix of E is equal to E_t. We assume that $T \geq N + K$ and non-singularity of $\chi'\chi$. The disturbances E are assumed to have multivariate normal distribution and Σ is variance-covariance matrix of the disturbances with independent and identically observations. In Eq. 5, the estimator or B is

$$\widehat{B} \equiv \begin{bmatrix} \widehat{\alpha} & \widehat{\beta} \end{bmatrix}' = (X'X)^{-1}(X'Y)$$

and the estimator of Σ is

$$\widehat{\Sigma} \equiv \frac{1}{T}\left(Y - X\widehat{B}\right)'\left(Y - X\widehat{B}\right).$$

Under the normality assumption, we have

$$\text{vec}(\widehat{B}') \sim \mathcal{N}\left(\text{vec}(\widehat{B}'), (X'X)^{-1} \otimes \Sigma\right).$$

We define $\Theta = \begin{bmatrix} \alpha & \theta \end{bmatrix}'$ and the null hypothesis given in Eq. 4 can be rewritten as

$$\Theta = \begin{bmatrix} \alpha & \theta \end{bmatrix}' = 0_{2\times N} = C - AB,$$

where $A = \begin{bmatrix} -1 & 0_K' \\ 0 & 1_K' \end{bmatrix}$ and $C = \begin{bmatrix} 0_N' \\ 1_N' \end{bmatrix}$.

[6] For convenience, we follow notations and treatments in Kan and Zhou (2012).

[7] In the mean-variance spanning procedure, while small sample tests assuming normality are generally preferred when the normality assumption is met, Kan and Zhou (2012) demonstrate that alternative tests, such as those based on the generalized method of moments (GMM), remain valid even when the data exhibits nonnormality. Although unreported results yield similar findings, we focus on reporting test statistics derived from the regression framework, as they offer more straightforward interpretation and communication.

Using maximum likelihood method, the estimator of Θ is

$$\widehat{\Theta} \equiv \begin{bmatrix} \widehat{\alpha} & \widehat{\theta} \end{bmatrix} = C - A\widehat{B}.$$

For computational ease, we define $\widehat{G}$ and $\widehat{H}$ as follows:

$$\begin{aligned} \widehat{G} &= TA\left(X'X\right)^{-1}A' \\ &= \begin{bmatrix} 1+\widehat{\mu}_1'\widehat{V}_{11}^{-1}\widehat{\mu}_1 & \widehat{\mu}_1'\widehat{V}_{11}^{-1}1_K \\ \widehat{\mu}_1'\widehat{V}_{11}^{-1}1_K & 1_K'\widehat{V}_{11}^{-1}1_K \end{bmatrix}, \end{aligned} \tag{6}$$

$$\begin{aligned} \widehat{H} &= \widehat{\Theta}\widehat{\Sigma}^{-1}\widehat{\Theta}' \\ &= \begin{bmatrix} \widehat{\alpha}'\widehat{\Sigma}^{-1}\widehat{\alpha} & \widehat{\alpha}'\widehat{\Sigma}^{-1}\widehat{\theta} \\ \widehat{\alpha}'\widehat{\Sigma}^{-1}\widehat{\theta} & \widehat{\theta}'\widehat{\Sigma}^{-1}\widehat{\theta} \end{bmatrix}, \end{aligned} \tag{7}$$

where

$$\widehat{\mu}_1 = \frac{1}{T}\sum_{t=1}^{T} r_{1t}$$

and

$$\widehat{V}_{11} = \frac{1}{T}\sum_{t=1}^{T}\left(r_{1t}-\widehat{\mu}_1\right)\left(r_{1t}-\widehat{\mu}_1\right)'.$$

The distribution of the null hypothesis can be verified that

$$\text{vec}\left(\widehat{\Theta}'\right) \sim \mathcal{N}\left(\text{vec}\left(\Theta'\right), \left(\widehat{G}/T\right)\otimes\Sigma\right).$$

By defining $U = |\widehat{G}|/|\widehat{H}+\widehat{G}|$, and denoting λ_1 and λ_2 are two eigenvalues of $\widehat{H}\widehat{G}^{-1}$, where $\lambda_1 \geq \lambda_2 \geq 0$, we have $1/U = (1+\lambda_1)(1+\lambda_2)$. The distribution of the asymptotic Wald (W), Likelihood ratio (LR), and Lagrange multiplier (LM) test statistics follows Chi-squared distribution ($\tilde{\chi}^2$) and the null hypotheses can then be written as follows.[8]

$$\text{W} = T(\lambda_1+\lambda_2) \overset{A}{\sim} \tilde{\chi}^2_{2N} \tag{8}$$

$$\text{LR} = T\sum_{i=1}^{2}\ln(1+\lambda_i) \overset{A}{\sim} \tilde{\chi}^2_{2N} \tag{9}$$

$$\text{KM} = T\sum_{i=1}^{2}\frac{\lambda_i}{1+\lambda_i} \overset{A}{\sim} \tilde{\chi}^2_{2N} \tag{10}$$

The test statistics identify whether the inclusion of the REIT index significantly improves the global-minimum variance portfolio. Rejecting the null hypothesis would indicate that a portfolio of the stock market index plus the REIT index has lower risk compared to the conventional stock market portfolio. In other words, a statistically significant shift of the efficient frontier to the left means that the REIT index provides diversification benefits to the stock market index investors, in which case the null is rejected.

3.3 The DCC Model Forecasting

A realistic dynamic portfolio allocation requires out-of-sample forecasting of the ex-ante covariances. In order to forecast ex-ante out-of-sample correlations between the stock market and REIT indices to optimize the global minimum variance portfolio, we use Engle and Sheppard (2001)'s DCC model in a 5-year rolling window framework.

We start by calculating continuously compounded returns:

$$r_{i,t} = \log\left(\text{index}_{i,t}\right) - \log\left(\text{index}_{i,t-1}\right),$$

where $\text{index}_{i,t}$ and r_t denotes the value of index of asset class i and continuously compounded return of the index at time t.[9] The asset class i is either the stock market or one of the REIT indices.

After computing the index returns, the residuals from ARMA(p,q) with appropriate lags are calculated:

$$\begin{aligned} r_{i,t} &= \delta_{i,0} + \sum_{k=1}^{p}\delta_{i,1}r_{i,t-k} + \sum_{l=0}^{q}\epsilon_{i,t-l}, \\ \epsilon_{i,t} &\sim \mathcal{N}(0, h_{i,t}) \end{aligned} \tag{11}$$

$$\epsilon_{i,t} = \sqrt{h_{i,t}}\eta_{i,t} \tag{12}$$

In Eq. 11, p and q are determined based on Bayesian information criterion (BIC). Residuals are then used in the univariate GARCH and multivariate DCC processes.

Let define a covariance matrix of H_t. The DCC implies that the covariance matrix is the

[8] See Kan and Zhou (2012) for further details.

[9] In this study, return and excess return terms are used interchangeably.

product of conditional correlation matrix of standardized disturbances with the square root of the product of the variances: $H_t = D_t R_t D_t$, where $D_t = \text{diag}\left[\sqrt{h_{ii,t}}\right]$, $h_{ii,t}$ are the variances of residuals and R_t is the conditional correlation matrix of standardized disturbances.

The estimation of the model is made in two steps. First, the variance ($D_t = \text{diag}\left[\sqrt{h_{ii,t}}\right]$) and second, the correlation (R_t) processes are forecasted separately. According to Engle and Sheppard (2001), separate forecasting of variance and correlation gives the least biased forecast.[10]

One-step ahead forecast of conditional variance matrix is:

$$E\left[D_{t+1} \mid \mathcal{F}_t\right] = \text{diag}\left(\sqrt{h_{1,t+1} \mid \mathcal{F}_t}, \sqrt{h_{2,t+1} \mid \mathcal{F}_t}, \vdots \sqrt{h_{n,t+1} \mid \mathcal{F}_t}\right) = \begin{bmatrix} h_{1,t+1|t} & \cdots & \cdots \\ \vdots & \ddots & \vdots \\ \cdots & \cdots & h_{n,t+1|t} \end{bmatrix},$$

$\epsilon_{i,t}$ is assumed as a process that is a univariate GARCH. Therefore, GARCH (1,1) model is defined as follows:

$$h_{i,t+1} = \omega_i + \alpha_i \epsilon_{i,t}^2 + \beta_i h_{i,t} \tag{13}$$

Eq. 13 defines the time-varying volatility process; $h_{i,t+1}$ is one-step ahead forecast of conditional variance of the disturbances; $\epsilon_{i,t}$ is the innovation of asset i at time t; i is the stock market index, or REIT indices. Coefficients are restricted with non-negativity to ensure the volatility process is always positive; the intercept, the coefficient of past shocks α and that of past conditional variance β are all restricted to positive. Also, $\alpha_i + \beta_i < 1$ ensures that the process is stationary.

Rather than being a forecast by itself, the one-step ahead forecast of conditional correlation matrix R_{t+1} is the ratio of the covariance forecast to the square root of the product of variances forecasts.

[10] See Orskaug (2009) for further details.

The one step-ahead forecast of correlation matrix conditional on the information set of $\mathcal{F}_t$ is:

$$E\left[R_{t+1}|\mathcal{F}_t\right] = \text{diag}\left(Q_{t+1}^{-1/2}\right) Q_{t+1} \text{diag}\left(Q_{t+1}^{-1/2}\right)$$

$$\begin{bmatrix} \frac{1}{\sqrt{q_{11,t+1}}} & \cdots & \frac{1}{\sqrt{q_{1m,t+1}}} \\ \vdots & \ddots & \vdots \\ \frac{1}{\sqrt{q_{n1,t+1}}} & \cdots & \frac{1}{\sqrt{q_{nm,t+1}}} \end{bmatrix} \cdot \begin{bmatrix} q_{11,t+1} & \cdots & q_{1m,t+1} \\ \vdots & \ddots & \vdots \\ q_{n1,t+1} & \cdots & q_{nm,t+1} \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{\sqrt{q_{11,t+1}}} & \cdots & \frac{1}{\sqrt{q_{1m,t+1}}} \\ \vdots & \ddots & \vdots \\ \frac{1}{\sqrt{q_{n1,t+1}}} & \cdots & \frac{1}{\sqrt{q_{nm,t+1}}} \end{bmatrix} = \begin{bmatrix} 1 & \cdots & \rho_{1m,t+1} \\ \vdots & \ddots & \vdots \\ \rho_{n1,t+1} & \vdots & 1 \end{bmatrix},$$

where Q_{t+1} is the variance-covariance matrix, in which q_{ij}, q_{ii} and q_{jj} are the forecast elements, where q_{ij} being the covariance matrix, with q_{ii} and q_{jj} being the variance of assets i and j: h_i and h_j, respectively. The typical element of R_{t+1} will be of the form

$$\rho_{ij} = \frac{q_{ij}}{\sqrt{h_i}\sqrt{h_j}}.$$

Thus, the DCC (1,1) forecasting model of covariance is as follows:

$$q_{ij,t+1} = (1 - a - b)\overline{\varrho_{ij}} + a\eta_{i,t}\eta_{i,t} + bq_{ij,t}, \tag{14}$$

$$\eta_{i,t} = \epsilon_{i,t} D_{i,t}^{-1} = \frac{\epsilon_{i,t}}{\sqrt{h_{i,t}}}, \tag{15}$$

where $q_{ij,t}$ is the one-step ahead forecast of covariance, $\overline{\varrho_{ij}}$ is the unconditional correlation between the residuals of market i and j, and standardized disturbances, $\eta_{i,t}$, are derived from the first step estimation of conditional volatility. Coefficients a and b represent the

effect of past shocks and past conditional covariance on current covariance. The reverting process implies $a+b<1$ and the non-negativity of coefficients a and b. The persistence of the correlation gets stronger as the sum of the two coefficients gets closer to 1.

The conditional correlations are obtained using the conditional variances from the first stage via GARCH (1,1) model that runs for each time series separately and conditional covariance from the second stage via DCC (1,1) model that runs for all-time series at once:

$$\rho_{ik,t+1} = \frac{q_{ij,t+1}}{\sqrt{h_{i,t+1}}\sqrt{h_{j,t+1}}},$$

where $\rho_{ik,t+1}$ represents one-step ahead forecast of conditional correlations.

3.4 Rolling Window Correlation Model

To serve as a benchmark model for the DCC model, the correlation forecast for $t+1$ is derived using a rolling window approach. Specifically, the correlation between asset classes for the next period is estimated as the pairwise correlation calculated over a rolling window of the last 5 years of data, up to time t.

This method assumes that the correlation structure between asset classes remains relatively stable over the short-term, and the most recent correlations provide the best estimate for the immediate future. Mathematically, the correlation at time $t+1$, ρ_{t+1}, is given by:

$$\rho_{t+1} = \text{Corr}\left(r_i, r_j \mid \tau - 5 \text{ years } \leq \tau \leq t\right),$$

where r_i and r_j represent the returns of asset classes i and j, respectively. The correlation is calculated using data from the most recent 5-year period leading up to time t.

This rolling window approach is useful in capturing time-varying correlations, as it adapts to changes in the underlying relationship between asset classes over time. By comparing the results of this model with more sophisticated models like the DCC model, we can evaluate the performance of different forecasting methods in predicting future correlations.

The main implication of the Rolling Window Correlation Model is that it assumes returns do not follow a specific data-generating process, making it a valuable null hypothesis in financial studies. If a more advanced model, such as the DCC model, outperform the Rolling Window Correlation Model in forecasting correlations, it indicates that this model is capturing additional information beyond what the rolling window method accounts for.

In our analysis, we compare the forecasting performance of the DCC model against the Rolling Window Correlation Model to evaluate whether the DCC model provides superior predictions of future asset correlations and portfolio optimizations.

3.5 Global Minimum Variance Portfolio Optimization

After documenting the statistical evidence for the diversification benefits of our sub-groups of REITs using a mean-variance spanning test, in this section, we choose the global minimum variance portfolio to evaluate and compare the economic values of the portfolios. We form dynamic portfolios consisting of the stock market index and our weighted REIT indices, one at a time, using both ex-ante and ex-post out-of-sample forecasts of variance-covariance matrix from the DCC and rolling window correlation models.

Built on Markowitz (1952)'s assumptions, modern investment theory assumes that investors are concerned solely with the mean and variance of the probability distribution of their portfolio return. Given this, we assume that portfolios providing minimum variance warrant consideration for investors. Hence, we use a mean-variance procedure to form portfolios.[11]

The classical optimization of the global minimum variance can be formulated as follows:

[11] Mean-variance procedures are special cases of the more general expected utility formulations. We justify the mean/variance procedure by assuming that all relevant probability distributions are same and that investors have a quadratic utility function; investors prefer more return to less. Levy and Markowitz (1979) shows that there is a very high probability that portfolios formed based on mean-variance criteria and maximizing the expected utility for a variety of utility functions would lead similar results.

$$\min_{w_{t,t+k}} \sigma^2_{p,x} = w'_{t,t+k} H_{t,t+k} w_{t,t+k}, \quad (16)$$

$$w'_{t,t+1}\mu = \mu_0,$$

$$\text{subject to } \sum_{i=1}^{N} w_{t,t+1} = 1,$$

where $i = 1, \ldots, m$ and $w_{t,t+k}$ is the vector of portfolio weights for time $t+1$ chosen at time t, $H_{t,t+k}$ is the conditional covariance matrix for time $t+1$ of returns, $r_{t,t+k}$ index log return from time t to time $t+k$, μ is assumed to be the vector of returns of risk-free assets, and finally $\mu_0 > 0$ is the required rate of return. Thus, the solution to Eq. 16 is:

$$w_{t,t+k} = \frac{H^{-1}_{t,t+k}\mu}{\mu' H^{-1}_{t,t+k}\mu}\mu_0,$$

where $w_{i,t+k}$ is an element of the optimized weight in vector $w_{t,t+k}$ and the portfolio share of asset i at time $t+k$ and $1 - \sum_{i=1}^{N} w_{i,t+k}$ is the share of risk-free asset in the portfolio. The corresponding portfolio return and variance are $w'_{t,t+k} r_{t,t+k}$ and $w'_{t+t+k} H_{t,t+k} w_{t,t+k}$, respectively. Coefficient k is equal to 0 for ex-post and 1 for ex-ante portfolio optimization.

We use a 5-year rolling window to forecast ex-ante covariances and then allocate the optimal weights based on this covariance matrix. Optimization uses the first five years (January 2000 to December 2004) to estimate coefficients. Therefore, we observe our REIT sub-groups' diversification behavior during and after the global financial crisis as we allocate our portfolio.

4 EMPIRICAL RESULTS

This section reports the empirical results from the mean-variance spanning test results and the analysis on ex-ante portfolio allocation in global minimum variance portfolio framework. However, we should note here that our portfolio allocation is different from traditional portfolio allocation. An investor who seeks to minimize the risk of their portfolio would generally diversify it by allocating the total capital among various financial securities, industries, and other categories. However, since our aim in this study is to investigate the relationship between the diversification power of REITs and their dividend payout policies, we limit the asset classes in our portfolio allocation to stock market and REITs only. We first create sub-groups of REITs based on their dividend payout ratios and add these sub-groups into the market portfolio. This way of portfolio setup can help us to identify the effect on the diversification benefits from the specified REIT sub-group, which is the main goal in this study. If dividend payouts are unrelated to REITs diversification benefits, then we should expect to see no significant change in the performance of the portfolio.

Generally, the findings of this study align with existing literature such as Burns and Epley (1982) and Sa-Aadu et al. (2010). That is, REITs expand the efficient frontier, which enhances portfolio efficiency. In addition, our research also introduces novel insights into REITs' role in portfolio diversification. This is, when dividend payout ratios are used to categorize REITs, the diversification benefits of these stocks vary. When using advanced forecasting models, such as the DCC model, high-dividend-paying REITs offer greater diversification benefits than low-dividend-paying REITs.

In detail, Pacholec (2022) demonstrated that certain REIT sectors consistently offered superior diversification benefits across different market conditions, and Badji et al. (2021) confirmed that sector-specific and sub-group diversification can provide varying levels of diversification benefits. We show that REIT subgroups, created by dividend payout ratios, also provide unique diversification benefits and that high-dividend-paying REITs perform better in providing diversification than low-dividend-paying REITs, adding another dimension to portfolio optimization. There are a number of studies arguing that certain sectors, like logistics and apartments, are better diversifiers than others, regardless of their dividend payout

policies. This study provides a new layer of insight into the characteristics that contribute to the diversification power of REITs.

Earlier studies such as Huang and Zhong (2013) and Fugazza et al. (2007) examined the diversification benefits of REITs using both ex-post and ex-ante portfolio models. Fugazza et al. (2007) found significant ex-post benefits when including REITs in portfolios. According to Huang and Zhong (2013), the 2008 financial crisis impacted REIT diversification. Using both ex-post and ex-ante models (rolling window correlation and DCC), we find that the DCC model consistently outperforms the rolling window model by generating portfolios with higher Sharpe ratios and lower standard deviations. Additionally, the study confirms that REITs' diversification benefits are dynamic, as they offered strong benefits pre- and during the 2008 financial crisis, but lost their diversification potential post-crisis. This echoes Huang and Zhong (2013)'s findings regarding financial crises' impact on asset diversification roles.

Our study provides a significant addition to the literature by showing that advanced forecasting models such as the DCC are not only superior to traditional methods at capturing time-varying correlations but also enhance portfolio performance. Its ability to produce better risk-adjusted returns and lower portfolio volatility aligns with the findings of Fugazza et al. (2007) regarding the importance of advanced modeling techniques. Furthermore, Marzuki and Newell (2021) found that REITs provided diversification benefits during the pandemic, despite higher volatility. Likewise, our study shows that REITs, particularly low-dividend-paying REITs, contributed significantly to diversification during the Covid-19 crisis.

4.1 Mean Variance Spanning Test Results

We use Huberman and Kandel (1987)'s Spanning Test to investigate equity REITs (test assets) diversification benefits for investors of the stock market (benchmark assets). By not allowing short selling, we aim to keep the focus on the shift in the efficient frontier purely for REIT related reasons and not capital market efficiencies or inefficiencies due to unobserved reasons.

To examine the diversification benefits over time, we divide our sample into four distinct sub-periods, using the onset and conclusion of the 2008 financial crisis as temporal benchmarks: pre-crisis, peri-crisis, and post-crisis. Additionally, we include the Covid-19 pandemic as a separate sub-sample. This sub-sampling approach is guided by existing literature, which emphasizes the importance of diversification benefits during recent financial crises.

We test the null hypothesis of spanning using asymptotic tests; Wald (W), likelihood ratio (LR), and the Lagrange multiplier (LM). The empirical test statistics of the spanning test at index and firm levels are given in Tab. 2 and 3. The columns in the table are reserved for benchmark assets. Our initial benchmark asset is the stock market index and cash, which is presented in the first three columns. Columns 4 through 6 assume that the benchmark assets are the stock market index, cash and an index representing low dividend- paying REITs while the test assets are high-dividend-paying REITs. Columns 7 through 9 assume that the benchmark assets are the stock market index, cash and an index representing high dividend-paying REITs while the test assets are low-dividend-paying REITs in this case. The rows of the table are reserved for the test assets of the spanning test. The first row of each panel in the table assumes that the test asset is an index representing all REITs in the country. The second and third rows of each panel in the table assumes that the test asset is an index representing high- and low-dividend-paying REITs.

4.1.1 Aggregate Index Level Spanning Test

We test whether the stock market investors can diversify their portfolio further by investing in an index of all REITs, or two indices of grouped REITs. Empirical results in Tab. 2 Panel A reports the full sample results. When all REITs are considered, the spanning test results show that the index representing all the REITs improves the efficient frontier when combined

Tab. 2: Mean-Variance Spanning Tests of REIT Portfolios at Index Level
This table presents the actual probabilities for the rejection of three asymptotic tests of spanning, Wald (W), likelihood ratio (LR), and Lagrange multiplier (LM), under the null hypothesis for different REIT groups. The asymptotic p-values of all three tests are set at 5% based on the asymptotic distribution of $\tilde{\chi}^2$ and actual p-values in brackets are based on their finite sample distributions under normality assumption.

	Equity			**Equity + Low REITs**			**Equity + High REITs**		
Test Assets	**W**	**LR**	**LM**	**W**	**LR**	**LM**	**W**	**LR**	**LM**
Panel A: Full Sample									
Index of All REITs	1301.36	834.63	24498.00						
	[0.000]	[0.000]	[0.000]						
Index of High REITs	121.03	115.60	27221.00	14.77	14.71	0.360			
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]			
Index of Low REITs	345.94	305.75	46308.00				21.68	21.53	0.092
	[0.000]	[0.000]	[0.000]				[0.000]	[0.000]	[0.762]
Panel B: Pre-2008 Financial Crisis									
Index of All REITs	153.73	110.78	1276.00						
	[0.000]	[0.000]	[0.259]						
Index of High REITs	147.96	127.07	22654.00	13.73	13.57	56002.00			
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]			
Index of Low REITs	17.39	45613.00	6036.00				1.66	1.66	52.212
	[0.000]	[0.000]	[0.014]				[0.198]	[0.197]	[0.000]
Panel C: Peri-2008 Financial Crisis									
Index of All REITs	119.82	74.45	2941.00						
	[0.000]	[0.000]	[0.086]						
Index of High REITs	28.68	45651.00	19.41	26.09	23.14	29.50			
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]			
Index of Low REITs	104.77	68.64	0.621				49.99	39.81	13.552
	[0.000]	[0.000]	[0.431]				[0.000]	[0.000]	[0.000]
Panel D: Post-2008 Financial Crisis									
Index of All REITs	437.98	322.19	0.031						
	[0.000]	[0.000]	[0.859]						
Index of High REITs	66.20	62704.00	15612.00	3.07	3.07	10.406			
	[0.000]	[0.000]	[0.000]	[0.080]	[0.079]	[0.001]			
Index of Low REITs	123.05	111.34	95694.00				2.54	2.54	24.78
	[0.000]	[0.000]	[0.000]				[0.111]	[0.111]	[0.000]
Panel E: Peri-Covid-19									
Index of All REITs	466.56	246.11	7104.00						
	[0.000]	[0.000]	[0.008]						
Index of High REITs	1999.00	45293.00	0.563	60.88	53.86	0.095			
	[0.157]	[0.156]	[0.453]	[0.000]	[0.000]	[0.758]			
Index of Low REITs	62.16	54.85	5538.00				77.14	66.16	2.049
	[0.000]	[0.000]	[0.168]				[0.000]	[0.000]	[0.152]

with the stock market index and cash. Further, we document that our sub-groups of REITs provide different diversification benefits. The index of both high- and low-dividend-paying US REITs provides diversification benefits to the US stock market investors in the full sample. The sub-group analysis also reports that the diversification potential of REITs is associated with REITs dividend policy. Moreover, the index of low-dividend-paying REITs (test assets) enhances portfolio diversification not only when combined with the stock market index and cash (benchmark assets) but also when included in portfolios alongside the stock market

index, cash, and the index of high-dividend-paying REITs (benchmark assets). Similarly, high-dividend-paying REITs (test assets) offer distinct diversification benefits when added to portfolios containing the stock market index, cash, and low-dividend-paying REITs (benchmark assets).

In the pre-2008 financial crisis period, as shown in Panel B, the equity REIT index, along with indices of sub-grouped REITs, has the potential to shift the efficient frontier. Our mean-variance spanning test results contribute to the existing literature by indicating that the U.S. REIT index offered diversification benefits during the 2008 global financial crisis, contrasting with the findings of Huang and Zhong (2013). Additionally, Panel D reveals that post-crisis, low-dividend-paying REITs gained in diversification potential. During the Covid-19 period, the index representing all REITs and low-dividend-paying REITs continued to provide diversification benefits for stock market investors, whereas high-dividend-paying REITs experienced a decline in their diversification effectiveness.

Our index level analysis makes several contributions to the literature. First, we identify that diversification produced by indices representing all REITs exist. We also document evidence at index level for the diversification benefits of a REIT sub-group. Empirical analyses indicate that the indices of low- and high-dividend- paying REITs have unique diversification benefits.

These results provide evidence that our REITs indices can contribute a different type of diversification when compared to the overall REIT index or to the other index of sub-grouped REITs. Moreover, during the 2008 financial crisis and the Covid-19 pandemic period, our REIT indices are an attractive asset class due to their diversification potentials. Our indices representing sub-groups of REITs are value-weighted, and can be considered as a portfolio of these firms with somehow fixed weights of REIT firms relative to market capitalization.[12] Assigning fixed weights to firms in a portfolio may not represent the most efficient approach to portfolio optimization. We posit that such a constraint could potentially reduce the diversification benefits within our REIT groups. Consequently, in the subsequent section, we will relax this restriction by allowing the covariance matrix of individual REIT firms to dictate the weighting of each REIT within the optimal portfolio. This approach will more accurately reflect the true diversification potential of individual REIT firms and the grouped REITs.

4.1.2 Individual Firm Level Spanning Test

We next test the diversification power of individual REITs in each sub-group. We test whether the stock market investors can diversify their portfolio further by investing in REITs, or two sub-groups REITs individually. Like the index level analysis in the previous section, our initial benchmark assets for the spanning test are the stock market index and cash while test assets in this case are individual REITs. Later, the test assets are REITs in low and high sub-groups.

Tab. 3 reports the evidence for firm level REIT diversification.[13] In Panel A, consistent with the findings at the index level, both aggregate REITs and segmented REIT sub-groups demonstrate diversification benefits for stock market investors, with the firm-level analysis showing even stronger significance. Furthermore, each REIT sub-group offers diversification advantages to stock market investors, regardless of the inclusion of the other REIT sub-group. Specifically, during the Covid-19 period, high-REITs also contribute to diversification at the firm level.

We argue that our sub-grouping of REITs does not just randomly divide REITs into different groups, but does so to give each REIT sub-group a unique diversification potential. If we assume that each group of REITs examined

[12] When REIT index level data is used in portfolio formation, the portfolio weight of each REIT in that specific group is forced to be related to its weight in the value-weighted index, which may not be the optimal weight for a REIT firm in the index.

[13] When portfolios are formed using firm level REIT data, the portfolio weight of each REIT is allowed to take any weight. Using firm level REIT data gives more flexibility in order to show the differential diversification power of REIT sub-groups.

Tab. 3: Mean-Variance Spanning Tests of REIT Portfolios at Firm Level
This table presents the actual probabilities for the rejection of three asymptotic tests of spanning, Wald (W), likelihood ratio (LR), and Lagrange multiplier (LM), under the null hypothesis for different REIT groups. The asymptotic p-values of all three tests are set at 5% based on the asymptotic distribution of $\tilde{\chi}^2$ and actual p-values reported in the table are based on their finite sample distributions under normality assumption.

	Equity			**Equity + Low REITs**			**Equity + High REITs**		
Test Assets	**W**	**LR**	**LM**	**W**	**LR**	**LM**	**W**	**LR**	**LM**
Panel A: Full Sample									
Index of All REITs	3897.96	1909.70	159.02						
	[0.000]	[0.000]	[0.716]						
Index of High REITs	2870.02	1617.5	142.58	5589.55	2271.1	148.73			
	[0.000]	[0.000]	[0.906]	[0.000]	[0.000]	[0.000]			
Index of Low REITs	3171.27	1692.2	159.12				5739.82	2279.7	179.36
	[0.000]	[0.000]	[0.216]				[0.000]	[0.000]	[0.032]
Panel B: Pre-2008 Financial Crisis									
Index of All REITs	739.97	494.63	95.224						
	[0.000]	[0.000]	[0.360]						
Index of High REITs	553.19	398.79	57.438	994.15	565.09	58.559			
	[0.000]	[0.000]	[0.878]	[0.000]	[0.000]	[0.854]			
Index of Low REITs	552.16	401.31	116.79				774.71	493.96	117.46
	[0.000]	[0.000]	[0.001]				[0.000]	[0.000]	[0.001]
Panel C: Peri-2008 Financial Crisis									
Index of All REITs	2097.27	532.29	78.412						
	[0.000]	[0.000]	[0.843]						
Index of High REITs	813.15	323.67	49.94	1791.02	406.64	54.878			
	[0.000]	[0.000]	[0.901]	[0.000]	[0.000]	[0.785]			
Index of Low REITs	1338.90	360.26	50.359				4143.49	480.66	52.142
	[0.000]	[0.000]	[0.721]				[0.000]	[0.000]	[0.658]
Panel D: Post-2008 Financial Crisis									
Index of All REITs	2124.35	1009.3	156.74						
	[0.000]	[0.000]	[0.296]						
Index of High REITs	1493.52	839.32	120.47	2628.65	1094.8	124.08			
	[0.000]	[0.000]	[0.827]	[0.080]	[0.000]	[0.759]			
Index of Low REITs	1757.69	892.35	141.18				3467.19	1208.00	119.82
	[0.000]	[0.000]	[0.081]				[0.000]	[0.000]	[0.462]
Panel E: Peri-Covid-19									
Index of All REITs	1228.99	734.8	157.85						
	[0.000]	[0.000]	[0.739]						
Index of High REITs	981.46	547.64	117.8	2922.28	764.41	110.58			
	[0.000]	[0.000]	[0.789]	[0.000]	[0.000]	[0.902]			
Index of Low REITs	1156.68	562.38	116.99				1767.36	645.69	124.44
	[0.000]	[0.000]	[0.659]				[0.000]	[0.000]	[0.152]

here are only a representation of the general REIT market, it is not a surprise to see that sub-groups of REITs provide diversification benefits to the stock market index investors, given that all REITs also provide diversification to the stock market index. However, columns 4 through 9 in Panel A in the table show that all sub-groups of REITs provide diversification to the stock market index as well as other sub-groups of REIT firms, confirming that each sub-group of REITs has its own unique diversification ability. This is an important finding that further supports the index level analysis. When investors are given the freedom to determine the allocation weights of each REIT firm, both categories of REITs demonstrate a unique and

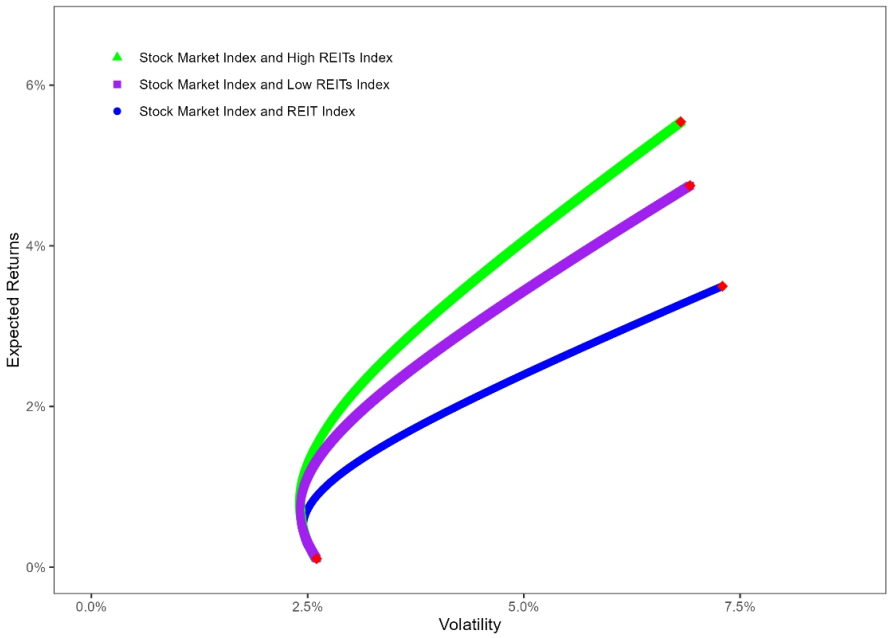

Fig. 1: Mean-Variance Efficient Frontier – Full Sample

statistically significant capacity to enhance the diversification of a stock market portfolio.

Panel B of Tab. 3 shows that the diversification potential of all REITs together and sub-grouped REITs is also highlighted in the pre-2008 financial crisis period. For all combinations of benchmark and test risky assets of equity market index and REIT indices, all three test statistics reject the null hypothesis of spanning, meaning that REIT diversification is present in this time period.

During the financial crisis period, Panel C of Tab. 3, the diversification potential of all individual REITs is consistent across the two sub-groups. High- and low-dividend-paying REITs continue being a good vehicle for diversifying a stock market portfolio. The diversification benefits of REITs are not limited by the choice of dividend payout policy when the US stock market index investors need it most. Furthermore, in the post-2008 global financial crisis period, Panel D, REITs continue to be a good source of diversification for stock market investors.

The analysis of our sub-groups of REIT firms across different sub-periods reveals that all individual REITs within these sub-groups contributed to diversification benefits relative to the stock market index before the financial crisis. However, following the crisis, only REITs characterized by high dividend payouts lost their diversification effectiveness within the portfolio that includes the stock market index, cash, and low-dividend-paying REITs.

We proceed by illustrating the impact of REIT sub-groups on the efficient frontier. Fig. 1 compares the efficient frontiers derived from the stock and REIT market indices and those from a combined stock market index with the index of REIT sub-groups. As shown in Panel A, the inclusion of REIT indices results in a notable alteration of the efficient frontier. Specifically, REIT sub-groups shift the efficient frontier upward, suggesting that investors can construct portfolios with higher expected returns for an equivalent level of risk. Notably, while the low-REITs index offers additional diversification advantages compared to the general REIT index, the high-REITs index provides the greatest

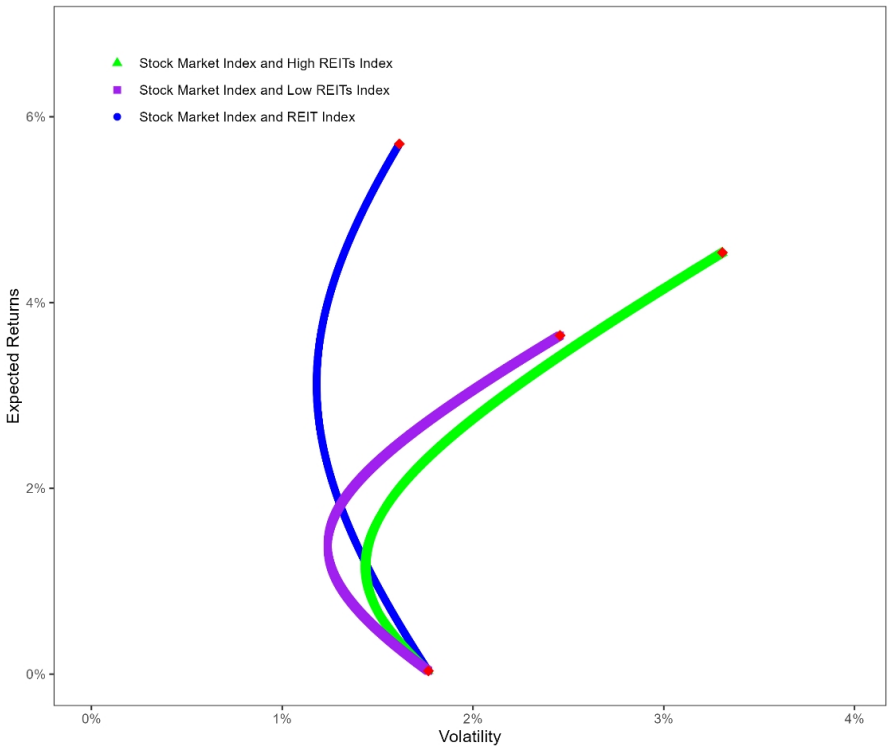

Fig. 2: Mean-Variance Efficient Frontier – Pre-2008 Financial Crisis Period

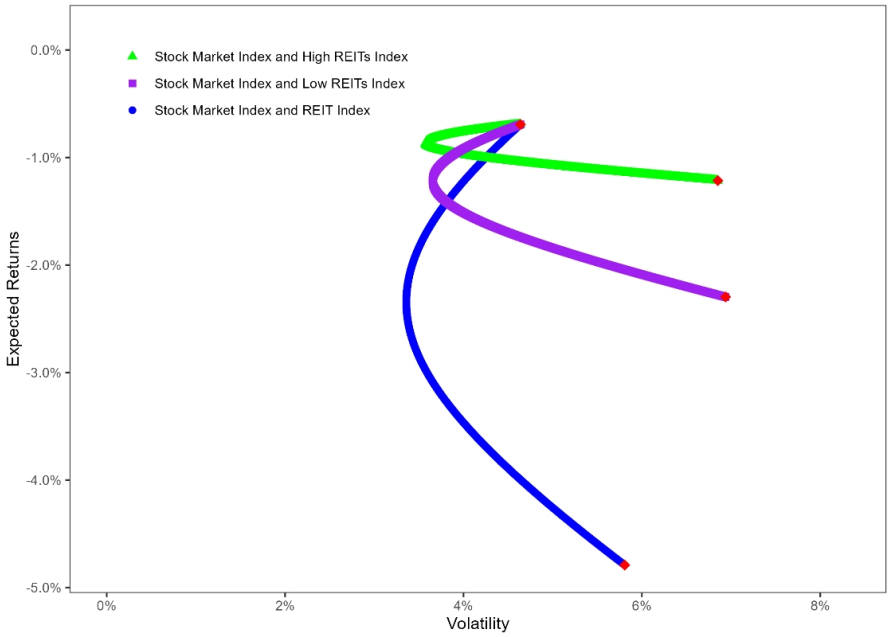

Fig. 3: Mean-Variance Efficient Frontier – Peri-2008 Financial Crisis Period

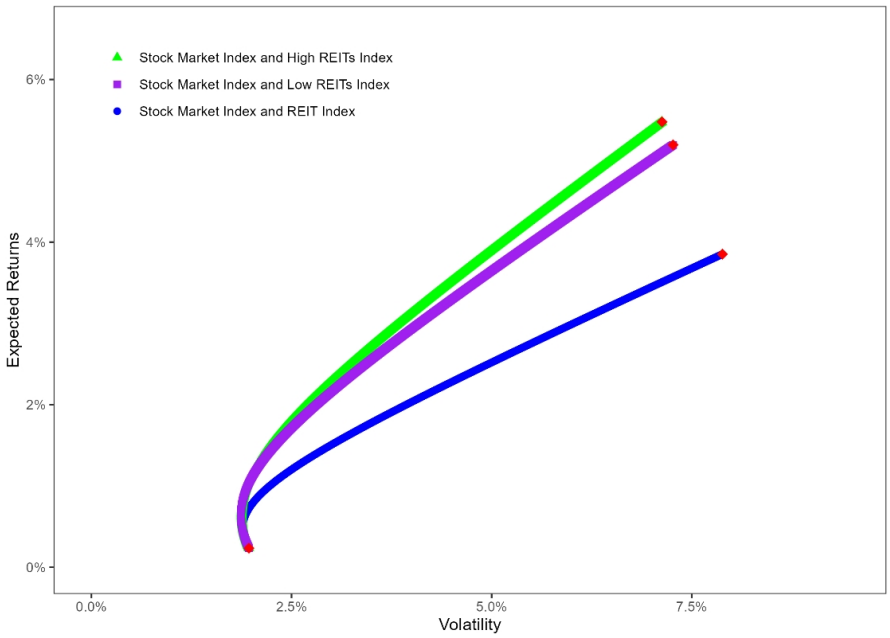

Fig. 4: Mean-Variance Efficient Frontier – Post-2008 Financial Crisis Period

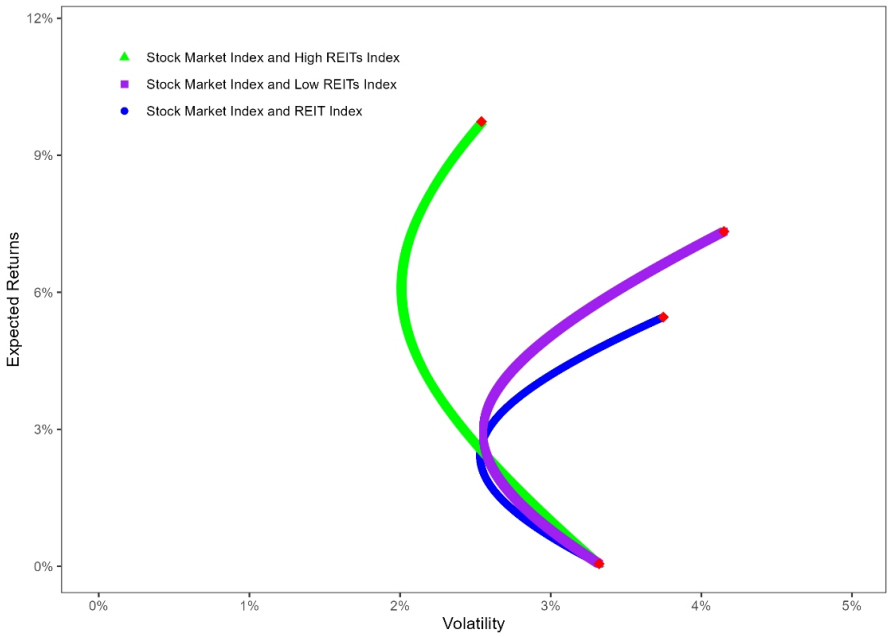

Fig. 5: Mean-Variance Efficient Frontier – Peri-Covid-19 Pandemic Period

diversification benefits. Panels B through E of Fig. 1 display the efficient frontiers for various sub-periods. The findings from the full sample analysis are corroborated across these sub-periods, demonstrating that each REIT sub-group continues to provide a unique level of diversification.

The results of the spanning tests indicate a shift in the efficient frontier at both the index and firm levels.[14] However, this shift appears to be statistically significant but does not necessarily translate into economically meaningful benefits. The figure only suggests that economic gains from portfolio optimization are achievable when considering either all REITs or specific REIT sub-groups.

An opposing viewpoint to our findings could argue that any inclusion of an asset class in a stock market portfolio is likely to enhance the efficient frontier, potentially attributing the improvements observed in this study to the idiosyncratic risk associated with REITs. However, the primary aim of this research is to assess whether the varying diversification benefits of REIT sub-groups, categorized by their dividend payout ratios, hold economic significance. Therefore, our analysis centers on the differences in efficient frontiers when distinct REIT sub-groups are integrated into the stock market portfolio.

Next, we present efficient frontiers of portfolios consisting the equity market index and REIT market indices. Fig. 1 through 5 report the efficient frontiers at index level for the full sample, pre-2008 financial crisis, peri-2008 financial crisis, post-2008 financial crisis, and peri-Covid-19 periods, respectively. Low REITs and High REITs represent indices of low-dividend paying and high-dividend paying REIT firms, respectively.

It is anticipated that the impact of idiosyncratic risk on the variations in efficient frontiers between portfolios comprising different REIT sub-groups is minimal. To further substantiate the economic advantages of diversifying with REIT sub-groups, we proceed to calculate the expected returns, standard deviations, and Sharpe ratios of these portfolios in the subsequent section.

4.2 Portfolio Allocation

Given the statistical and visual evidence of the diversification potential of REITs at both index and firm levels, our analysis points to the following conclusion: REITs provide diversification benefits and the diversification capacity is unique for each of the REITs sub-groups. However, whether these sub-groups actually diversify the stock market portfolio in a real-world portfolio optimization scenario is a question that requires further investigation. We next examine global minimum variance portfolios consisting the stock market index and our sub-grouped REIT indices or individual firms.[15]

Short-sales are not allowed since we optimize global minimum variance portfolios. Portfolios are optimized using ex-post estimates and ex-ante forecast of covariance matrix from two different models. We choose a traditional and comparatively simpler forecasting model (rolling window correlation model) and a more recent and more complicated model (DCC model) to forecast the covariance matrix to be used in portfolio optimization.

Our portfolio optimization starts at the beginning of 2005 because we use the first 5 years of the data to estimate the initial coefficients of the model necessary for both ex-post and ex-ante covariance matrix. We use a 5-year rolling window to estimate ex-post and forecast ex-ante covariance matrices at each point in time after the first estimation. Thus, we are able to document the diversification opportunities of REIT market at both index and firm levels for the period covering the 2008 financial crisis and its afterwards. Additionally, we have extended our analysis to explore the diversification potential during the recent Covid-19 pandemic.

This framework allows us to investigate the following research questions: Can REIT sub-

[14] Firm level efficient frontiers are not reported due to their similarity to the index level efficient frontiers.

[15] We excluded cash from portfolio allocation to further focus on REIT market's diversification potential. However, portfolios consisting of cash, in addition to the stock market and sub-grouped REITs produce qualitatively similar results.

groups provide ex-ante diversification benefits at index and firm levels? If so, which sub-group of REITs produces the most efficient global minimum variance portfolio? What is the function of the forecasting model? Specifically, does employing a more complex model yield benefit? Lastly, we examine whether the diversification advantages provided by our sub-grouped REITs remain stable over time and how they evolve during periods of economic downturns.

Using index and firm level data, Tab. 4 reports expected returns, standard deviations, and Sharpe ratios of portfolios of the stock market and REITs. Columns 1 and 2 of the table displays ex-post and ex-ante global minimum variance portfolio statistics using the rolling window correlation model. Columns 3 and 4 use the DCC model to optimize the portfolios in ex-post and ex-ante frameworks. Descriptive statistics of portfolios formed using REIT indices are reported in Panel A and the portfolios in Panel B are formed using individual REITs.

An important observation of the table is that considerable differences exist in expected returns/risk relationships of the portfolios consisting of different sub-groups of REITs. Panel A of the table presents the statistics for the global minimum variance portfolio utilizing index-level data, while Panel B provides these statistics based on firm-level data. According to the ex-post optimization with rolling window covariance forecasting model, a stock market portfolio that also includes the index of low-, and high- dividend-paying REITs would produce around 4.57%, and 4.85% annual expected return while the standard deviations for these portfolios is 16.78% and 16.64%. The DCC model expected returns on the portfolios are similar to that of rolling window correlation model, but standard deviations are smaller, 14.92% and 14.78%, respectively. Compared to the rolling window correlation model, the DCC model produces portfolios with smaller standard deviations, which points to superiority of the latter. The superior Sharpe ratios observed with the DCC model (0.42 compared to 0.35 for the rolling window model) underscore the enhanced performance and benefits of utilizing this approach. The results indicate that the REIT sub-indices formed based on dividend payouts have different diversification powers and the DCC model produces more efficient portfolios.

Further, we document that the index of high-dividend-paying REITs provides the largest diversification benefits; high-dividend-paying REIT indices have higher Sharpe ratios than low-dividend-paying REIT indices. The superiority of the index of high-dividend-paying REITs in portfolio optimization does not change when using the covariance matrix ex-post estimates or ex-ante forecasts from both models.

Panel B of Tab. 4 gives global minimum-portfolio statistics using firm level data. In accordance with our analysis using index level data, we observe similarities in the expected returns of portfolios consisting of the stock market index plus a REIT sub-index of low- or high-dividend-paying firms while standard deviations do change greatly between the two methods. The DCC model shows a higher Sharpe ratio (0.4292) compared to the rolling window model (0.3674). This suggests that including individual REIT firms, as opposed to REIT indices, under the DCC model, can enhance portfolio performance. The highest Sharpe ratio is observed in the portfolio of stock market index with high-dividend-paying REITs under the DCC model (0.5222), indicating that high REIT firms combined with stocks offer significant diversification benefits. In the portfolio of stock market index with low-dividend-paying REITs, the DCC model again performs better, with a Sharpe ratio of 0.5132, compared to 0.4178 in the rolling window model. This confirms the effectiveness of the DCC model in managing portfolios with low REITs.

The DCC model consistently outperforms the rolling window model across all scenarios, offering better risk-adjusted returns as evidenced by higher Sharpe ratios. This suggests that the DCC model's ability to dynamically adjust correlations results in more effective diversification and improved portfolio performance. Portfolios that include high-payout REITs tend to show better performance in terms of Sharpe ratios, particularly when using the DCC model.

Tab. 4: Global Minimum Variance Portfolio Statistics – Weekly Index and Firm Level Data
This table presents expected returns, standard deviations, and Sharpe ratios of global minimum variance portfolios consisting the stock market index and one of the two REIT indices based on their dividend payout policies; high-payers and low-payers. Index level portfolios are updated every week while firm level portfolios are updated every four weeks. In Rolling Window Correlation Model, no method is imposed on var-cov matrix while in DCC Model assumes the Dynamic Conditional Correlation Model. Ex-post results use information up until t in portfolio allocation and Ex-ante results use information until $t-1$. Short sales are not allowed.

	Random Walk Model		**DCC Model**	
	Ex-post	**Ex-ante**	**Ex-post**	**Ex-ante**
Panel A1: Portfolios with REIT Indices – Stock + Low REITs				
Expected Return	0.1159	0.1157	0.1159	0.1157
Standard Deviation	0.0022	0.0022	0.0001	0.0001
Sharpe Ratio	52.3090	52.2187	2931.5469	2930.5320
Panel A2: Portfolios with REIT Indices – Stock + High REITs				
Expected Return	0.0495	0.0493	0.0495	0.0493
Standard Deviation	0.0022	0.0022	0.0001	0.0001
Sharpe Ratio	22.4000	22.3100	1272.2300	1270.7300
Panel B1: Portfolios with REIT Firms – Stock + Low REITs				
Expected Return	0.0194	0.0192	0.0124	0.0123
Standard Deviation	0.1605	0.1606	0.1396	0.1391
Sharpe Ratio	0.0917	0.0912	0.0682	0.0677
Panel B2: Portfolios with REIT Firms – Stock + High REITs				
Expected Return	0.0179	0.0178	0.0205	0.0199
Standard Deviation	0.1664	0.1665	0.1326	0.1319
Sharpe Ratio	0.0799	0.0794	0.1087	0.1063

Overall, the table highlights the advantages of using the DCC model and using a sub-group of REITs based on their dividend payouts for constructing global minimum variance portfolios, particularly when dealing with assets like REITs with time-varying correlations.

Mean-variance efficient test statistics and efficient frontiers suggested that high-dividend-paying REITs expand the investment universe by providing extra diversification. The results on portfolio analysis presented Panel B of Tab. 4 confirm this finding when the DCC model is employed by producing higher Sharpe ratios for the portfolio with high REITs.

The portfolio allocation analysis concluded that each sub-groups of REITs provides a different diversification level. The DCC model produces portfolios of lower risk compared with rolling window correlation model. The performance of each model is similar in ex-post and ex-ante optimization. Portfolios with high-dividend-paying REITS offers the highest Sharpe ratios to stock market investors at both index and firm level analysis.

4.3 Time Varying Diversification Benefits Analysis

Using index and firm level data in the previous sections, we found that a portfolio containing high-dividend-paying REITs and the stock market index outperformed one that contained low-dividend-paying REITs. It is imperative to note that these empirical results are based on averages. This study provides a valuable opportunity to examine diversification benefits associated with our sub-groups of REITs over time. For a particular sub-group of REITs to be deemed superior in portfolio optimization, it must consistently outperform the other sub-group. Validating the persistence of diversification advantages of a REIT sub-group over time would further substantiate the practice of classifying REITs based on dividend payout ratios.

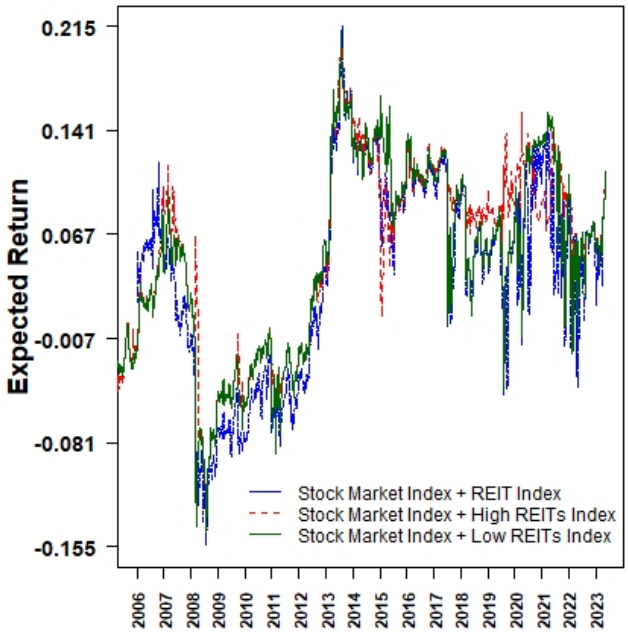

Fig. 6: Index Level Global Minimum Portfolio Ex-ante Time-Varying Expected Returns

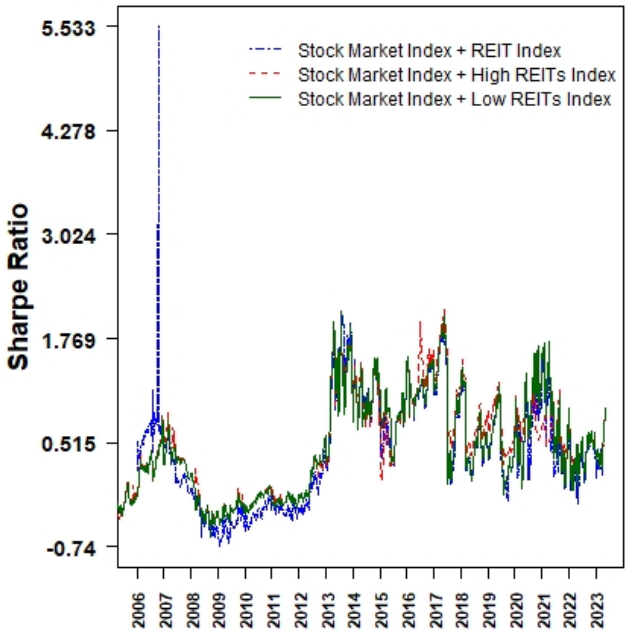

Fig. 7: Index Level Global Minimum Portfolio Ex-ante Time-Varying Sharpe Ratios

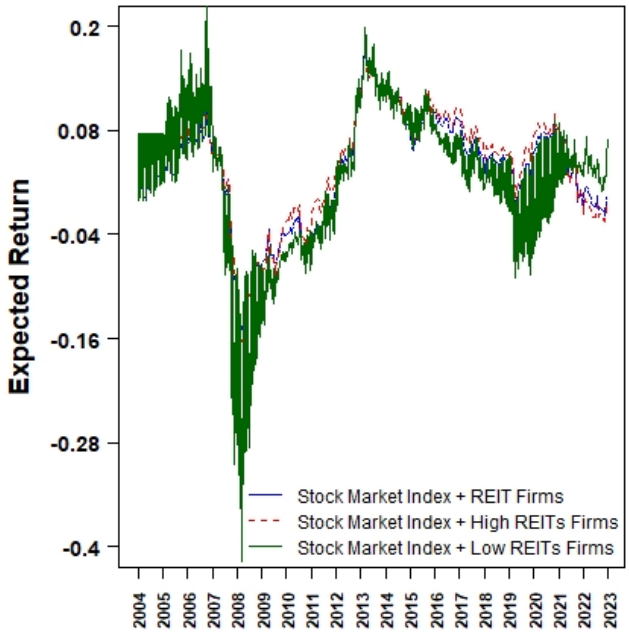

Fig. 8: Firm Level Global Minimum Portfolio Ex-ante Time-Varying Expected Returns

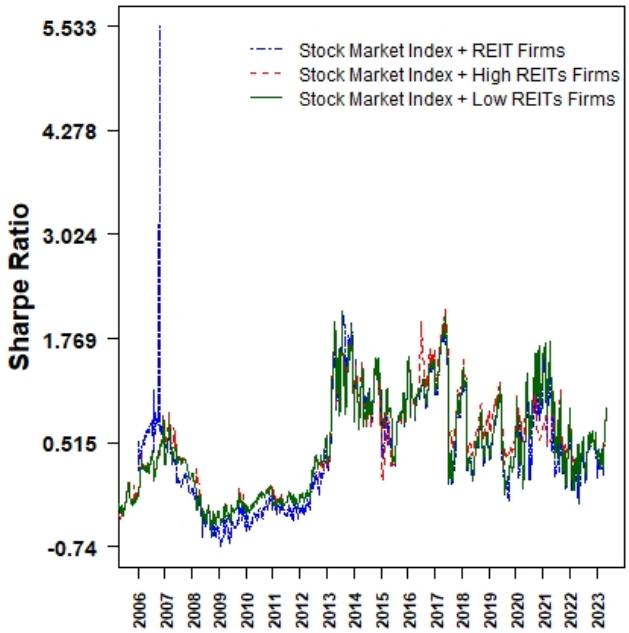

Fig. 9: Firm Level Global Minimum Portfolio Ex-ante Time-Varying Sharpe Ratio

Thus, we now examine the time-varying properties of portfolio optimization. Fig. 2 displays expected returns and Sharpe ratios of the portfolios optimized using ex-ante forecasts of the covariance matrix from the DCC model. Panels A and B display expected returns and Sharpe ratios of portfolios including indices of low- and high-dividend-paying REITs plus the stock market index from January 2005 to December 2022. At the index level portfolio optimization, high-dividend-paying REITs plus the stock market index portfolios have the higher expected returns and Sharpe ratios most of the time, which confirms our results in mean-variance spanning test and portfolio optimization analysis. In the firm-level optimization analysis, as illustrated in Panels C and D, the superior performance of high-dividend-paying REITs is evident. While the differences between portfolios of various REIT sub-groups may not be distinctly observable during certain brief periods, a careful examination reveals that high-dividend-paying REITs consistently deliver higher expected returns and Sharpe ratios during the 2008 financial crisis. Conversely, during the Covid-19 period, low-dividend-paying REITs exhibit higher expected returns and Sharpe ratios, corroborating the findings presented in Panel E of Tab. 2.

Next, we present figures of time-varying expected returns and Sharpe ratios of global minimum variance portfolios at index and firm levels. Forecasts of covariance are from the DCC model. Fig. 6 and 8 report the expected return on the portfolio of the stock market index and grouped REITs indices and firms. Fig. 7 and 9 represent the Sharpe ratios of the portfolio of the stock market index and grouped REITs indices and firms. Grouped REIT indices are weighted average of REITs based on their dividend payout ratio. Low REIT and High REIT represent low-dividend paying and high-dividend paying REITs, respectively.

5 CONCLUSION

The literature places great interest in understanding the diversification benefits and portfolio performance of an actively managed portfolio. Especially so, during a liquidity crisis when the market faces large shocks and investors need diversification the most. The majority of the studies examining REIT diversification potential and REIT performance in portfolio allocation are limited by in-sample analysis or use unrealistic methods such as ex-post covariance matrix estimates. We use two distinct models to empirically study the differential diversification power of REIT sub-groups formed using dividend payout ratios. The performance is measured before, during, and after the global financial crisis in 2008 and during the Covid-19 period to help understand diversification benefits over time.

Using index and firm level data at weekly frequency, we forecast ex-post and ex-ante variance-covariance matrices employing a rolling window correlation and a DCC model to test diversification benefits of REIT sub-groups formed based on dividend payout ratio. We use several methods to study the issue, including a regression-based mean- variance spanning test, mean-variance efficient frontiers, and an out-of-sample minimum variance portfolio allocation practice in ex-ante optimization framework.

The most important finding of the current study is that diversification benefits of the REIT market are affected by the dividend payout ratios of REITs. Not only do REITs expand the investment universe for the stock market index investors and provide more profitable or less risky portfolios, the diversification benefits vary directly according to REIT dividend policy. REITs sub-grouped by their dividend payout ratios offer different levels of diversification. Furthermore, these REIT sub-groups have the capacity to left-shift the efficient frontier of a market portfolio with or without the other sub-group of REITs.

The primary aim is to realistically test the diversification benefits of REITs and the role of dividend policy in diversification by using an

out-of-sample portfolio optimization with ex-ante variance-covariance matrix forecasts. In addition to confirming some of the empirical findings in the literature, the current study presents further evidence of the diversification power of REITs and its relationship with dividend policy. The contributions in this study allow new insights to academics, active portfolio managers, as well as REIT market regulators with respect to the relationship between REITs and the stock market and in turn the role of REITs in mixed-asset portfolios.

The inherent illiquidity of the real estate market makes it more suited for long-term investments. However, real estate market securities such as REITs have been developed to provide more liquid and stock-like securities to real estate market investors. Although REITs share similarities with general stocks, they are generally less liquid and the level of illiquidity can vary across different countries. Additionally, the 2008 global financial crisis demonstrated the severity of liquidity risks in the REIT market. As a result, one of the significant challenges faced by the real estate securities market is the need to create more liquid variations of these securities, gain access to more liquid markets such as the digital-securities market, or both.

It is recognized that the lack of liquidity in REITs could contribute to the low correlation between REITs and general stock market indices. However, we believe that any such correlation bias resulting from illiquidity would be uniform across all sub-groups of REIT-stock market index correlation pairs. The primary focus of the paper is to analyze the impact of dividend policy on dynamic correlations using ex-ante variance-covariance matrices based on both a rolling window correlation and a DCC model. This effect would still be present regardless of whether correlations may be downwardly biased or not.

The paper highlights numerous notable aspects, namely its novel methodology for analyzing the diversification advantages of REITs by classifying them according to dividend payout ratios. By utilizing both the Dynamic Conditional Correlation (DCC) model and a rolling window correlation approach, the paper provides a thorough analysis that accurately represents the changing nature of asset correlations throughout time. Adopting this dual-method approach strengthens the reliability of the results and enables a more profound comprehension of how different sub-groups of REITs contribute to diversifying investment portfolios throughout different economic eras, such as the 2008 global financial crisis and the Covid-19 pandemic. Moreover, the utilization of both ex-ante and ex-post optimization frameworks offers a comprehensive evaluation of portfolio performance in practical situations.

Our study complements existing research on REITs, while also pushing the boundaries of current scientific knowledge by focusing on dividend-based sub-groups and their distinct diversification benefits. By utilizing advanced forecasting models, our results highlight the importance of considering time-varying correlations when optimizing REIT-heavy portfolios. It adds new layers of understanding to the role of REITs in multi-asset portfolio optimization, reaffirming established findings.

Nevertheless, the study is not without limitations. An evident limitation is the dependence on past data, which could restrict the relevance of the conclusions to future market situations, particularly considering the fast-changing character of financial markets. Moreover, since the study only examines U.S. REITs, the findings may not be applicable to REITs in other countries subject to distinct legal and market conditions. One further constraint is the possible influence of liquidity limitations on the outcomes, especially during times of market distress. Although this issue is acknowledged, it remains a factor that could influence the observed diversification benefits. Finally, the study's classification of REITs based solely on dividend payout ratios, while innovative, may overlook other significant factors that influence REIT performance and investor behavior.

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SUBSTITUTION BETWEEN ACCRUAL AND REAL EARNINGS MANAGEMENT: IMPACT OF FIRM CHARACTERISTICS, AUDIT QUALITY, AND INSTITUTIONS

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ABSTRACT

We study the trade-off between real earnings management activities (REM) and accrual-based earnings management (AEM) among newly listed Vietnamese firms from 2009 to 2019. First, we found that firms exhibit REM as well as AEM around listing events to beat earnings targets. We further explore whether managers use REM and AEM as substitutes, considering both internal factors- firms' characteristics and external factors like audit quality and institutional environments. Our results indicate that companies employ a greater amount of AEM and less REM when they have a higher firm size, measured by total assets, experience higher levels of liquidity. Nevertheless, firms experiencing higher levels of cash flow from operating activities, net operating assets are more likely to engage in REM and but less likely to use AEM. However, when considering external factors including audit quality and institutional environments, there is limited evidence of a trade-off between the two methods. While audit quality appears to constrain only AEM, the corruption index has a negative impact on REM. Interestingly, consistent with previous studies, we also provide evidence that managers make adjustments to the level of accruals after the fiscal year-end based on the actual level of real earnings realized during the year.

KEY WORDS

real earnings management, accrual-based earnings management, trade-off, audit quality, institutional environments, firms' characteristics

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1 INTRODUCTION

Earnings management (EM) has been a key topic in accounting literature, focusing primarily on accrual-based earnings management (AEM) and more recently on real earnings management (REM) (Habib et al., 2022). Previous research has explored EM during events like IPOs and SEOs, showing that companies often manipulate earnings to boost firm value and stock prices. Similarly, firms seeking listing may engage in AEM or REM to meet listing

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requirements and create positive investor expectations. Understanding the trade-off between AEM and REM is crucial for evaluating their impact around listing events.

According to Zang (2012), managers switch between the two types of EM based on the comparative cost involved. Recent studies focus primarily on internal factors, particularly firm characteristics, to explain the substitution between AEM and REM. Various internal factors are likely to influence managers' choice in favor of EM methods (Anagnostopoulou and Tsekrekos, 2017; Bassiouny, 2016; Jang and Kim, 2017), despite mixed results.

In addition to internal factors, the decision to employ one of the two methods of EM is likely to be influenced by external factors such as audit quality and institutional environments. Scholars suggest that auditors possess mechanisms that enable them to scrutinize REM and AEM. However, the evidence about the effect of audit quality on these two types of EM remains inconclusive. Futhermore, the choice between AEM and REM is also influenced by the institutional environments of a country. Differences in institutional characteristics lead to varying motivations for firms to select between these two methods of earnings management (Braam et al., 2015; Gao et al., 2017). For instance, Cohen et al. (2008) found that firms shifted from AEM to REM after the enactment of the SOX. On the other hand, Gao et al. (2017) argued that frequent government intervention and varying legal environments across provinces influence Chinese firms' EM decisions. These studies have mainly focused on audit quality or institutional environments as external regulatory mechanisms for constraining EM methods without considering a combined analysis of both factors. Therefore, research on external factors and earnings management should include a comprehensive investigation of the combination of both factors.

Following prior studies, this study aims to investigate whether firms use both types of EM around listing and to examine the impact of internal factors (i.e., firm characteristics) and external factors like audit quality and institutional environments on firm behavior in choosing between REM and AEM. Our study contributes to ongoing research on EM in several ways.

First, our research is conducted in the context of the Vietnamese market, which exhibits several unique features distinguishing it from other countries, as detailed below. Unlike other Asian markets where stock exchanges operate as private or joint-stock companies—Vietnam's exchanges remain state-owned and government-regulated. Despite this, the market faces persistent challenges, including weak policies, a complex legal framework, low transparency, poor regulatory coordination, and issues like market manipulation and herd behavior (Duong, 2023). According to Goncharov and Zimmermann (2007), the legal system and accounting standards influence EM by offering varying accounting flexibility. In Vietnam, the government-led, rules-based system—based on outdated IAS/IFRS through the Vietnam Accounting Standards (VAS)—enforces rigid, uniform policies that often misalign economic substance with accounting treatment, creating opportunities for EM (Duong, 2025). Finally, in developed markets, the IPO-to-listing gap is typically short—ranging from 5 to 70 days (Boubaker et al., 2017)—but in Vietnam, it is often longer due to stricter and separate processes. This raises concerns about earnings management (EM) during listings, which we aim to examine.

Second, unlike previous studies that typically use one method to measure EM, this study extends the literature by considering both REM and AEM as substitutes for managing earnings.

Finally, our study adds to the literature by jointly considering internal factors (firm characteristics) and external ones (audit quality and institutional environments) that influence managers' trade-offs between REM and AEM. While the impact of institutional environments on EM is well-documented at the cross-country level, little is known at the local level. To address this gap, we evaluate institutional environments at the provincial level—a novel approach in the existing literature.

The rest of this research is structured as follows: Section 2 contains the literature review and hypothesis development. Section 3 presents the sample and research design. Section 4 reports the main empirical results. Section 5 presents the discussion, and Section 6 concludes and discusses the implications of the study's key findings.

2 RELATED LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

2.1 REM and AEM Around Corporate Events

Agency theory suggests income smoothing can be achieved through accounting discretion or manipulating real activities. Recent studies have shifted the focus from AEM to REM, examining the likelihood of managers distorting earnings by manipulating real transactions around corporate events. For instance, Li (2019), Cohen et al. (2020), Roychowdhury (2006) provided compelling evidence of using REM by altering the level of discretionary expenses, including research and development expenses, as well as expenses related to sales, administration, general operations, or overproduction.

Previous studies on EM have mostly focused on only one type of EM, neglecting other types that are likely to occur (Cohen et al., 2008). Few studies have considered both AEM and REM (Boulhaga et al., 2022), with the main emphasis on IPOs and SEOs, while limited attention has been given to listing events. Unlike developed markets, in certain contexts like Vietnam, listings and IPOs are separate procedures, with listing regulations being stricter compared to IPO regulations (Nguyen and Duong, 2021). Furthermore, the actual listing date occurs considerably later than the issue date.

Given the techniques of EM, as discussed in the literature review, firms are likely to employ a combination of EM methods around equity events. Hence, managers can utilize REM or AEM to meet their target around the listing event. Considering the points mentioned above, the first hypothesis is:

H_1: *Newly listed firms exhibit evidence of both REM and AEM.*

2.2 The Role of Internal Factors – Firm Characteristics in Constraining AEM and REM

EM is a crucial component of strategic decision-making, executed through company operations and accounting policies. Consequently, firm characteristics play a significant role in influencing EM, as they can act as constraints. These characteristics are vital to understanding how and why companies engage in EM.

Firm Characteristics and AEM

Regarding firm size, the agency theory suggests that larger firms may have stronger internal control systems and better oversight of their transactions, which could potentially prevent them from manipulating earnings. Some authors, such as Bassiouny (2016) and Ashiq et al. (2022) found that larger firms may possess stronger internal control systems, better control over their transactions, and a deeper understanding of their activities than small firms. Therefore, this likely prevents large firms from manipulating earnings. A study conducted by Aburisheh et al. (2022) found an insignificant correlation between firm size and AEM, the studies conducted by Bassiouny (2016) identified a positive relationship between firm size and AEM driven by increased capital market pressure and the bargaining power of large firms.

Leverage, or a firm's use of debt to finance operations, has been studied in relation to earnings manipulation, particularly to meet debt covenant obligations. While some studies suggest that firms engage in income-boosting to reduce the risk of covenant breaches, the relationship between leverage and AEM remains mixed. Rodríguez-Pérez and van Hem-

men (2010) found a negative correlation between AEM and leverage, while other studies Ashiq et al. (2022) and Rakshit et al. (2021) found no significant relationship. Research also examines factors like firm age, liquidity, cash flow from operating activities (CFO), and financial health, with inconsistent findings. Some studies (Jang and Kim, 2017; Li, 2019; Rakshit and Paul, 2020; Zang, 2012) report a negative correlation between CFO and AEM, while others Andreas (2017) found a positive correlation.

Firm Characteristics and REM

Research on the impact of firm characteristics on REM is growing, but it remains somewhat limited and open to debate. For example, Hoang and Nguyen (2018) demonstrated that large firms tend to have better-designed internal control systems than small firms, reducing the level of REM. Conversely, Roychowdhury (2006) argued that firm size mainly acts as a control variable, as it is positively correlated with REM. Additionally, when the firm characteristics are measured by age, Gul et al. (2009) concluded that firms with a long history are likely to have more experience in corporate governance and are exposed to greater reputational risks. As a result, managers in these firms would be more conservative in manipulating REM. However, the opposite was found in the research by Hoang and Nguyen (2018).

The Trade-Off between REM and AEM in Connection with Firm Characteristics

The argument is that managers may consider both REM and AEM to achieve their targets. Investigating each type of EM individually is insufficient to fully capture their overall impact (Pappas, 2015). Research on AEM and REM concerning firm characteristics has been undertaken. Authors argue that managers balance between REM and AEM by considering their respective costs, and they adjust the extent of AEM in response to the level of REM employed (Zang, 2012). The investigation into the trade-off between REM and AEM has been extended by identifying a range of firm characteristics that explain the cost of the two methods. For example, firm size has also been used as a control proxy for a trade-off between AEM and REM in the studies by Zang (2012). Moreover, the impact of leverage on AEM-REM substitution has been explored in a study of Anagnostopoulou and Tsekrekos (2017). Authors discovered a positive influence of financial leverage on a company's upward real earnings but no significant impact on income-increasing accrual earnings. In contrast, Awuye and Aubert (2022) found that leverage only constrains AEM, and firms with a high level of leverage tend to switch to REM.

The relative use of AEM and REM also depends on the flexibility of the accounting systems within firms (Cohen and Zarowin, 2010; Gao et al., 2017; Owusu et al., 2022; Zang, 2012). Due to constraints imposed by accounting regulations and the reversal of accruals, the flexibility to manipulate accruals earnings in the current period is limited by the accruals utilized in previous periods. Net operating assets at the beginning of the year can be used as a substitute to measure the degree of accrual management in preceding periods. Furthermore, it is supposed that companies with longer operating cycles tend to possess greater flexibility in reversing accruals. Subsequently, operating cycles are used to measure firms' accounting flexibility. Both net operating assets and operating cycles serve as indicators of companies' accounting system flexibility. They should be considered as measures of the relative costliness of the two types of EM in the study.

Existing research indicates that REM and AEM are influenced by ownership structure. According to the agency theory, managers of state-owned enterprises may lack motivation to improve earnings quality due to easier access to capital (Ding et al., 2007; Gaio and Pinto, 2018). According to Zang (2012) and Roychowdhury (2006), ownership structure tends to impose greater constraints and scrutiny over REM compared to AEM. Therefore, when institutional ownership is high, firms are more likely to employ the AEM strategy over REM.

Previous studies have two main gaps. First, the trade-off between REM and AEM has not been thoroughly understood, as most studies

focused on specific firm characteristics without considering a comprehensive set of internal control variables. Second, there is a lack of comprehensive research on the trade-off between AEM and REM around listing events. This leads to the following hypothesis:

H_2: *Other things being equal, the relative degree of AEM versus REM is associated with the firm's characteristics.*

2.3 The Role of External Factors in Constraining AEM and REM

2.3.1 The Role of Audit Quality in Constraining AEM and REM

According to agency theory, external auditors act as monitoring devices to help shareholders obtain reliable data and minimize information asymmetry in a company's reporting. This, in turn, reduces conflicts between stockholders and managers. Additionally, signaling theory suggests that hiring a reputable auditor serves as a positive signal to potential investors about a company's true value when issuing stocks to the market.

Audit Quality and AEM

Many studies have found a negative association between auditor size, as measured by Big N, and AEM in various contexts, including the United States (Francis and Yu, 2009) and European countries (Alhadab and Clacher, 2018). However, some scholars, such as Duong (2023); Habbash and Alghamdi (2017), have found that the presence of Big N does not mitigate AEM. Furthermore, there has been a growing scholarly emphasis on auditor tenure (Carlin et al., 2015). Previous studies argue that auditor tenure is a characteristic of audit quality. The authors suggest that the length of time the audit firm has been engaged with the client may potentially influence the quality of the audit. However, the findings of studies in this area have led to mixed conclusions.

Audit Quality and REM

Notable studies by Chi et al. (2011) and Cohen and Zarowin (2010) revealed that a higher level of REM is significantly associated with audit quality. Similarly, Choi et al. (2018) concluded that Big 4 auditors constrain not only AEM but also REM. Interestingly, Alhadab and Clacher (2018) found that audit quality does not constrain all forms of EM in the IPO year.

While ample evidence exists of the association between audit quality and AEM, fewer studies have explored how audit quality affects REM. Moreover, according to Zang (2012), audit quality can impact the trade-off between AEM and REM. Therefore, further research is needed to understand the role of audit quality in constraining both types of EM. Consequently, the third hypothesis will be examined accordingly:

H_3: *Other things being equal, the relative degree of AEM versus REM is associated with audit quality.*

2.3.2 The Role of Institutional Environments in Constraining AEM and REM

Stakeholder theory suggests companies can succeed by effectively managing their relationships with key stakeholders. The characteristics of stakeholders are influenced by the diverse institutional environments across different countries. Scholars have made numerous efforts to develop alternative measures to understand these institutions, such as examining legal environment changes, corruption control levels, and political connections.

With a study conducted in 30 countries, Braam et al. (2015) concluded that firms with political connections have a higher probability of substituting AEM for REM compared to firms without political affiliations. The authors also concluded that political connections significantly influence REM and AEM decisions. Recently, Chen et al. (2020) indicated that firms in provinces with lower GDP growth rates than the national or neighboring provinces are more likely to participate in REM. Based on the concept of power distance, Halabi et al. (2019) documented a positive relationship between power distance, religiosity, and REM. The study also supported the idea that REM is seen as more ethical and justifiable than engaging in AEM.

Institutional environments are often evaluated based on the levels of corruption. According to Kimbro (2002), countries with better legislation, a more efficient legal system, a higher concentration of accountants, and high-quality financial statement standards tend to have lower levels of corruption. Moreover, González and García-Meca (2014) found that AEM is expected to be higher in countries with higher levels of corruption. Additionally, Lourenço et al. (2020) suggested that the perception of corruption is associated with greater motivations for firms in emerging economies to manipulate earnings, although this effect is not observed in developed countries. In the context of mergers and acquisitions from the European area, Christopoulos et al. (2023) provided compelling evidence to show a positive correlation between corruption and AEM but a negative correlation between corruption and REM.

Briefly, the review of the EM literature indicates that although the impact of institutional environments on EM at the cross-country level is widely documented, there is limited understanding of the association between EM and institutional environments at the local level. From the aforementioned works, it is worth noting that there are few studies investigating the impact of institutional environments on both types of EM within a growing economy, particularly at the provincial level. To contribute to the literature, our study aimed to assess the institutional environments measured by the corruption index at the provincial level, which has not been done in previous studies.

H_4: *Other things being equal, the relative degree of AEM versus REM is associated with institutional environments.*

Finally, Zang (2012) and Gao et al. (2017) supposed that at the end of an accounting period, firms can still manipulate discretionary accruals by adopting accounting methods or estimates. However, REM involves actual changes in business activities that occur within the financial year. The extent of AEM depends on the unexpected degree of REM undertaken during the year. Companies can observe the impact of REM on earnings at the end of the fiscal year and then offset an unexpected impact by using AEM. Therefore, AEM is undertaken after unexpected REM. Our predictions are as follows:

H_5: *Firms adjust the amount of AEM after realizing REM. The degree of AEM is inversely related to the unexpected degree of REM.*

3 METHODOLOGY AND DATA

3.1 Data Collection

This study's sample includes all firms listed on HOSE between 2009 and 2019. It examines the trade-off between REM and AEM during listing events over four years (the year before listing, the listing year, and the two subsequent years).

The data for estimating EM, firm characteristics, and audit quality was obtained from all firms listed on HOSE's annual reports and financial statements. The data was sourced from two open-source databases: HOSE and FIINGROUP Vietnam. Financial statements from the preceding two years were collected to estimate REM and AEM in the year before listing. Banks and financial institutions were excluded due to their different reporting criteria. After removing those firms, the final dataset consists of 888 observations for 222 firm-years in eight sectors: industrials, energy, consumer staples, consumer discretionarymaterials, real estate, utilities, and health care.

Moreover, data on the corruption index were collected from the annual Provincial Competitiveness Index (PCI) report issued by the Vietnam Chamber of Commerce and Industry (VCCI portal `https://pcivietnam.vn/en/publications`).

3.2 Measuring the Variables

3.2.1 EM Measurement

Real Activities Manipulation (REM)

REM involves making a range of operational decisions throughout the year. Based on a study conducted by Roychowdhury (2006), this research examines three types of REM, including expediting sales timing, managing production costs, and controlling discretionary expenses.

The first type, which accelerates sales timing, is estimated by the abnormal level of cash flow from operations. We rely on the study of Roychowdhury (2006) and Cohen and Zarowin (2010) to show that normal CFO levels can be represented as a linear equation involving sales and the change in sales, as follows:

$$\frac{\text{CFO}_{it}}{A_{i,t-1}} = \alpha_0 + \alpha_1 \frac{1}{A_{i,t-1}} + \alpha_2 \frac{\text{REV}_{it}}{A_{i,t-1}} + \alpha_3 \frac{\Delta\text{REV}_{it}}{A_{i,t-1}} + \epsilon_{it}, \quad (1)$$

where CFO_{it} is net cash flows from operating activities of firm i in year t; REV_{it} is sales of firm i in year t; ΔREV_{it} is the disparity in sales between year $t-1$ and year t of firm i; $A_{i,t-1}$ is total assets of firm i in year $t-1$; α_0 is a constant; α_1, α_2, α_3 are the coefficients of regression; ϵ_{it} is the error term.

The abnormal CFO is estimated as the difference between the actual CFO and the normal level of CFO calculated using the estimated coefficient from Eq. 1.

The second type, discretionary expenses, can be represented as a linear equation involving sales, as shown in the following equation:

$$\frac{\text{DISX}_{it}}{A_{i,t-1}} = \alpha_0 + \alpha_1 \frac{1}{A_{i,t-1}} + \alpha_2 \frac{\text{REV}_{i,t-1}}{A_{i,t-1}} + \epsilon_{it}, \quad (2)$$

where DISX_{it} is the discretionary expenditures (comprising advertising and administrative expenses) of firm i in year t. The abnormal discretionary expenses (DISX) are calculated as the disparity between the actual values and the predicted normal levels derived from Eq. 2.

The third type, production costs, is measured as the total cost of goods sold and inventory changes, as calculated using the following Eq. 3:

$$\frac{\text{PROD}_{it}}{A_{i,t-1}} = \alpha_0 + \alpha_1 \frac{1}{A_{i,t-1}} + \alpha_2 \frac{\text{REV}_{it}}{A_{i,t-1}} + \alpha_3 \frac{\Delta\text{REV}_{it}}{A_{i,t-1}} + \alpha_4 \frac{\Delta\text{REV}_{i,t-1}}{A_{i,t-1}} + \epsilon_{it}, \quad (3)$$

where PROD_{it} is the total cost of goods sold and the inventory changes from $t-1$ to t of firm i. The abnormal production costs (PROD) are estimated as the difference between the actual values and the normal levels predicted from Eq. 3; $\Delta\text{REV}_{i,t-1}$ is the disparity in sales between year $t-2$ and year $t-1$ of firm i.

To fully capture the impact of REM, we create comprehensive REM metrics by combining three proxy variables. In accordance with Gao et al. (2017) and Li (2019), we multiply abnormal discretionary expenses and cash by -1 and then sum these values.

Accruals Earnings Management (AEM)

Total accruals are divided into long and current accruals. Changes in the balances of current liability accounts and current asset accounts reflect current accruals, which are the most manipulated in EM. Moreover, in Vietnam context and around listing events, by using four models with total accruals-based and current accruals-based to measure EM, Nguyen and Duong (2021) concluded that when Vietnamese firms prepare for listing events, they tend to focus on boosting their prior-year earnings. They do this by using current accruals rather than total accrual models. In line with prior research in the literature review, this study employs discretionary current accruals (DCA) to measure EM (Nguyen and Duong, 2021; Duong, 2023; Teoh et al., 1998), which are examined using the equation below:

Current Accruals Model

$$\frac{\mathrm{CA}_{it}}{A_{i,\frac{t-1+t}{2}}} = \alpha_0 + \alpha_1 \frac{1}{A_{i,\frac{t-1+t}{2}}} + \\ + \alpha_2 \frac{\Delta\mathrm{REV}_{it}}{A_{i,\frac{t-1+t}{2}}} + \epsilon_{it}, \tag{4}$$

$$\mathrm{NDCA}_{it} = \alpha_0 + \alpha_1 \frac{1}{A_{i,\frac{t-1+t}{2}}} + \\ + \alpha_2 \frac{\Delta\mathrm{REV}_{it} - \Delta\mathrm{TR}_{it}}{A_{i,\frac{t-1+t}{2}}}, \tag{5}$$

$$\mathrm{DCA}_{it} = \frac{\mathrm{CA}_{it}}{A_{i,\frac{t-1+t}{2}}} - \mathrm{NDCA}_{it}, \tag{6}$$

Current Accruals Measurement

$$\mathrm{CA}_{it} = \Delta\mathrm{CAsset}_{it} - \Delta\mathrm{Cash}_{it} - \\ - \Delta\mathrm{CL}_{it} + \Delta\mathrm{STD}_{it}, \tag{7}$$

where:

- CA_{it} is the current accruals of firm i in year t;
- NDCA_{it} is the nondiscretionary current accruals of firm i in year t;
- DCA_{it} is the discretionary current accruals of firm i in year t;
- $\Delta\mathrm{CAsset}_{it}$ is the change in current assets of firm i between year $t-1$ and year t;
- $\Delta\mathrm{Cash}_{it}$ is the change in cash and cash equivalent of firm i between year $t-1$ and year t;
- $\Delta\mathrm{CL}_{it}$ is the change in current liabilities of firm i between year $t-1$ and year t;
- $\Delta\mathrm{STD}_{it}$ is the change in debt included in current liabilities of firm i between year $t-1$ and year t;
- $\Delta\mathrm{TR}_{it}$ is the change in trade receivables of firm i between year $t-1$ and year t;
- $A_{i,\frac{t-1+t}{2}}$ is the average of beginning and end of year total asset of firm i in year t.

3.2.2 Independent Variable

In line with previous studies, this study focuses on the primary indicators of firm financial characteristics, including state-owned, firm size, financial leverage, liquidity, age, net operating assets, operating cycle, and Z-score as a measure of financial health.

State ($\mathrm{State}_{i,t}$) is a dummy variable equal to 1 if firm i in year t has any state ownership, and 0 otherwise (Ding et al., 2007; Gaio and Pinto, 2018; Wang and Yung, 2011).

Firm size ($\mathrm{Size}_{i,t}$) is represented by the log of total assets of firm i in year t (Ashiq et al., 2022; Bassiouny, 2016; Zang, 2012).

Firm leverage ($\mathrm{Lev}_{i,t}$) is the amount of debt in the firm's capital structure, while firm liquidity ($\mathrm{Liq}_{i,t}$) is the value of current assets divided by current liabilities of firm i in year t (Awuye and Aubert, 2022).

Firm age ($\mathrm{Age}_{i,t}$) is firm age of firm i in year t (Jang and Kim, 2017; Rakshit and Paul, 2020).

NOA ($\mathrm{NOA}_{i,t-1}$) is the net operating assets of firm i in year $t-1$, calculated as the sum of shareholders' equity (excluding cash and marketable securities) and total debt, divided by lagged sales.

Cash flow from operation ($\mathrm{CFO}_{i,t}$) is net cash flows from operations scaled by total assets of firm i in year t.

Firm's operating cycle ($\mathrm{Operating}_{i,t-1}$) is calculated as the total of days receivable and days inventory minus the days payable at the beginning of the year (Gao et al., 2017; Owusu et al., 2022; Zang, 2012).

Firm financial health ($\mathrm{Zscore}_{i,t-1}$) is measured using a modified version of Altman's Z-score for firm i in year t (Altman, 2000; Luu, 2023; Rusmin et al., 2024; Zang, 2012).

Big 4 ($\mathrm{Big4}_{i,t}$) is assigned a value of 1 if the auditor is from the Big 4 and 0 otherwise. Auditor tenure ($\mathrm{Tenure}_{i,t}$) is the number of consecutive years the auditing firm has been engaged with firm i in year t (Duong, 2023; Zang, 2012).

The corruption index ($\mathrm{Corrup}_{i,t}$) measures the amount of bribes paid by firms to provincial officials. It is derived from surveys conducted across all 63 provinces by the Vietnam Chamber of Commerce and Industry (VCCI) in collaboration with the United States Agency for International Development (USAID). Firms operating in different provinces are considered, and the indicator is normalized to a ten-point scale, with the highest-performing provinces receiving a score of 10 and the lowest-performing ones receiving a score of 1.

3.3 Model Specification

This study used three models by running Panel Data Regression using Stata 17. To determine the appropriate estimation approach for panel data, we begin by conducting the Breusch-Pagan Lagrangian Multiplier (LM) test (Breusch and Pagan, 1980). A significant result suggests that a panel regression model is preferred over pooled OLS. We then estimate both fixed effects (FE) and random effects (RE) models. To choose between them, the Hausman test is applied (Hausman, 1978). If the null hypothesis is rejected, it indicates that the random effects model may yield inconsistent estimates due to correlation between individual effects and the regressors. In such cases, the fixed effects model is deemed more appropriate.

Model 1:
REM and AEM Around Corporate Events

In the first hypothesis, the investigation begins with the application the parametric t-test to evaluate whether the means REM and AEM significantly deviate from zero. Moreover, Gao et al. (2017); Li (2019) indicate that firms are inclined to manipulate earnings to meet key financial benchmarks, especially around corporate events. Zang (2012) contributes to this discussion by identifying critical earnings benchmarks that firms strive to meet, including the preceding year's earnings, the analyst consensus forecast (plan) earnings, and a specific threshold of zero earnings. Zero earnings are defined as earnings before extraordinary items divided by lagged assets, with a value range between 0 and 0.005 (Roychowdhury, 2006). Consequently, this study classifies as suspects of Earnings Management (EM) those firms whose earnings closely meet these benchmarks.

Continuing to the second stage, a model of suspected firms has been utilized to determine whether companies use AEM or REM to inflate their earnings. For this purpose, the following logit model is adopted to explain EM suspect firms.

$$\begin{aligned}\text{logit}\,(\text{suspect}_{i,t}) = \quad & (8)\\ \text{logit}\,(&\beta_0 + \beta_1\,\text{AEM}_{i,t} + \\ &+ \beta_2\,\text{REM}_{i,t} + \beta_3\,\text{Zscore}_{i,t-1} + \\ &+ \beta_4\,\text{State}_{i,t} + \beta_5\,\text{Big4}_{i,t} + \\ &+ \beta_6\,\text{Tenure}_{i,t} + \beta_7\,\text{NOA}_{i,t-1} + \\ &+ \beta_8\,\text{Operating}_{i,t-1} + \beta_9\,\text{CFO}_{i,t} + \\ &+ \beta_{10}\,\text{Age}_{i,t} + \beta_{11}\,\text{Size}_{i,t} + \\ &+ \beta_{12}\,\text{Lev}_{i,t} + \beta_{13}\,\text{Liq}_{i,t} + \\ &+ \beta_{14}\,\text{Corrupt}_{i,t}),\end{aligned}$$

where Logit $(\text{suspect}_{i,t})$ refers to the likelihood that firm i in year t is suspected of meeting earnings benchmarks. It equals one (1) if the firm meets the earnings benchmark and zero (0) otherwise. Suspect 1 refers to firms that just beat the consensus forecast (planned earnings), Suspect 2 refers to firms that just beat the previous year's earnings, and Suspect 3 refers to firms that just beat zero earnings. Suspect all earnings benchmarks is an indicator variable that equals one (1) if the firm-year just meets one of the earnings benchmarks and zero (0) if it misses all benchmarks. $\text{AEM}_{i,t}$ is accruals discretionary of firm i in year t, the proxy for accrual-based EM. $\text{REM}_{i,t}$ is aggregated the real activities manipulation of firm i in year t, measured into one proxy, taking their sum.

Model 2 and Model 3:
A Trade-Off between REM and AEM

$$\begin{aligned}\text{REM}_{i,t} = \gamma_0 &+ \gamma_1\,\text{Zscore}_{i,t-1} + \quad (9)\\ &+ \gamma_2\,\text{State}_{i,t} + \gamma_3\,\text{Big4}_{i,t} + \\ &+ \gamma_4\,\text{Tenure}_{i,t} + \\ &+ \gamma_5\,\text{NOA}_{i,t-1} + \\ &+ \gamma_6\,\text{Operating}_{i,t-1} + \\ &+ \gamma_7\,\text{CFO}_{i,t} + \gamma_8\,\text{Age}_{i,t} + \\ &+ \gamma_9\,\text{Size}_{i,t} + \gamma_{10}\,\text{Lev}_{i,t} + \\ &+ \gamma_{11}\,\text{Liq}_{i,t} + \gamma_{12}\,\text{Corrup}_{i,t} + \\ &+ \text{Year}_i + \epsilon_{it}\end{aligned}$$

$$\begin{aligned} \text{AEM}_{i,t} = {} & \delta_0 + \delta_1\, \text{Zscore}_{i,t-1} + \\ & + \delta_2\, \text{State}_{i,t} + \delta_3\, \text{Big4}_{i,t} + \\ & + \delta_4\, \text{Tenure}_{i,t} + \\ & + \delta_5\, \text{NOA}_{i,t-1} + \\ & + \delta_6\, \text{Operating}_{i,t-1} + \\ & + \delta_7\, \text{CFO}_{i,t} + \delta_8\, \text{Age}_{i,t} + \\ & + \delta_9\, \text{Size}_{i,t} + \delta_{10}\, \text{Lev}_{i,t} + \\ & + \delta_{11}\, \text{Liq}_{i,t} + \delta_{12}\, \text{Corrup}_{i,t} + \\ & + \text{Year}_i + \\ & + \text{UnexpectedREM}_{i,t} + \epsilon_{it}, \end{aligned} \tag{10}$$

where Year_i listing year dummy variables to control the year effect. $\text{UnexpectedREM}_{i,t}$ is the level of AEM is affected by an unexpected level of REM (Gao et al., 2017; Zang, 2012). Therefore, the unexpected REM has been incorporated into Eq. 10, estimated as the residual from Eq. 9.

For Models 2 and 3, following panel model selection, the Modified Wald test is employed to detect heteroskedasticity, and robust standard errors are applied where necessary. Given the firm-specific nature of EM and the panel structure (222 firms over four years), clustering by firm accounts for within-firm correlation and unobserved heterogeneity. The final models incorporate all diagnostic tests and use cluster-adjusted standard errors. Additionally, the existence of outliers, which are data points that differ significantly from others, can lead to important changes in substantive conclusions regarding relationships among variables (Aguinis et al., 2013). To identify influential observations on all regression coefficients as a whole, Cook's Distance must be predicted from models to explore sensitivity to exclude outliers. Accordingly, to reduce the impact of extreme values (outliers), specific observations were eliminated from the dataset.

4 RESULTS

Tab. 1: Descriptive Statistics

Variables	Mean	Median	Std Dev	25%	75%
REM	0.1082	0.1000	0.5217	−0.1047	0.3043
AEM	0.0262	0.0128	0.1969	−0.0764	0.1170
Zscore	2.4016	1.9080	1.7804	1.0978	2.9926
State	0.3930	0.0000			
Big4	0.2207	0.0000			
Tenure	3.0440	3.0000	1.8357	1.0000	4.0000
NOA	0.6625	0.6763	0.2001	0.5120	0.8232
Operating	369.0000	197.6630	500.0000	108.6810	336.0483
CFO	1.36e+11	3.43e+10	4.10e+11	−2.28e+10	1.65e+11
Age	16.7173	13.0000	11.1017	8.0000	24.0000
Size	9.0640	8.9851	0.5413	8.6640	9.3644
Lev	1.4084	1.1669	1.1032	0.5279	2.0205
Liq	2.0852	1.5129	1.4992	1.1444	2.3563
Corrup	5.9649	5.9400	0.9842	5.1600	6.6700
Suspect 1	0.5259	1.0000			
Suspect 2	0.3671	0.0000			
Suspect 3	0.8063	1.0000			
Suspect all earnings benchmarks	0.8569	1.0000			

Tab. 2: Pearson Correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1) REM	1											
(2) AEM	−0.27***	1										
(3) Zscore	0.23***	0.01	1									
(4) Tenure	0.03	−0.08**	−0.06*	1								
(5) NOA	0.02	−0.10***	0.19***	0.02	1							
(6) Operating	−0.20***	0.03	−0.32***	0.05	−0.13***	1						
(7) CFO	0.22***	−0.18***	−0.08**	0.20***	−0.01	−0.14***	1					
(8) Age	0.08**	−0.06*	0.02	0.03	−0.21***	−0.18***	0.09***	1				
(9) Size	−0.09**	0.04	−0.39***	0.23***	−0.20***	0.13***	0.50***	0.04	1			
(10) Lev	−0.21***	0.04	−0.42***	−0.03	−0.27***	0.11***	−0.02	0.10***	0.34***	1		
(11) Liq	0.04	0.09***	0.50***	0.03	0.13***	0.10***	−0.10***	−0.13***	−0.31***	−0.50***	1	
(12) Corrup	−0.07*	−0.07**	0.03	0.03	0.10***	0.08**	−0.11***	−0.06*	−0.15***	0.05	−0.01	1

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Tab. 3: Results for Testing H_1 (Discretionary Accruals and Real Earnings Management)

	Mean	Q1	Median	Q3	Std
AEM	0.0262***	−0.0764	0.0128	0.1170	0.1969
REM	0.1082***	−0.1047	0.1000	0.3044	0.5218

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

4.1 Descriptive Statistics

Tab. 1 presents the descriptive Statistics of all variables. According to Altman (2000) in the revised model, a score below 1.23 indicates high financial distress. The sample has a Z-score of 2.4016 at the 50th percentile, which exceeds the 1.23 cutoff for financial distress, suggesting that most firms in the sample exhibit strong financial health.

Regarding state ownership, the average state ownership in our sample is 39.3 percent. In terms of auditor quality, the mean value for firms audited by one of the Big Four is 0.2207, indicating that a Big Four firm audited 22.07% of the sample firms. Additionally, the average auditor tenure suggests that sample firms have maintained a partnership with their auditors for over three years. The mean of Net Operating Assets (NOA) is 0.6625, and at the 25th percentile, NOA is 0.5120, indicating that firms have net operating assets exceeding half of their total assets. Similarly, firms have an average operating cycle of 369 days, an average age of 16.7 years, a leverage ratio of 1.4, and a corruption index of 5.96.

Tab. 2 presents the Pearson correlation coefficients among the variables analyzed in the main tests. The table indicates a significant negative correlation between REM and AEM. Overall, the correlation matrix does not indicate any significant issues with multicollinearity.

4.2 Empirical Results

4.2.1 REM and AEM Around Listing

Tab. 3 presents the descriptive statistics for the EM variables. As shown in Tab. 3, the means, medians, and third quartiles (Q3) for both AEM and REM are positive. This study uses two-tailed t-test to determine whether the means of AEM and REM differ significantly from zero (0). The results in Tab. 3 demonstrate that the means of AEM and REM are statistically significantly different from zero at the 1% level.

Tab. 4 illustrates the estimation results for the conditional fixed-effects logistic regression of suspect firms. Only in the Suspect 3 model (zero earnings benchmark) do both AEM and REM show a positive relationship which is significant at the 10% level. In contrast, in the models of suspects just beating plan earnings, beating last year's earnings, and beating all earnings benchmarks, the coefficients for suspects are significant and positive for either REM or AEM, but not both. These findings

Tab. 4: Estimation Results for the Conditional Fixed-Effect Logit Model of Suspect Firms

Variables	Suspect 1 (forecast consensus)	Suspect 2 (last-year earnings)	Suspect 3 (zero earnings)	Suspect all earnings benchmarks
AEM	0.6394**	0.3485	0.8374**	0.7443**
	(0.2820)	(0.3975)	(0.3733)	(0.3159)
REM	0.1179	0.4146**	0.3745**	−0.0042
	(0.1782)	(0.2025)	(0.1639)	(0.1691)
Zscore	0.1173*	−0.4626***	0.0309	0.0204
	(0.0669)	(0.1133)	(0.0395)	(0.0448)
State	0.2838**	−0.0194	0.0316	0.0351
	(0.1447)	(0.1755)	(0.0942)	(0.0618)
Big4	0.1149	0.0187	0.1673	−0.0665
	(0.1650)	(0.1934)	(0.1518)	(0.1037)
Tenure	0.0170	−0.0199	0.0131	0.0316
	(0.0465)	(0.0575)	(0.0386)	(0.0323)
NOA	−1.6096***	0.1897	−2.4886***	−0.7713*
	(0.6114)	(0.6941)	(0.8037)	(0.4502)
Operating cycle	−0.0001	0.0015***	0.0002	0.0001
	(0.0002)	(0.0003)	(0.0001)	(0.0001)
CFO	3.39e−13**	0.0000***	0.0000***	0.0000*
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Age	−0.0913*	−0.3376***	−0.3076***	−0.1108***
	(0.0515)	(0.0638)	(0.0543)	(0.0286)
Size	−3.4005***	−1.4461**	−0.7402	−0.7002***
	(0.5634)	(0.5879)	(0.5313)	(0.2545)
Lev	0.2675**	−0.1202	−0.3394***	−0.0657
	(0.1223)	(0.1377)	(0.1252)	(0.0672)
Liq	0.1847**	0.2576***	0.0693	0.0645
	(0.0836)	(0.0975)	(0.0614)	(0.0529)
Corrup	−0.1207	−0.4527***	0.1399*	−0.1090*
	(0.0882)	(0.1247)	(0.0826)	(0.0581)
Prob	0.0000	0.0000	(0.0000)	(0.0000)
N	614	728	302	238

Notes: Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

which are consistent with prior research support the prediction that firms have a stronger incentive to manipulate their earnings upward by using different types of earnings management, particularly around the time of listing and when beating their earnings targets. In conclusion, H_1 is supported, and the results provide evidence of EM behavior among Vietnamese firms during the study period. Interestingly, the results from the four models indicate that firms tend to use one type of EM rather than both. The choice between these two types of EM will be addressed in the next section of the study.

4.2.2 REM and AEM Trade-Off

Firm Characteristics in Constraining AEM and REM

Hypothesis H_2 predicts that the relative use of AEM versus REM is influenced by a firm's characteristics. In the REM model, the coefficients for size and liquidity are negative and statistically significant. In contrast, the AEM model shows positive coefficients for these two factors, which are significant at the 1% and 5% levels. The negative coefficient for size in the REM model indicates that firms with larger assets have less flexibility for REM, leading

them to rely more on AEM. Likewise, liquidity also shows negative coefficients, supporting that higher financial liquidity makes REM costlier. As a result, firms may prefer AEM to reduce the risk of being detected by current and potential creditors.

Tab. 5: The Real and Accrual-Based EM

Variables	**REM Equation (Model 2)**	**AEM Equation (Model 3)**
Zscore	0.0064	0.0165**
	(0.0147)	(0.0067)
State	0.0575***	−0.0151
	(0.0211)	(0.0138)
Big4	0.0232	−0.0294*
	(0.0286)	(0.0175)
Tenure	−0.0023	−0.0018
	(0.0080)	(0.0051)
NOA	0.1684*	−0.3787***
	(0.1010)	(0.0661)
Operating	3.17e−06	0.0000
	(0.0000)	(0.0000)
CFO	2.74e−13***	−1.39e−13***
	(0.0000)	(0.0000)
Age	0.0004	−0.0157
	(0.0235)	(0.0113)
Size	−0.3439***	0.1448**
	(0.1108)	(0.0580)
Lev	−0.0175	−0.0018
	(0.0221)	(0.0170)
Liq	−0.0229*	0.0275***
	(0.0133)	(0.0088)
Corrup	−0.0512***	0.0014
	(0.0165)	(0.0093)
Year dummies	controlled	controlled
Unexpected REM		−0.0354***
		(0.0117)
_cons	3.3632***	−0.8221
	(1.0756)	(0.5568)
N	849	841
adj. R^2	0.1600	0.1960
Breusch and Pagan Lagrangian test (Prob > chibar2)	0.0000	0.0024
Hausman test (Prob > chi2)	0.0006	0.0220

Notes: All values in the above table are reported after excluding outliers; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Conversely, the CFO and NOA exhibit positive coefficients in the REM model and negative coefficients in the AEM model. This indicates that when AEM becomes more costly due to higher cash flows or greater net operating assets, firms are more likely to resort to real manipulation. Moreover, state-ownership firms are more likely to manipulate earnings through REM rather than AEM.

In summary, the partial of hypothesis H_2 is accepted, indicating that the trade-off between REM and AEM is influenced by certain firm characteristics, such as net operating assets (NOA), cash flow from operations (CFO), size, and liquidity (liq).

Audit Quality and Institutional Environments in Constraining AEM and REM

The results do not provide sufficient evidence to support the assertion that REM increases with the involvement of Big 4 auditors or with longer auditor tenure. In contrast, the findings indicate that AEM is negatively associated with Big 4 auditors at the 10% significance level.

Tab. 5 demonstrates that while the institutional environment shows insignificant results in the AEM equation, it significantly impacts the REM model. The findings reveal a relationship between institutional environments and earnings management, indicating that REM is constrained by the level of corruption indicated by the corruption index.

Unexpected Degree of REM and AEM

Hypothesis H_5 predicts that the level of AEM is engaged after REM is realized. It can be inferred that if the REM turns out unexpectedly low during the year, managers may increase the use of accruals through various accounting methods. As a result, there is a negative correlation between AEM and unexpected REM. The coefficients from this study reveal a negative and statistically significant relationship between the level of AEM and the amount of unexpected REM at the 1% level. These findings suggest that firms adjust their level of AEM following the realization of REM during the period.

5 DISCUSSION

5.1 EM Around Listing Events

While previous studies have been conducted around SEO and IPO events in developed countries—where the lag between IPO and listing is typically measured in days—this study is conducted in Vietnam, a stock market where the time between IPO and listing can be significantly longer, often extending to several years. The findings are consistent with those of (Cohen et al., 2008; Cohen and Zarowin, 2010; Gunny, 2010; Li, 2019; Zang, 2012), showing that, in addition to AEM, firms also employ REM as a tool for EM around listing events to achieve certain profit benchmarks to meet listing conditions and create excessively optimistic investor expectations.

5.2 REM and AEM Trade-Off

In line with studies conducted in developed country markets and consistent with agency theory and positive accounting theory, this study, conducted in the Vietnamese market—with its distinct listing regulations, government-influenced accounting standards, and taxation policies—shows that the tendency of Vietnamese firms to make trade-off decisions is influenced by costs and varies across different contexts.

Firm Characteristics in Constraining AEM and REM

Around listing events, firms with higher liquidity and larger total assets tend to employ more AEM and less REM. This implies that firms with extensive assets have greater flexibility and a higher degree of subjective judgment regarding their estimates, allowing them to enhance accrual earnings. The outcomes from testing H_2 show that firms with higher levels of current financial liquidity are more likely to use AEM to minimize the risk of detection by current and potential creditors, supporting conclusions drawn by Rakshit and Paul (2020) and Pappas (2015). Additionally, liquidity ratios represent a company's financial status, incorporating current assets and liabilities. AEM involves manipulating financial reports through current accruals, such as accounts receivable, accounts payable, inventory, accrued liabilities, or current expenses. Firms with higher liquidity ratios can effectively utilize short-term assets and liabilities, enabling easier adjustments to short-term accruals. In other words, companies with high liquidity levels tend to rely more on current accruals, thereby reducing the need for REM.

Conversely, the CFO and NOA exhibit positive coefficients in the REM model and negative coefficients in the AEM model. This indicates that when AEM becomes more costly due to higher cash flows or greater net operating assets, firms are more likely to resort to real manipulation. This finding contrasts with the result observed by Li (2019) but aligns with the result generated by Yoon and Miller (2002), suggesting that CFO may serve as an indicator of a firm's productivity and efficiency. Therefore, if firms have lower levels of CFO or NOA, management is more likely to engage in REM to enhance financial performance, and vice versa. Moreover, state-ownership firms are more likely to manipulate earnings through REM rather than AEM. This finding aligns with the research conducted by Tran and Dang (2021) in Vietnam and Wang and Yung (2011) in China, which suggests that state-owned enterprises manage earnings less through accruals than privately owned enterprises.

Audit Quality and Institutional Environments in Constraining AEM and REM

The findings regarding audit quality align with established agency theory and signaling theory, as well as empirical evidence, indicating that REM is more likely to remain undetected, while AEM is typically constrained by audits from Big Four accounting firms. This is consistent with the research of Zang (2012) in the US and Rusmin (2010) in Singapore and Owusu et al. (2022) in the UK, suggesting that auditor quality can mitigate AEM but not REM. This finding is consistent with the research of Al-

hadab and Clacher (2018), indicating that audit quality is insufficient to fully restrain all forms of EM. Consequently, it does not influence the trade-off between AEM and REM, as it affects only one type of earnings management, leading to the rejection of hypothesis H_3.

Regarding the impact of the institutional environment on EM, while most previous research primarily focuses on country-level effects, this study examines the institutional environment as measured by the corruption index, using province-level characteristics. The findings indicate that higher levels of corruption are linked to a lower incentive for managers to enhance real earnings. However, this relationship is not observed in the accrual earnings model. It can be inferred that a reduced level of informal charges—petty corruption paid by firms—can lead to decreased expenses, resulting in lower levels of real earnings activities. These results, which differ from those previously concluded by Braam et al. (2015), suggest that institutional environments do not influence the trade-off between REM and AEM, providing no support for hypothesis H_4. Instead, this study finds that the corruption index serves to mitigate REM. In economies with high levels of corruption, managers are more likely to engage in manipulating operating activities rather than focusing on accruals.

Finally, the findings show a direct substitutive relation between REM and AEM. The degree of the AEM is negatively correlated with the level of unexpected REM realized during the year. The finding is consistent with previous research conducted by Cohen et al. (2008), Cohen and Zarowin (2010), Zang (2012) and Gao et al. (2017), implying that managers adjust accruals after the fiscal year-end based on the results of prior REM during the period, supporting the view that these two strategies are executed sequentially.

5.3 Limitations and Future Research

Despite the overall strength of this study, its findings should be viewed within the context of the following limitations. Firstly, this study is based on a sample of listed firms in Vietnam, so its findings may not be applicable to other contexts. Moreover, this study is limited by the lack of data before listing, with a maximum timeframe of ten years, and the sample is restricted to newly listed firms on HOSE, affecting generalizability. Additionally, endogeneity is present in the earnings management (EM) analysis. Although alternative measures and robust methods were used, endogeneity may still impact results. Future research should extend the timeframe, incorporate dynamic endogeneity with lag periods, and include data from all listed firms in Vietnam to address these limitations and enhance validity. Caution is advised in interpreting the results due to these constraints.

6 CONCLUSIONS

In conclusion, this study provides empirical evidence on how firms engage in both types of EM and how they make trade-offs between AEM and REM based on firm characteristics, audit quality, and the institutional environment in relation to listing events over four years.

Our study contributes to the existing literature in the following ways. First, unlike prior studies that use a single measure of EM, this study extends the literature by treating REM and AEM as substitutes. Around the listing event, firms appear motivated to use either method to meet listing requirements and foster overly optimistic investor expectations. Second, while prior studies focus on firm characteristics and a single type of EM, this study examines their influence on both AEM and REM using a broad set of controls. The findings show that trade-off decisions between AEM and REM are shaped by firm size, liquidity, CFO, and net operating assets (NOA). Specifically, firms with greater liquidity and assets favor AEM, whereas those with higher CFO and NOA rely more on REM. Third, considering external factors like audit quality and institutional environment, limited trade-off between AEM and REM is

observed. Audit quality restricts only AEM, while the corruption index negatively affects REM. Finally, the study suggests that firms adjust their accrual level at year-end based on the level of REM realized throughout the year. These findings are consistent with the sequential nature of these two activities.

Implications

For Investors: Investors should be cautious of earnings manipulation (AEM and REM) around listing events, especially in new firms. Larger, more liquid companies tend to use accrual-based manipulation, while firms with lower CFO or NOA favor real earnings management. Careful financial analysis is essential, as Big 4-audited firms typically show less AEM.

For Auditors: Firms on the Ho Chi Minh Stock Exchange may use REM and AEM to meet listing profits. Auditors should understand these models and scrutinize short-term items like receivables and revenue, especially in state-owned firms with high CFO and NOA, which are more prone to REM.

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SOCIAL NETWORKS AND CONSPICUOUS FOOD CONSUMPTION: A COMPARATIVE STUDY AMONG GENERATIONS Z, X, AND Y IN THE CZECH REPUBLIC

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ABSTRACT

This study examines the links between conspicuous consumption and user activity on social media platforms, focusing on Generations Z, Y, and X. A set of statements focusing on conspicuous consumption, consumer behaviour on social media, and their food consumption habits was developed and tested on a sample of 679 respondents from the Czech Republic comprising these generations. Factor analysis was used to group tested statements into factors, and regression analysis was used to examine their association with salient consumption patterns. While the link between social media activity and conspicuous consumption was only confirmed for Generation X, the online behaviour of Generation Z, the confirmed influence of influencers on the purchasing behaviour of this generation, suggests a potential link that requires further investigation.

KEY WORDS

conspicuous consumption, social networks, comparison of generations, food consumption

JEL CODES

E210, M31, O32

1 INTRODUCTION

The nature of conspicuous consumption (CC) has been constantly developing due to changing conditions in society since Veblen's time. Besides high prices and luxury, through which consumption conspicuously demonstrates social status, other factors have been increasingly considered indicators of wealth and success. Such factors include personality, values, self-perception, and identity (Bronner and de Hoog, 2019; Chen et al., 2008; Nguyen and Tambyah, 2011). With the increasing presence of social media in daily life, conspicuous consumption has expanded to include various categories (Dinh et al., 2024; Shamu et al., 2024), including food, where consumer behaviour can visibly demonstrate social status and personal values (McDonnell, 2016).

BRENKUSOVÁ PAVELKOVÁ, Jana, TURČÍNKOVÁ, Jana, and ŠÁCHA, Jakub. 2025. Social Networks and Conspicuous Food Consumption: A Comparative Study Among Generations Z, X, and Y in the Czech Republic. *European Journal of Business Science and Technology,* 11 (1): 85–98. ISSN 2694-7161, DOI 10.11118/ejobsat.2025.004.

Given the importance of consumption visibility with respect to CC (Heffetz, 2011), then comes the question whether social networks and consumer behaviour presented there are also important elements influencing and enabling CC. Social networks have experienced turbulent development in recent years and are now part of the lives of more than just the youngest generations (Cheng and Li, 2014; Zareie et al., 2019). Due to this development, electronic word-of-mouth (eWOM) is also becoming increasingly important in purchasing behaviour (Kim and Ko, 2012). Here, the role of opinion leaders includes not only friends and family but also influencers (Berryman and Kavka, 2017; Reinikainen et al., 2021).

These influencers have close relationships with their followers and build trust through their content. Followers are then influenced by their opinions and may adapt their purchasing behaviour (Brown and Hayes, 2008; Freberg et al., 2011; Gundová and Cvoligová, 2019). The generations more open to such influence are mainly Generation Z, Generation Y, and partly Generation X, who grew up with digital technologies and encountered them during their youth when their personalities were formed (Kardes et al., 2015). Thus, the aim of this study is to explore how the nature of user behaviour on social networks, among other factors previously defined in literature, relates to the propensity for conspicuous consumption and if there are differences among the three analyzed generations Z, Y, and Y. Such findings can contribute not only to theory development but also to the marketing of business operations in the food industry since no papers with this focus both scientific and popular have been retrieved.

This research is focused on food and beverages as a product category. This is because food can have symbolic meaning when consumed and may represent a consumer's identity and lifestyle (Niva, 2006, 2007) as well as demonstrate his or her social status (Landström et al., 2009). Thus, foodstuffs can be an appropriate product for CC. The relationship between CC and functional foods was demonstrated, for example, by Barauskaitė et al. (2018) in their research. Photos of food are also often shared via social networks. Foodporn or 'foodstagramming' are increasingly common phenomena on social networks such as Instagram or SnapChat, which are driven by several motives as affective, expressive, and functional (Abril et al., 2022; Chang, 2022). Food was also chosen due to its affordability for all consumers and because it constitutes a significant item in consumers' expenditures – in the Czech Republic, it represents 23% of the total household budget spending (CZSO, 2022a).

2 LITERATURE REVIEW

Several influences affect consumers at once when they consume. In CC, the most important factor is the visibility of that consumption. It is an integral part of it, and through this consumption, a consumer wants to demonstrate or enhance his or her social status (O'Cass and McEwen, 2004; Heffetz, 2011).

2.1 Conspicuous Consumption – History and Trends

It was Thorstein Veblen who named and explored conspicuous consumption in his book The Theory of Leisure Class (1899). Since his time, however, the definition of CC has expanded. Whereas in the 1950s and 1960s, CC was primarily about the demonstration of wealth and comparison with immediate neighbours ("keeping up with the Joneses"), after the 1960s, the reference group was taken to be the upper middle class (Schor, 1999) or the socially situated upper class (Truong, 2010). Another element that helped develop CC was the development of mass media, where consumption became more sophisticated and involved more people with different socio-cultural backgrounds (Galbraith, 1987). Rapid economic development increased mobility, educational opportunities (Collins, 2000), and the development of new communication media, which

made consumption even more visible, showed the importance and need for further exploration of elements influencing CC (Patsiaouras, 2010).

Conspicuous consumption can be defined as "the behavioural tendency to value status and acquire and consume products that provide status to the individual." (O'Cass and McEwen, 2004, p. 10). In the past, CC was often confused with status consumption. These two types of consumption have a very strong positive mutual correlation. With status consumption, the consumer buys the product for the purpose of enjoyment in consumption, and with conspicuous consumption, it is for the purpose of presenting the consumption to others (O'Cass and McEwen, 2004; Riquelme et al., 2011). Several groups of factors are then associated with status consumption: status orientation, materialism, self-perception, consumption ethnocentrism (Nguyen and Tambyah, 2011), and susceptibility to interpersonal influences (Riquelme et al., 2011).

In the context of 21st-century CC, it is necessary to consider not only consumer characteristics such as the consumer's income group and gender (O'Cass, 2001; Açıkalın et al., 2009). According to Chen et al. (2008), on the one hand, CC is a means of presenting one's own wealth; on the other hand, the intangible symbolism of the products consumed, such as romantic efforts to impress a partner, also plays a role (Griskevicius et al., 2007). The product used as conspicuous could also symbolize the identity, personality, or lifestyle of the consumer (Niva, 2006, 2007; Yang and Mattila, 2017).

The aforementioned visibility of consumption (Heffetz, 2011) remains the most important factor and has developed the most thanks to the progress in technologies such as social networks. These allow consumers to present consumption directly at the very moment of consumption (Brooner and de Hoog, 2019) and therefore create a link between social visibility of consumption and conspicuous consumption as Shamu et al. (2024) proved in their research on wedding ceremonies.

2.2 Social Networks

Social networks play an indispensable role in the lives of today's consumers. They have become increasingly widespread in recent years especially with young consumers (Vogels, 2019), and some users have become addicted to them. The fear of missing out effect (FOMO effect) also plays a big role, forcing consumers to keep coming back to the networks (Cheng and Li, 2014; Solomon, 2017; Gómez-Galán et al., 2020), which creates a wide field for visible consumption, which can lead to conspicuous consumption (Dinh and Lee, 2024). Through social media, people receive and broadcast messages, obtain information, express themselves and their self-image, promote their opinions through self-generated content and thus increase their social status (Boczkowski et al., 2018; Ford, 2022),

Kietzmann et al. (2011) named 7 basic functional blocks of social media: identity (i.e., characteristics of the user behaviour), conversation, sharing content, presence of other users, relationships, reputation and groups, and communities. Social networks can have negative effects on their users, for example, on a personal level (evaluation of one's performance), a social level (status and skills in society), and a psychological level (lack of self-esteem and anxiety), see Gómez-Galán et al. (2020), Reis and Maia (2024). But there are many positives, such as creating and maintaining relationships among friends (Cheung et al., 2011; Dhir et al., 2018) for example via sharing "foodporn" photos (Fasanelli et al., 2020), devising a space for creativity, learning new skills, inspiring other users (Arab and Díaz, 2015), and for relaxation and fun (Erdem and Yılmaz, 2021).

Understanding the possibilities of social media as well as being able to interact through these media with consumers is nowadays very important for the efficient creation of marketing strategies. This is because users form relationships with other ordinary users through the media as well as with brands in different ways (Brennan and Parker, 2020). One of the highly recommended strategy for brands is partner with social medial influencers, to increase their

visibility and reach (Joshi et al., 2025; Nadroo et al., 2024).

2.2.1 Influencers

Social media influencers is a new form of self-made celebrity, usually acting as opinion leaders. Consumers adapt their purchasing behaviour and choose brands that influencers recommend (De Veirman et al., 2017; Gundová and Cvoligová, 2019; Farivar and Wang, 2022). Freberg et al. (2011, p. 90) define influencers as: "third-party endorsers who shape audience attitudes through blogs, tweets, and the use of other social media". Often, an influencer is then considered an expert on certain topics, for example, cosmetics, fashion, lifestyle, gastronomy, etc. (Van Norel et al., 2014).

An influencer can be both a classic celebrity and a self-made celebrity who has gained followers through his or her work and activities on social networks (Fietkiewicz et al., 2018; Enke and Borchers, 2019). Their fame is then based on their identity, aspirations, and followers' appreciation (Djafarova and Trofimenko, 2019). The influencer's authenticity (Ember, 2015), manifested, for example, in their ability to interact, is important in creating and building trust between the influencer and his or her followers. Influencer authenticity and credibility leads to loyalty and puts the influencer in a better position as an opinion leader (Jun and Yi, 2020; Cheah et al., 2024). The desire to be closer to and imitate the influencer than lead to CC (Dinh and Lee, 2024).

Given the role of influencers in the minds of their followers and the basic functions of social media, we hypothesize whether social media behaviour is directly related to CC behaviour among other factors already mentioned in theory (Status consumption, self-perception etc.).

2.3 Generations X, Y, and Z

As already mentioned, due to the use of social networking sites, Generations X, Y and Z were selected for this research.

Generation X, representing people born between 1965 and 1976 – as defined, for example, by Kardes et al. (2015), was the first generation to experience important changes in technology when their attention shifted from traditional mass media to the Internet. This has made this generation more adaptive (Fuciu, 2021) and not shy away from new technologies. They are said to focus on the quality of life and spend more on food, clothing, and entertainment (Kardes et al., 2015).

Generation Y (1977–1995) has fewer problems questioning authority (Kardes et al., 2015), is more self-conscious, and consumers of this generation are aware of their self-brand (Solomon, 2017). This generation likes to travel due to greater opportunities thanks to globalization and is very open to the world. They have grown up with digital technology and are used to being connected 24 hours a day (Kardes et al., 2015). Although they use the internet more for work purposes (Kotler et al., 2021), on social networks they prefer a combination of educative, informative and entertaining communication (Kusá and Urmínová, 2020). In their online shopping behaviour, the hedonic motive is the most influential (Koch et al., 2020).

Generation Z, born after 1995 and before 2010 (Kardes et al., 2015), is the first generation growing up in a fully digital world (Bernstein, 2015). Through social networks, they establish strong connections with both themselves and the outside world, while using social media as a source of information and new trends (Solomon, 2017; Yussof et al., 2018; Korombel and Ławińska, 2019). Social networks also influence their purchase behaviour through user-generated content (e.g., by influencers), where positive emotions cause impulse purchases of, e.g., fashionable clothing (Djafarova and Bowes, 2021). Their engagement on social media also increases their propensity to search for discounts, as they are a price-sensitive generation (Koch et al., 2020). For brands and companies seeking to engage this generation social media visibility has become a necessity. For example, Halová and Müller (2024) described in their research the importance of using different types of content on different networks to attract attention during the recruitment process. Social networks are also a key communication channel for sustainability and sustainable fashion

behaviour (Kusá and Urmínová, 2020). They are also strongly influenced by influencers, but only if they believe in their credibility and their knowledge in specifics areas (Zatwarnicka-Madura et al. 2022).

According to the Czech Statistical Office, 58% of the population aged 16+ used social networks in 2022, which is 53% more than in 2009 (CZSO, 2022b). The generation that spent the most time on social networks in the Czech Republic was Generation Z (85%). 69% of Generation Y and 58% of Generation X users spent at least an hour on social networks daily. Facebook was the most used social network, used by all generations, with Instagram in second place (used predominantly by Generation Z, 89%, followed by Generation Y, 61%). Other growing networks used mostly by Generation Z were TikTok and Snapchat (AMI Digital, 2022).

3 METHODOLOGY AND DATA

This research focuses on CC and the factors that play the major role in this consumption. It is partly based on the works of other authors who have studied conspicuous and status consumptions in the past and adopts some of the batteries of claims tested in their research studies (Chaudhuri and Majumdar, 2006; Nguyen and Tambyah, 2011; Riquelme et al., 2011; Assimos et al., 2019). The whole research is then adapted to the topic of CC of food and beverages.

Primary research data was collected through a questionnaire survey disseminated online between October 2022 and December 2022 in the Czech Republic. A total of 679 respondents from 3 different age generations were collected: 248 respondents from Generation Z, 207 respondents from Generation Y, and 224 respondents from Generation X (see Tab. 1). Respondents were approached based on the age distribution of the population of the Czech Republic (16% of Generation Z; 25% of Generation Y and 19% of Generation X). The data was then adjusted for incomplete responses from respondents. We managed to get more Generation Z respondents than necessary, but decided to keep them as the research is related to social networks, where Generation Z is the generation that uses them most often.

The questionnaire consisted of several sections. The section relevant to this paper contained a battery of statements partly drawn from research focusing on conspicuous and status consumption (Assimos et al., 2019;

Tab. 1: Characteristics of respondents

		Generation Z	Generation Y	Generation X	Total
Respondents (in absolute numbers)		248	207	224	679
Income (in %)	0–5 000 CZK/month	40.73	0.48	0.89	15.32
	5 001–10 000 CZK/month	37.50	3.38	0.89	15.02
	10 001–20 000 CZK/month	12.90	8.70	8.93	10.31
	20 001–30 000 CZK/month	5.65	34.30	26.79	21.35
	30 001–40 000 CZK/month	1.61	32.37	33.04	21.35
	40 001 and more CZK/month	1.61	20.77	29.46	16.64
Household income in terms of meeting needs and quality of life (in %)	Insufficient	0.81	0.00	0.45	0.44
	Low	8.47	6.28	4.91	6.63
	Sufficient	18.95	25.12	25.89	23.12
	Satisfactory	60.89	59.42	58.48	59.65
	High	10.89	9.18	10.27	10.16

Source: Questionnaire survey, 10–12/2022, $n = 679$

Chaudhuri and Majumdar, 2006; Nguyen and Tambyah, 2011; Riquelme et al., 2011), supplemented by statements focusing on social networks, influencers, and food characteristics. In total, there were 38 statements, with respondents expressing their levels of agreement on a 7-point Likert scale, with 1 = strong disagreement and 7 = strong agreement with a particular statement.

The data was analysed using Spearman's correlations, which are suitable for categorical data, and further processed using factor analysis, which is a suitable method designed to group variables with similar characteristics into larger factors (Brown, 2015). Subsequently, the relationship between the factors and the variable defining CC was examined *("When I know that I will consume the food before others, I buy more expensive and better-quality food to be perceived better in the group.")* by regression analysis.

4 RESULTS

4.1 Pilot Research: The Conspicuous Consumption of Generation Z

Research focusing only on Czech Generation Z ($n = 246$) served as pilot research and validation of the methods. The research confirmed that Generation Z is active on social media. Although other authors suggest that social media are an important source of inspiration for this generation (e.g., Gundová and Cvoligová, 2019; Djafarova and Bowes, 2021) in categories such as food and beverages, this influence was found to be less significant. Yet, research has shown that 55% of respondents follow influencers, and 43% of respondents admitted being inspired by various influencers.

The research tested a battery of statements with a total of 36 variables using a Likert scale (1 = strongly disagree, 7 = strongly agree), some of which were tailored to the topic of food consumption and some to general consumer behaviour. Factor analysis was used to categorize the variables into 7 different factors (labelled as Price; Social networks; Origin and composition of products; Materialism; Personality, values, and opinions of the social surroundings; Brand; Situational factors), and then regression analysis was used to look for relationships among these factors and the tendency to CC. In the analysis, only the factors Price; Origin and composition of products; Materialism and Personality, values, and opin-

Tab. 2: Social networks and influencers (in %)

	I take social networks as a source of inspiration.			*I follow various personalities and celebrities on social media.*			*Every day I look at new posts on social media from people I follow.*			*I have purchased a product more than once based on an influencer recommendation.*		
Value	**Z**	**Y**	**X**	**Z**	**Y**	**X**	**Z**	**Y**	**X**	**Z**	**Y**	**X**
1	12	22	52	8	32	60	31	63	32	31	57	79
2	10	16	13	12	19	17	13	8	19	17	14	9
3	8	15	11	9	10	8	14	7	10	11	9	2
4	18	16	7	8	12	4	10	6	12	8	7	3
5	17	11	6	15	13	5	6	3	13	16	7	2
6	15	11	4	18	9	1	13	5	9	12	6	2
7	20	9	7	30	6	5	14	8	6	5	2	3

Source: Questionnaire survey, 10–12/2022, $n = 679$

ions of the surroundings could be statistically demonstrated. Thus, the direct influence of social networks on conspicuous consumption could not be statistically demonstrated.

4.2 Research: The Conspicuous Consumption of Generations X, Y, and Z

After the pilot research, the methodology for measuring both the tendency for CC and the battery of statements was partly modified.

Data analysis shows that people are most price-sensitive when it comes to food and beverage expenditures, as indicated by the mean of the variables focusing on price (mean value 4.4) and discount (mean value 5), but quality (mean value 5.2) and ingredients (mean value 4.3) also play an important role. However, respondents confirmed that they tailor their purchases to the person with whom they will consume the food. The mean of this variable was 4.5, with a mode of 6. All 3 generations had similar values, with the lowest scores by Generation Y (mean value 4.48) and the highest being Generation X (mean value 4.53). The data also shows that respondents like to try new products and that concern for sustainability plays a role in their purchases.

4.2.1 Social Networks

As far as social networks are concerned, Generation Z is the most likely to look for inspiration for food purchases there (mode = 5). Generation Z also confirmed that they use social networks daily (mean value 5.1, mode 7) and take social networks as a source of inspiration (mean value 4.4, mode 7). In total, 63% of Generation Z respondents confirmed that they follow celebrities or personalities on social media, but only 32% of respondents claimed to have already purchased a product based on influencer recommendations. 41% of respondents expressed they would like to try food and beverages they saw presented on social media, for example, from influencers.

Generation Y seems to be noticeably less interested in social media. Only 40% of respondents indicated using them as a source of information, and only 28% agreed with the statement that they followed celebrities and personalities on social media. The mode for both variables was 1. And 34% of respondents admitted checking social networks daily.

Generation X shown a noticeable lack of interest in both social networks as a source of inspiration (mean = 2.4), following influencers (mean = 2), and following their recommendations (mean = 1.6). This statement is supported by the negative correlation between the respondent's age and the social network as a source of inspiration variable (coefficient = −0.38) and between the respondent's age and the celebrity and personality following variable (coefficient = −0.54).

A negative statistically significant correlation was also found between the following celebrities and personalities and the respondent's income, which reached a value of −0.405, as well as between other variables related to the use of social networks.

4.2.2 Factor and Regression Analyses

Subsequently, the data was analysed using factor analysis, which combined 37 variables (see Tab. 3) into 7 factors:

- sensitivity to others – influence of the environment, experience and recommendations of others, need for approval from the environment;
- social network activity – inspiration, sharing consumption online, following others;
- origin and sustainability – origin and production process, eco-friendly packaging;
- materialism – preference for luxury, prestige brands, a public image a person has;
- price – price sensitivity and the influence of discounts;
- quality and brand – product quality, composition, and brand;
- personality and grandstand – expressing personality, values, and creating an impression through consumption.

Next, the regression analysis was designed to determine which of these factors were statistically significant in relation to the tendency to CC. The variable "When I know that I will consume the food in front of others, I buy more expensive and better-quality food to be perceived better in the group." was selected

Tab. 3: Factor analysis

Sensitivity to others	I keep an eye on what people in my area are buying for food to make sure I am buying products that are on trend.
	When I don't have experience with a particular brand of food or drink, I often ask other people about their experience.
	I buy foods and beverages that I think others would approve of.
	When making purchases, I am guided by who I will subsequently consume the food and beverage with.
	When I buy food and drink, I act on information and recommendations from my friends and acquaintances.
Social network activity	I also look to social media for inspiration when buying food.
	I like to try new products and brands.
	I follow different personalities and celebrities on social media.
	I have purchased a product more than once based on an influencer's recommendation.
	I share food and drink photos on social media.
	I take pictures of my food or drink and share these pictures with my friends and the surroundings.
	I take social media as a source of inspiration.
	I like to try foods and drinks that I see on social media, for example, from influencers and celebrities I follow.
	I follow certain groups of people on social media.
	I look at new posts on social media every day from people I follow.
Origin and sustainability	I shop at package-free stores or use reusable packaging (canvas bags, sustainable bags, etc.).
	I shop at speciality stores.
	I prefer food in organic packaging.
	When buying food, I also consider the origin and production process of food and drink.
Materialism	Buying prestigious brands makes me happy.
	I like to buy more expensive foods that impress others.
	I like luxury in my life.
	I am attracted to buying branded and more expensive products.
	The things I buy say a lot about how I am doing in life.
	It happens that I adapt my behaviour and appearance in situations in front of people when I feel it is necessary.
	I like to buy unusual brands to differentiate myself and accentuate my personality.
	I feel part of a social group when I buy the same products as people in that group.
	I buy products to support my image in the group.
Price	When buying groceries, price is the most important thing for me.
	When buying groceries, I am often influenced by a discount.
	I would be happier if I could afford to buy more expensive and branded food.
Quality and grandstand	I often choose food and beverages according to brands when shopping.
	For food and drink, I mainly buy products that I consider to be of good quality.
	When buying food and drink, I consider the composition of the food.
Personality and impression	By buying certain foods and drinks that are typical of me, I express my personality.
	By buying certain foods and drinks that are typical of me, I express my values.
	Buying branded food and drink gives me the opportunity to impress others.

as the explained variable for the regression analysis and Sensitivity to others; Origin and sustainability; Materialism; Quality and Brand; and Personality and grandstand out of the explanatory variables from the factor analysis were identified as statistically significant at the 5% level of significance. Price ended as a statistically significant factor at the 10% level of significance. The adjusted coefficient of determination for this model was 0.56 (see Tab. 4).

Tab. 4: Regression analysis
Explained variable: *When I know that I will consume the food in front of others, I buy more expensive and better-quality food to be perceived better in the group.*

Variable	Coefficient	Std. error	*t*-ratio	*p*-value
Constant	2.2842400	0.0415572	54.970	< 0.001 ***
Sensitivity to others	0.7438040	0.0415878	17.890	< 0.001 ***
Origin and sustainability	0.1352180	0.0415878	3.251	0.001 ***
Materialism	0.5902600	0.0415878	14.190	< 0.001 ***
Price	0.0854451	0.0415878	2.055	0.040 **
Quality and brand	−0.4015670	0.0415878	−9.656	< 0.001 ***
Personality and grandstand	0.6265220	0.0415878	15.070	< 0.001 ***

Source: Questionnaire survey, 10–12/2022, $n = 679$

Tab. 5: Regression analysis – Generation Z, Y, X
Explained variable: *When I know that I will consume the food in front of others, I buy more expensive and better-quality food to be perceived better in the group.*

	Generation Z ($n = 248$)		**Generation Y** ($n = 207$)		**Generation X** ($n = 224$)	
Variable	**Coefficient**	***p*-value**	**Coefficient**	***p*-value**	**Coefficient**	***p*-value**
Constant	2.359	< 0.001	2.265	< 0.001	2.414	< 0.001
Sensitivity to others	0.798	< 0.001	0.749	< 0.001	0.715	< 0.001
Origin and sustainability	*−0.071*	*0.407*	*0.043*	*0.596*	0.190	0.049
Materialism	0.160	0.033	*0.093*	*0.158*	0.162	0.035
Price	0.517	< 0.001	0.614	< 0.001	0.608	< 0.001
Quality and brand	*0.061*	*0.460*	*0.073*	*0.301*	*0.097*	*0.175*
Personality and grandstand	−0.388	< 0.001	−0.472	< 0.001	−0.319	< 0.001
Adjusted coefficient of determination	0.490781		0.657564		0.521375	

Note: Results marked in *italics* were proven insignificant. Source: Questionnaire survey, 10–12/2022, $n = 679$.

For each generation, all factors were found to be always significant except for the factor Price, which was not significant for either generation, and the factor Social network activity, which was not statistically significant for generations Z and Y but was significant for generation X (see Tab. 5).

5 DISCUSSION AND CONCLUSIONS

This research focused on conspicuous consumption, its relationship to social network uses by Generations Z, Y, and X, and intergenerational comparisons among them. These generations were selected because of their frequent use of social networks in their daily lives and participation in the labour market; thus we could assume regular income (Kardes et al., 2015). The paper aimed to explore how the nature of the user behaviour of these generations on social networks relates to their tendency to CC. The results of the analyses show that respondents do not follow social networks and influencers much in relation to food and beverage topics. The exception is Generation Z, but even its representatives were expected to reach higher scores due to the findings of Gundová and Cvoligová (2019) and Djafarova and Bowes (2021) confirming that being a subject of influence by influencer marketing.

Yet, it can be said that Generation Z follows social networks daily and draws inspiration from the content provided there. In total, 63% confirmed that they follow various celebrities and personalities; however, only 33% claim to have ever purchased a product based on a recommendation from influencers. According to the results, Generation Y and X have a lower interest in social networks. For Generation Y, only 31% of respondents confirmed social networks as a source of inspiration, and only 28% confirmed that they follow influencers. For Generation X, interest in social networks and influencers was even lower. On the other hand, the ratio of respondents who followed influencers to the number of respondents who have purchased a product based on an influencer's recommendation is interesting – for Generation Y, the ratio is 28% to 15%, and for Generation X it is 11% to 7%. Thus, it can be concluded that Generation Y consumers, if they follow an influencer, are more than 50% likely to purchase a product recommended by an influencer, and for Generation X, the likelihood is more than 60%.

This work included factors such as materialism, personality, gaining status in society, and other factors that have already been studied in relation to CC (Nguyen and Tambyah, 2011; Riquelme et al., 2011; Brooner and de Hoog, 2019) and investigated whether the nature of social network use, which has experienced a rapid increase in recent years and has become an integral part of consumers' lives (Gómez-Galán et al., 2020), can also be identified as an independent significant factor influencing CC. This hypothesis could not be proven for all respondents, and the significance of this factor came out as independent only for Generation X. In general, this generation doesn't show a big propensity for CC and activity on social networks, yet the results suggest that social networks play a role in the case of CC. This relationship may be due to the lower use of social networks, where experiences and photos are shared daily, by this generation. Thus, if someone from this generation uses networks frequently, they may be more prone to CC. Gen X is also the oldest of the three examined, so it is likely that they already have established consumption behaviour and may be more honest and accurate in their questionnaire responses.

The factors most influencing CC of food are: Sensitivity to others; Origin and sustainability, Materialism, Quality and brand, and Personality and grandstand, which proved to be statistically significant for all analysed generations. An interesting result is the factor Price, which came out as significant in the overall model but did not show statistical significance across generations.

This research had its limitations. The choice of a quantitative approach via a questionnaire survey poses challenges to the issue due to the superficiality of the respondents' answers and the length of the questionnaire, causing possible respondents' fatigue.

6 IMPLICATIONS AND FURTHER RESEARCH LINES

Although a direct relationship between the nature of social network use and CC as an independent factor has not been demonstrated across all analysed generations, it is worthwhile to explore this topic further. The use and degree of impact of social networking, at least for Generation Z, is evident in our research and as it has been in previous research (e.g., Gundová and Cvoligová, 2019; Djafarova and Bowes, 2021). Future research would benefit from an application of qualitative research, which would provide deeper insights into the mindset of consumers and could shed more light on their purchase decision-making process in visible consumption.

6.1 Managerial Implications

This study offers several possible managerial implications for marketing in the food industry. It evaluates the factors that consumers generally consider when making food choices. Although the price of food still plays an important role, consumers also consider other factors such as brand, quality, food origin, and sustainability. These factors should then be

the focus of marketing for these companies. The research also confirmed consumers' use of social media and followership of influencers, although less than expected in the food and drink category. Even when consuming food, consumers are influenced by their surroundings and their desire to express themselves and show their personalities through their consumption. Collaborating with influencers may then be one way for companies to support these tendencies.

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EVALUATION AND SIMULATION METHODS FOR AMBIDEXTERITY ENGINEERING OF DIGITAL SUPPLY CHAIN SYSTEMS

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ABSTRACT

Global mergers and faster business cycles create weakly harmonized supply chain (SC) systems. Industry 4.0's smart digitalization opportunities significantly alter business model innovation rates. Consequently, the complexity of aligning value exploration and exploitation has increased, often missing the needed integration level. A holistic systems engineering (SE)-driven methodology for innovation, transformation, and optimizing smart SC systems is not available so far. Case studies at SAP SE's development organization for Industry 4.0 SCM solutions and three automotive companies explored objectives, obstacles, and methods for digital transformation. The results were synthesized into a holistic SC business model transformation and optimization methodology. Complementary to traditional SCM, the study proposes SE-driven meta-modelling to improve the performance, resilience, and synchronization of end-to-end supply chains. Moreover, holistic simulations and evaluation methods for the ambidexterity of SC business models have been developed, enhancing the effectiveness of value exploration and exploitation, and innovation productivity by holistically viewing emergence and convergence throughout SC capabilities' life cycles. Ambidexterity management and dynamic capabilities are addressed by SE methods like capability engineering and complex dynamic systems theory, integrated into a concise SE model.

KEY WORDS

systems engineering, supply chain engineering, ambidexterity engineering

JEL CODES

L21, M15, O32, O33

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1 INTRODUCTION

This follow-up study refers to a 2023 published systematic review of methods for activating SC business models' value potentials in the Industry 4.0 context using a systems engineering approach (Nuerk and Dařena, 2023). The previous and present study presents the result of the main author's PhD Dissertation in Systems Engineering and Informatics, submitted in July 2024 at Mendel University in Brno. The grounds for the need for a harmonized SE methodology are briefly stated in this introduction.

The complexity of SC business models is increasing due to industrial globalization, emerging ecosystems, and rising business dynamics (Davey et al., 2021; Dumitrescu et al., 2021). Weakly harmonized IT landscapes and fragmented alignment result in poor SC design, lack of integration, and unsynchronized supply chains (Childerhouse and Towill, 2011; Nuerk, 2019; Wu et al., 2006). Proper capability alignment with competitive strategies and SC integration drives performance in dynamic environments (Chen et al., 2018; Childerhouse and Towill, 2011; Liu et al., 2013; Nuerk, 2019; Shaw et al., 2005; Wang, 2011), though configuration depends on context (Godsell, 2008).

Investigating contingency relationships is needed for operationalising strategic fit, which can be implemented by a profile deviation approach (McLaren et al., 2011; Sabherwal and Chan, 2001). Many concepts exist for business-IT alignment, but integration into holistic engineering frameworks is lacking (Spósito et al., 2016). Integrating key constructs in an SE model for capability alignment in business model transformation will close this gap. Additionally, businesses must manage increasing environmental dynamics, higher demand variability, shorter product lifecycles, and ambitious sustainability goals (Hermann et al., 2016; Mo et al., 2023). Industry 4.0 enables processes like autonomous planning and manufacturing, sustaining performance in multi-tier supply chains (Zott and Amit, 2010).

Enterprises as complex dynamic systems reveal value opportunities through the emergence process and interactions of components (Levy, 2000; Rebovich, 2008). Thus, SC business models need continuous alignment to maintain operational excellence. In referring to the dynamic capability (DC) theory, evaluating fitness levels helps balance exploration and exploitation, relating to ambidexterity (Teece, 2018; Teece et al., 1997; O'Reilly and Tushman, 2008; Raisch et al., 2009). DC theory emphasizes the importance of exploring, assimilating, and exploiting knowledge for business performance (Liu et al., 2013; Arndt et al., 2018).

Absorptive capacity enables orchestrating and recombining capabilities to respond to business dynamics effectively (Brettel et al., 2011; Teece, 2007). Ideally, systematic findings on dynamic capabilities (DC), absorptive capacities, and ambidexterity can be modelled and adopted by systems engineering (SE) discipline capability engineering (Henshaw et al., 2011). To fully exploit the value potentials of the current economic paradigm change, concepts from business modelling, Industry 4.0, SCM, AI, and enterprise architecture need to be incorporated into an SE approach. A holistic view of enterprise systems and context enhances transparency, integrating functions and improving the understanding of the relationship between innovations and alignment processes (Brettel et al., 2011; Altman and Tushman, 2017).

Therefore, SE must integrate value-adding SC processes and balance innovation, transformation, and convergence. A SE-driven model with three main phases—(1) sensing and interacting, (2) SC design and transformation, and (3) SC planning and optimization—provides an integrated view of smart data-driven SC business models' emergence, convergence, and efficiency (Nuerk and Dařena, 2023). The methodological needs for innovating and maximizing digital SC systems' value potentials throughout these phases must be explored, focusing on objectives driven by digitalization.

Designing best practices and useful artefacts requires understanding interoperability drivers

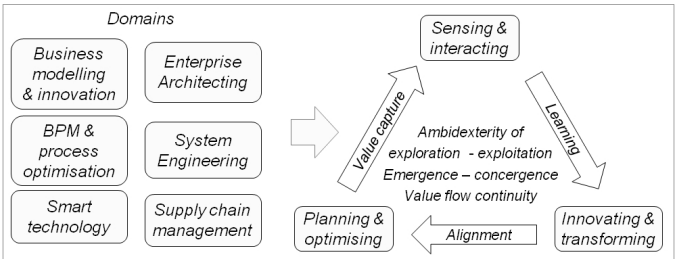


Fig. 1: The SE model phases and concepts' source domains (Nuerk and Dařena, 2023)

of smart processes, observed transformation obstacles, and promising approaches to overcome them. Systematic, qualitative research using case studies is needed to explore the requirements of target organizations and how smart SCM IT capabilities impact their deep structure (Silva and Hirschheim, 2007; van Donk and van der Vaart, 2005). Case studies help identify significant interoperability drivers for smart data-driven supply chains and methods useful for the SE model phases, balancing exploration and exploitation and leading to continuity in SC performance and resilience (Yin, 2018; Bryman and Bell, 2011).

2 RESEARCH OBJECTIVE

Businesses face declining visibility along their supply chains due to the rising distribution of value-added processes among more partners, coupled with increasing business volatility and uncertainties simultaneously. SC integration and interoperability significantly impact SC performance, agility, and resilience. This study explores the main requirements and methods for simulation and evaluation keeping SC business models in an ambidexterity state, ensuring continuous SC performance and resilience. The study aims to develop a holistic and concise SE methodology tested through case study research in the automotive industry. The research objective and question are:

RO: *Develop a SE-driven methodology for evaluating and simulating ambidexterity in digital SC business models to balance exploration and exploitation, ensuring continuous SC performance and resilience.*

RQ: *What core methods enable improving performance and resilience while balancing value exploration and convergence activities in SC business models?*

The explored SE methods should provide concise information for maintaining digital SC business models and their capabilities in a fit and ambidexterity state, addressing business dynamics. The findings aim to help SE systematically manage increasing dynamics in SC systems and environmental volatility, guiding organizations in ongoing innovation and value exploitation. The final model should offer methods for maintaining SC business models' efficiency and resilience, balancing exploration with exploitation activities. As SC systems often lack needed integration quality across domains and organizations, better-aligned and integrated SC innovations will significantly improve firms' performance relative to competitors (Chen et al., 2010; Rai et al., 2006).

This study drives SE towards becoming a key discipline for SC design, focusing on innovation, operational excellence, and resilience, aligning with the INCOSE Vision 2035 (Davey et al., 2021). A harmonized SE model, avoiding methodological redundancies, is seen as a driver for innovations and value exploitation in digital SC business models.

3 METHODOLOGY AND RESEARCH PROCESS

The study is grounded in a 2023 systematic literature review by Nuerk and Dařena, covering concepts from SE, business modelling, Industry 4.0, SCM, AI, and enterprise architecture methods. This review establishes the need for a harmonized SE-driven model with three main phases: (1) sensing and interacting, (2) SC design and transformation, and (3) SC planning and optimization (Nuerk and Dařena, 2023). The present study aims to enrich this SE model into a consistent methodology for systematically managing increasing SC dynamics and environmental volatility while fostering ongoing innovation and value exploitation. To detail these methodological requirements, qualitative research investigates target organizations and IT's strategic impact on their deep structure (Silva and Hirschheim, 2007).

According to Davey et al. (2021), SE needs a strong scientific base and shared formal ontologies across domains to adapt methods for maximizing application value (Wu et al., 2006). The field research explores the core methods of the SE model and develops reusable artefacts for evaluating SC business models' effectiveness. Additionally, the model must provide SE methods for assessing and balancing business model capabilities throughout their lifecycles. A multiple case study design was chosen for context-dependent generalization through replication (Yin, 2018). This approach ensures the development of a comprehensive SE methodology that addresses the increasing dynamics in SC systems and environmental volatility, enabling organizations to innovate continuously and exploit value effectively.

3.1 Case Study Research at SAP SE

To collect in-depth knowledge about the transformation and optimization of digital SC models, case study research was conducted at SAP SE's Headquarters in Walldorf, Germany. The selected business divisions at SAP SE are involved in various global digitalization initiatives, such as Catena-X for automotive, providing valuable insights into digitalization requirements and trends. The study explored core objectives, obstacles, and promising methods for industrial organizations using semi-structured interviews. These interviews were conducted with experts from SAP Business Units of Industry 4.0, Digital SC Innovations, Smart Manufacturing, and field services for Business Transformation and SC Planning and Optimization.

The research explored areas where traditional SC domain engineering is limited and how SE can holistically complement industrial digitalization. It also identified SC objectives and priorities that have evolved due to smart digitalization. Focused methods were identified to enable SE to quickly evaluate prevailing value enablers and the systematic processes of smart SC business operations. Extensive work sessions were conducted with nine participants (listed in Tab. 5 in the Annex). These sessions introduced the research topic, followed by semi-structured interviews, which were transcribed as shown in Fig. 2. Nine reports, each between 8,800 and 12,500 words, were created as the outcome of the case study and validated through workshops with participants. The case study transcripts were analyzed using QCAmap, following Mayring's (2014, 2023) qualitative content analysis method. Due to the explorative nature and complexity of the topic, inductive category formation was used to remain open to the concepts extracted from the reports. A summary of the category system, as the content analysis output, is highlighted in Fig. 3.

The categories formatted during the analysis were grouped into main categories for SC objectives and value enablers, and the SE model phases. Focus activities that enable orchestrating the SE model phases to balance SC performance, resilience, exploration, and exploitation were identified and emphasized in red ink Fig. 3. Based on the synthesized findings, methods were designed to evaluate the effectiveness of value signal sensing and value exploitation by business model components and SCM IT capabilities for driving useful conver-

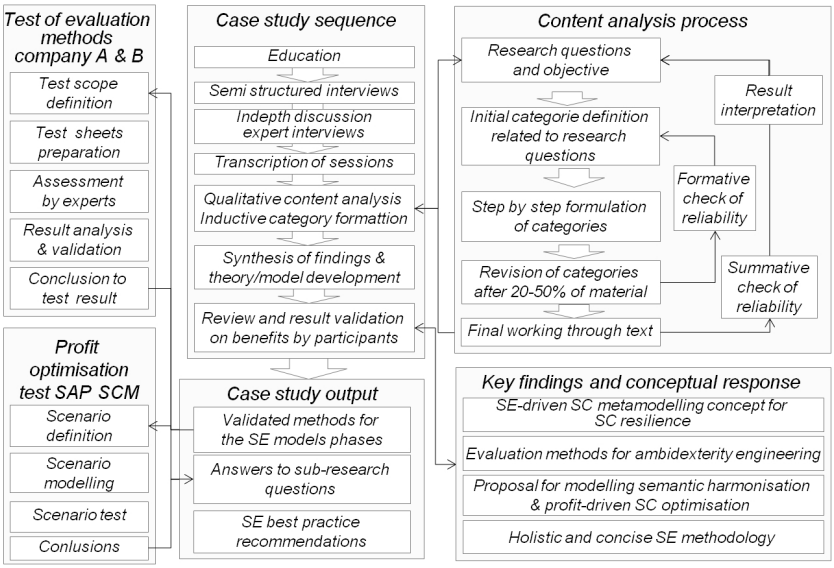


Fig. 2: The case study process including the content analysis due to Mayring (2014), the process for testing the evaluation methods using industry case and SCM scenario test (Nuerk, 2024)

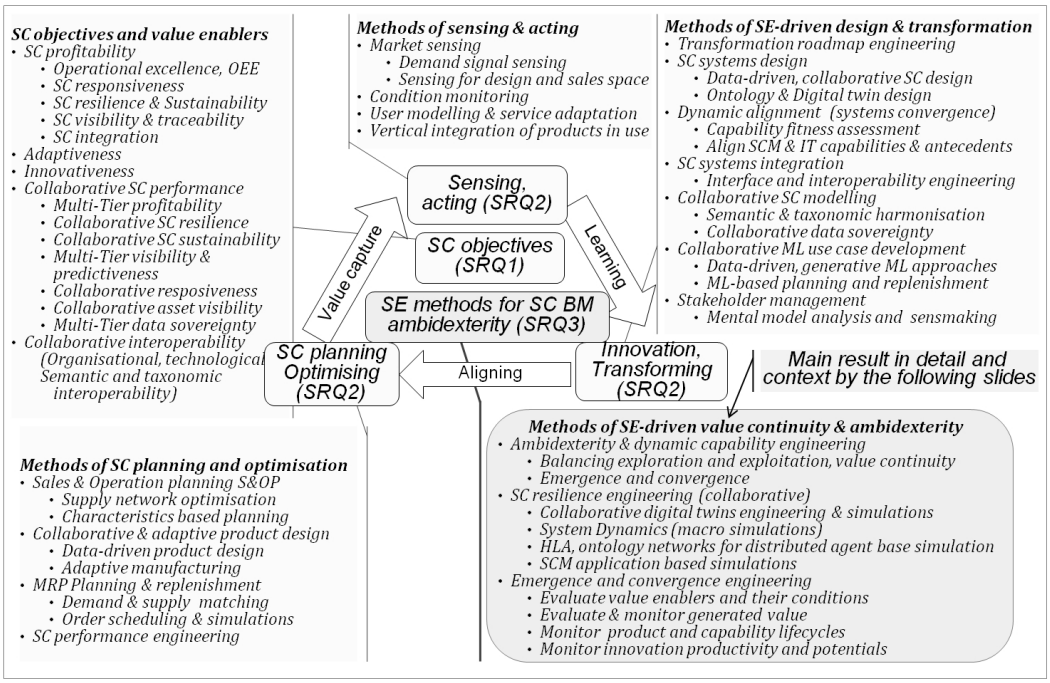


Fig. 3: Formatted SE methods for engineering SC business model ambidexterity (Nuerk, 2024)

gence processes. The case study was replicated at an innovative European make-to-order automotive supplier, an industrial manufacturer, an automotive systems supplier, and a European sports car maker, enriching the research with insights from industrial experts. The developed evaluation methods were tested at these companies. Contributions from the case study participants are indicated in the following sections as P_1 to P_9, according to Tab. 4 in the Annex.

3.2 Industrial Case Studies and Test of Evaluation Methods

As a core objective, the industrial case studies explored in-depth findings on current initiatives and implementation activities in Industry 4.0. Objectives, obstacles, and main efforts were examined and analyzed similarly to the SAP SE case studies. These findings were categorized and mapped to the SE model phases' activities. In addition, the two evaluation methods that have been tested are highlighted in the bottom left area of Fig. 2. The participants reviewed and validated the entire SE-driven methodology. Through this process, the study provides a robust framework for understanding and implementing SE-driven methodologies to enhance SC performance, resilience, and innovation in the context of Industry 4.0.

3.2.1 Test of SCM IT Capabilities' Fit Evaluation (Systems Convergence)

Evaluating companies' SCM IT capabilities has been identified as a significant component of the SE-driven model for achieving convergence in digital SC business models. Therefore, a systems theory-based approach, consistent with a configurational theory, was tested at sample Company B by participant P_9 and the author.

State-of-the-Art: According to contingency theory, aligning patterns between corporate strategic contexts and structural characteristics can lead to high business performance and prevent systemic misalignment (Oh and Pinsonneault, 2007). Strategic alignment is essential for formulating and implementing a strategy. Business value relies on resource-centred perspectives and contingency theory, which posits that aligning parameters of strategy, context, and structure leads to excellent performance. Makadok (2001) describes dynamic capabilities (DC) as potentials for innovative capacity, enabling organizations to transform by effectively reconfiguring capabilities to remain competitive (Makadok, 2001). Ambidexterity refers to balancing efforts to develop DC by exploring innovations and pre-creating enterprise capabilities such as artefacts and organizational knowledge against the exploitation efforts for rent creation (O'Reilly and Tushman, 2008). In this regard, the present measurement approach enables evaluating capabilities' levels concerning pre-developed artefacts, facilitating their fast and appropriate selection and utilization in various business situations. To fulfil fitness conditions, each high-order SCM IT capability must support SC objectives and align with the company's strategy, expressed as the desired future level of SC objectives. Fig. 4 illustrates how strategic business attributes determine the needed future capabilities, matched by current SC capabilities. The Euclidean distance between current and desired capabilities indicates the need for alignment activities. This systems approach is consistent with configurational theory, defining 'fit' as consistency across multiple design and context dimensions. The concepts combine holistic and detailed views of systems in their contexts.

Tab. 1 shows the detailed assessment filled out by Participant P_9, for evaluating SCM IT capabilities for Supply Network Planning and Factory Scheduling, which have a significant impact on SC objectives, rated on a five-point Likert scale. Fig. 5 presents the analysis of current and future levels for SNP and Factory planning IT capabilities, while Fig. 6 shows the fitness levels for SC objectives. The evaluation highlights strengths in (1) factory scheduling, optimizing plant schedules considering process technology constraints, and (2) multi-objective supply network plan optimization aligning with procurement and financials. The company's SCM simulations show fit for handling internal situations but lack early warnings of external adversities.

The misfit calculations in Fig. 7 and 8 highlight strengths in customer service, delivery reliability, and midterm Demand and Supply Network Planning. The company is highly profitable in internal processes but shows gaps in collaborative processes and lacks agile responsiveness to short-term changes. This aligns with SAP expert interviews, emphasizing the need for increased SC resilience from better collaboration and visibility. Fig. 7 shows high misfit levels, indicating a demand for improved SC synchronization. Fig. 8 highlights deficiencies in collaboration effectiveness and responsiveness,

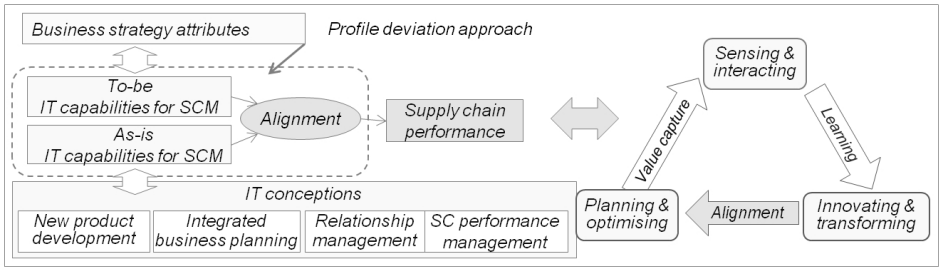


Fig. 4: Configurational theory-based capabilities fit evaluation (Nuerk, 2024; Sabherwal and Chan, 2001)

Tab. 1: Evaluation of SCM IT capabilities fitness by rating as-is and to-be levels

	SC capabilities	SC agility & responsiveness		SC profitability & OEE		SC resilience & sustainability		Collaboration effectiveness		Delivery reliability & predictability		Mean as-is	Mean to-be	Mistfil level
		As-is	To-be	As-is	To-be	As-is	To-be	As-is	To-be	As-is	To-be			
Supply Network planning	Demand signal management	3.00	5.00	4.00	4.00	3.00	4.00	4.00	5.00	5.00	5.00	4.54	4.60	2.45
	Multi-objective plan optimisation	4.00	4.00	5.00	5.00	4.00	5.00	4.00	5.00	5.00	5.00	4.40	4.80	1.41
	Plan optimisation based on profit	3.00	4.00	5.00	5.00	4.00	5.00	3.00	3.00	4.00	4.00	3.80	4.20	1.41
	Transportation optimisation	3.00	4.00	5.00	5.00	4.00	5.00	4.00	5.00	4.00	5.00	4.00	4.80	2.00
	Long-term capacity levelling	4.00	5.00	4.00	5.00	4.00	5.00	3.00	4.00	5.00	5.00	4.00	4.80	2.00
	S&OP alignment with procurement	5.00	5.00	4.00	4.00	3.00	4.00	4.00	5.00	4.00	4.00	4.00	4.40	1.41
	S&OP alignment with financials	4.00	4.00	3.00	3.00	3.00	3.00	3.00	4.00	4.00	4.00	3.40	3.60	1.00
	Strategic sourcing	3.00	4.00	4.00	4.00	4.00	5.00	3.00	4.00	4.00	4.00	3.60	4.20	1.73
Factory scheduling	Factory scheduling (Block planning)	4.00	5.00	4.00	4.00	3.00	3.00	3.00	4.00	5.00	5.00	3.80	4.20	1.41
	SC synchronisation (collaborative)	4.00	5.00	4.00	4.00	4.00	5.00	3.00	5.00	5.00	5.00	4.00	4.80	2.45
	SC end-to-end visibility in time	3.00	5.00	4.00	5.00	3.00	5.00	4.00	5.00	4.00	5.00	3.60	5.00	3.32
	Predictive Maintenance	4.00	5.00	3.00	4.00	3.00	4.00	3.00	4.00	4.00	5.00	3.40	4.40	2.24
	Modelling and simulations	4.00	5.00	4.00	5.00	4.00	5.00	4.00	5.00	3.00	3.00	3.80	4.60	2.00
	Means of fitness contribution	3.19	3.94	3.50	3.75	3.06	3.81	3.00	3.81	3.69	4.54			
	Misfit level	4.00		2.00		3.74		3.87		1.73				

Source: Nuerk (2024); Legend: 1 = no support for SC objectives; 2 = low support; 3 = medium support; 4 = high support; 5 = very high support.

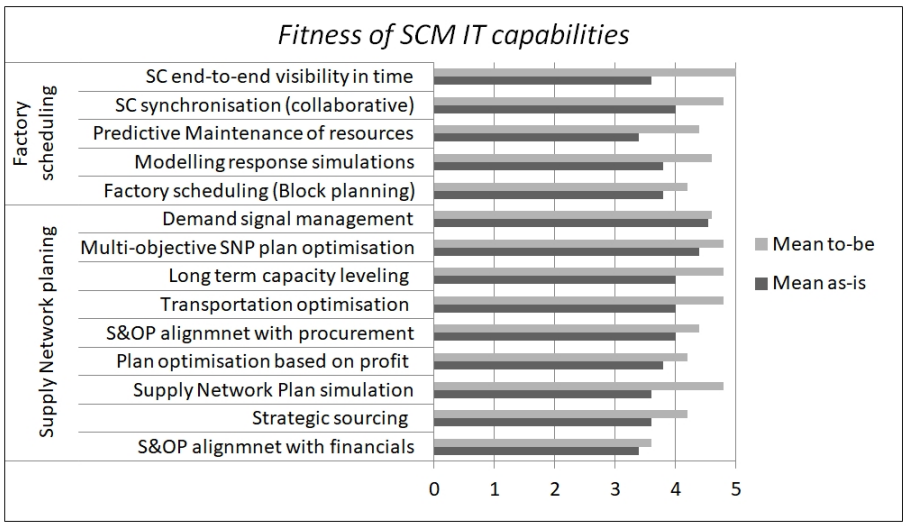


Fig. 5: Fitness levels of SCM IT capabilities (high levels are high support for SC objectives) (Nuerk, 2024)

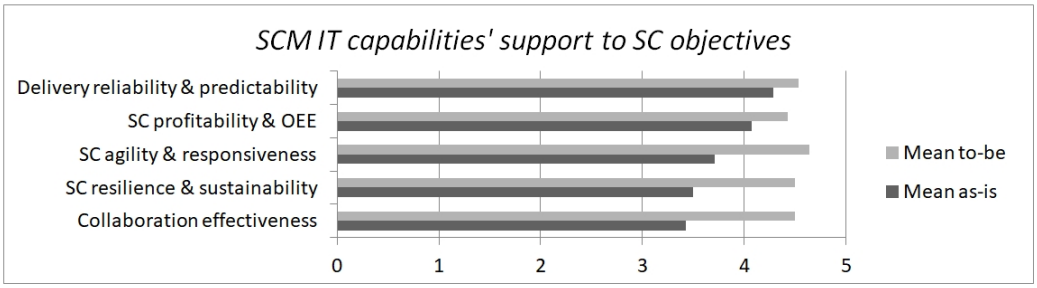


Fig. 6: SC capabilities' support to SC objectives (Nuerk, 2024)

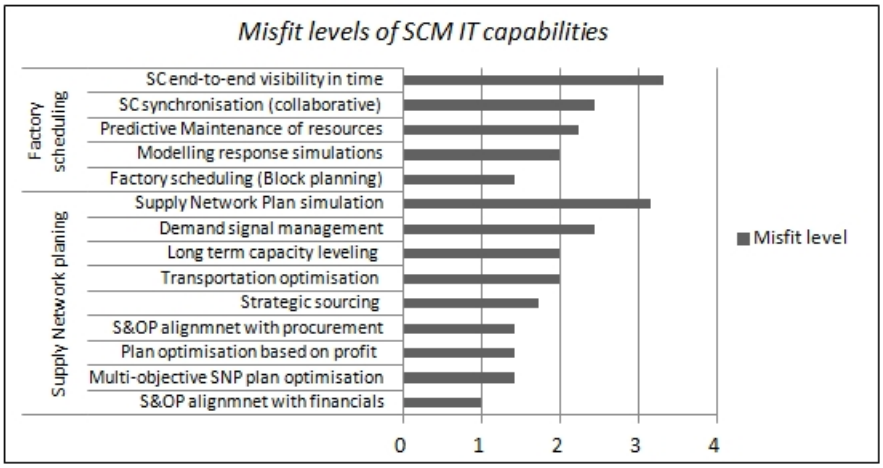


Fig. 7: Misfit levels of SCM IT capabilities (high levels indicate a high extent of misfits) (Nuerk, 2024)

affecting SC resilience and performance continuity.

Tab. 2 summarises the SCM IT capability fitness evaluation findings, demonstrating the method's ability to identify misfits concerning SC objectives. The result helps to define areas needing improvement for system and SC business model convergence, supporting value-oriented transformation and alignment roadmaps. The concept enables the evaluation of the various needed capability levels for changing business situations, contributing to dynamic capabilities development. Thus, the SCM IT capability fitness evaluation method is part of the SE-driven SC engineering and transformation model, leading to superior business performance by aligning as-is architecture with ideal fitness levels.

According to the test findings, the introduced capability fit evaluation answers the following

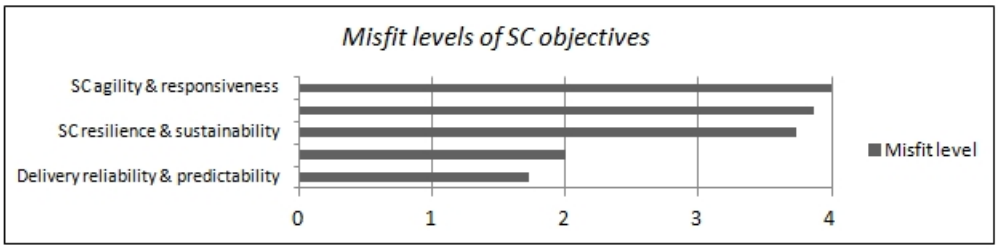


Fig. 8: SCM IT capabilities misfit impact on SC objectives (Nuerk, 2024)

Tab. 2: High priorities identified by the test analysis SCM IT capabilities fit

SCM IT Capability	As-is level	To-be level	Fit ratio	Comment	Related KPIs
SC end-to-end visibility in time	3.6	5.0	3.3	Higher transparency in the supply chain is needed to improve resilience by response in time.	SC responsiveness
Supply Network Plan simulation	3.6	4.8	3.2	Capabilities are needed that enable simulations of macro-level effects on the supply network.	Plan profitability
SC synchronization (collaborative)	4.0	4.8	2.5	Capabilities are needed to simulate better SC synchronization on the extended supply network.	Plan profitability, Collaboration effectiveness
Demand signal management	4.5	4.6	2.4	The company will exhaust real-time demand sensing to predict demand changes more reliably.	Forecast accuracy
Predictive Maintenance of resources	3.4	4.4	2.2	The need for more reliable simulation capabilities goes hand in hand with the reliability of resource maintenance prediction.	Plant utilization and OEE, Plant throughput in tonnes per day
Modelling response simulations	3.8	4.6	2.0	Better simulation modelling integrated from macro implications to real-time response is needed.	SC responsiveness, Profitability
Transportation optimization	4.0	4.8	2.0	The need for more reliable simulation capabilities goes hand in hand with the reliability of long-term capacity planning and transportation optimization.	Transportations adherence
Long-term capacity levelling	4.0	4.8	2.0		Resource & labour availability

questions necessary for developing a value-focused capability development and implementation roadmap:

1. What are the right levels of fit, needed for SCM IT capabilities?
2. What are the right levels of their antecedents?
3. What capability levels are needed for ideal contingencies in context?
4. What dynamics of capabilities are required?
5. What useful artefacts should be modelled as absorptive capacities?

3.2.2 Test of Evaluating Value Sensing and Exploitation (Systems Emergence)

Value sensing must detect signals with the potential for transformation into value propositions (VP) or business processes' benefits (exploitation).

Evaluating these value potentials and allocating them to business model components is crucial for innovation. These evaluations enhance understanding of organization-specific emergence processes and possible convergence deficiencies in exploiting expected value. A company's ability to use external knowledge relies on existing related knowledge, essential for identifying.

Tab. 3 shows the evaluation sheet with ratings of relationships between various sensing types as value signal sources impacting business model dimensions like value proposition, creation capabilities, and processes. This assessment, filled out with the participant, highlights how value-generating relationships between enablers and exploiting capacities vary over time. A pairwise Likert scale evaluation of current (as-is) and future (to-be) values expresses estimated potentials, supporting the development of dynamic capabilities. Participant P_7 consulted multiple business areas in Company A—marketing, sales, spare parts management, distribution partners, portfolio management, and product design—to sense value signals and proposition characteristics. Discussions with manufacturing, resource design, and process engineering provided insights into value drivers

Tab. 3: Sheet for evaluating the effectiveness of value sensing and exploitation

Value sources/sensing type	Market & demand signal sensing		Environment & Operations sensing		Vertical Product data		Collaborative engineering		Expert knowledge		Mean	Mean	
Business model dimension	**As-is**	**To-be**	**As-is**	**To-be**	**As-is**	**To-be**	**As-is**	**To-be**	**As-is**	**To-be**	**as-is**	**to-be**	**Potentials**
Value proposition													
Differentiation & customisation	5.00	5.00	1.00	1.00	1.00	5.00	4.00	5.00	5.00	5.00	3.20	4.20	4.12
Market relatedness, customer focus	5.00	5.00	1.00	1.00	2.00	5.00	4.00	5.00	5.00	5.00	3.40	4.20	3.16
Complementary products	4.00	4.00	1.00	1.00	2.00	5.00	4.00	4.00	3.00	5.00	2.80	3.80	3.61
Connected information flow	2.00	2.00	1.00	1.00	2.00	5.00	3.00	3.00	1.00	1.00	1.80	2.40	3.00
Value creation capabilities													
Short time-to-market	2.00	3.00	1.00	1.00	2.00	3.00	3.00	5.00	3.00	4.00	2.20	3.20	2.65
Enhancing product configuration	3.00	5.00	2.00	3.00	2.00	4.00	2.00	3.00	2.00	3.00	2.20	3.60	3.32
Reconfigurability, scalability	3.00	4.00	1.00	2.00	2.00	4.00	2.00	4.00	3.00	5.00	2.20	3.80	3.74
Synchronise product combinations	2.00	4.00			2.00	4.00	3.00	4.00	3.00	4.00	2.50	4.00	3.16
Faster adoption of opportunities	2.00	3.00	1.00	1.00	2.00	4.00	4.00	5.00	3.00	3.00	2.40	3.20	2.45
Value capture, processes													
Reduced R&D time	2.00	3.00	1.00	1.00	2.00	3.00	3.00	5.00	2.00	4.00	2.00	3.20	3.16
Enable data-driven design	3.00	5.00	1.00	1.00	2.00	4.00	3.00	4.00	3.00	3.00	2.40	3.40	3.00
Improve predictability	4.00	5.00	1.00	2.00	2.00	3.00	4.00	4.00	2.00	3.00	2.60	3.40	2.00
Improve synchronisation	2.00	3.00	3.00	5.00	2.00	5.00	3.00	5.00	3.00	4.00	2.60	4.40	4.36
Improve decision support	4.00	5.00	3.00	4.00	2.00	5.00	3.00	3.00	4.00	5.00	3.20	4.40	3.46
Increase flexibility, agility	3.00	3.00	4.00	4.00	3.00	4.00	4.00	5.00	5.00	5.00	3.80	4.20	1.41
Close experience gap	4.00	5.00	2.00	2.00	2.00	4.00	2.00	3.00	2.00	4.00	2.40	3.60	3.16
Improve resource availability	2.00	3.00	4.00	5.00	2.00	3.00	2.00	3.00	3.00	3.00	2.60	3.40	2.00
Enable preventive maintenance	2.00	2.00	5.00	5.00	3.00	4.00	2.00	3.00	2.00	3.00	2.80	3.40	1.73
Value contribution by sensing type (mean)	3.11	3.63	1.94	2.22	2.11	4.00	3.11	4.00	3.11	3.85			
Remaining value potentials		4.24		5.66		2.24		2.83		3.61			

Source: Nuerk (2024). Legend to model validation: 1 = does not contribute to value generation; 2 = contributes weakly to value generation; 3 = contributes to value generation; 4 = contributes strongly to value generation; 5 = contributes very strongly to value generation.

and relationships with external information and sensing.

The broad information scope and central impact of many parties on the effectiveness of emergence and convergence highlight the need for a central SE role to maximize value contributions from investments in value signals. Fig. 10 presents the evaluated current (as-is) and expected future (to-be) value potentials by sensing types for a business division, using means calculation. Fig. 9 highlights the current value exploitation and expected potentials by business model components.

The Euclidean distance measures the gap between current (as-is) and projected (to-be) value potentials. Fig. 11 and 12 show the effectiveness between value exploitation and the remaining potential for BM dimensions and sensing types. The test findings highlight where value is sensed, and exploited, and where further sensing or alignment is needed. They also show where value expectations were not met or exceeded. Participants of the industrial case studies and SAP SE affirmed this method as a high-priority, continuous lessons-learned activity in innovation and transformation management (P_1, P_3, and P_7). Such evaluations enhance transparency on innovation potentials and knowledge, delivering insights into value-enabling sensing patterns. Assessing sensed signals and exploited business value as a ratio of innovation capacities to potentials significantly benefits product and capability innovation. Collecting value signals in a repository and regularly learning from these opportunities can enhance pre-knowledge and drive value-generating business model dimensions. Fig. 11 and 12 present evaluated unfulfilled value

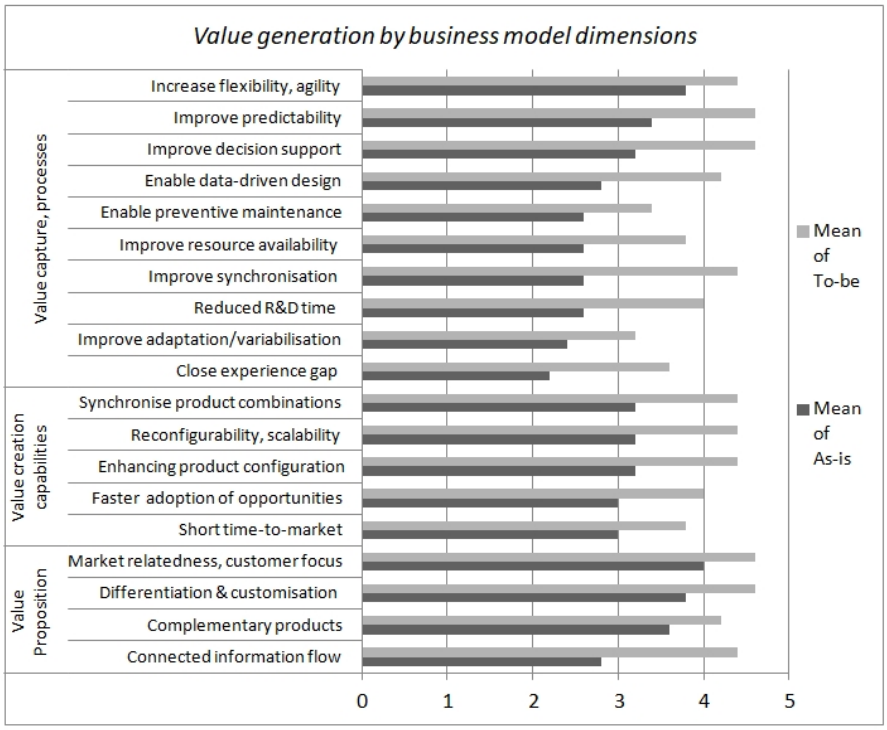


Fig. 9: Effectiveness of value exploitation (high levels show high effectiveness (Nuerk, 2024)

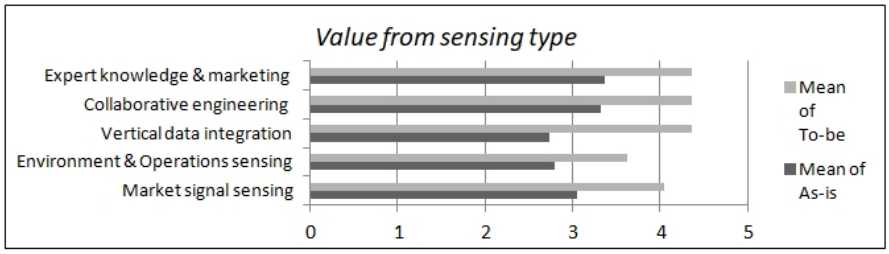


Fig. 10: Effectiveness of value sensing by sensing type (Nuerk, 2024)

expectations by BM dimensions and sensing types, respectively (Nuerk, 2024).

Repetitive evaluations over time build knowledge about innovation emergence and monitor value, providing insights into the organization- and context-specific value processes and their promoter conditions. Evaluating the relationships between innovation potentials and capacities offers valuable information for balancing exploration and exploitation efforts, significantly contributing to SC business model ambidexterity engineering. The tested method for evaluating value sensing and exploitation effectiveness provides insights in:

1. Which sensing sources contribute to different levels of value?
2. Which BM components release value?
3. Which conditions promote the emergence of value enablers?

The findings on simulation methods and the tested evaluation methods are discussed in the context of SC business model ambidexterity in Chapter 4.

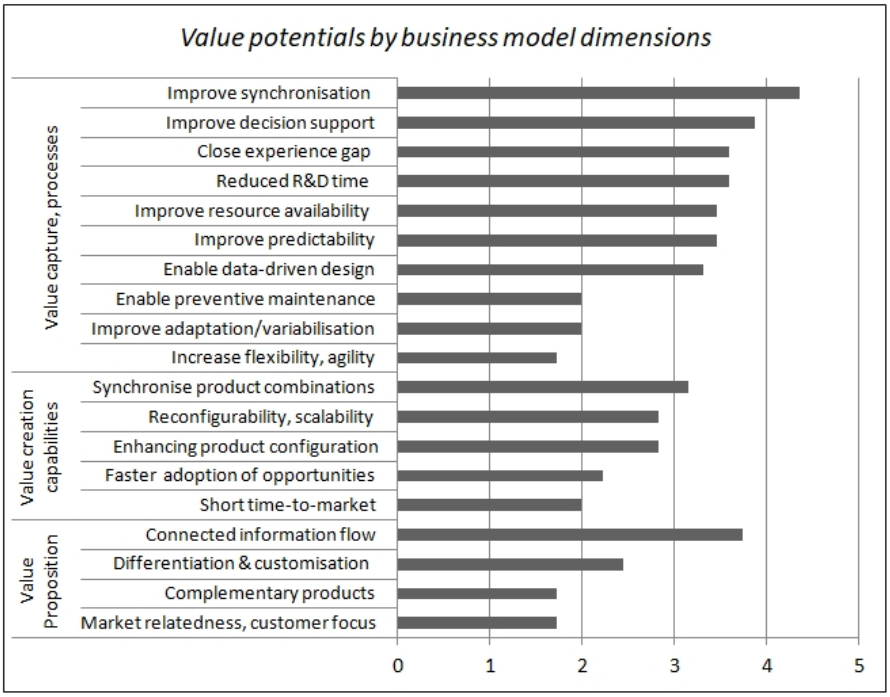


Fig. 11: Unfulfilled value expectations by BM dimension (Nuerk, 2024)

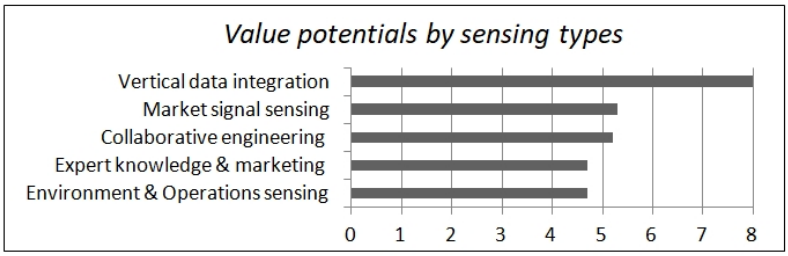


Fig. 12: Unfulfilled value expectations by sensing types (Nuerk, 2024)

4 RESULT AND DISCUSSION

The results presented in this chapter focus on SE-driven meta-modelling (4.1) to enable collaborative SC resilience and support ambidexterity of SC business models (4.2) through macro and micro simulations (4.3) and evaluations of performance and emergence and convergence (4.4). Section 4.5 summarises the findings in the context of the SE methodology and highlights their benefits for mastering various ambidexterity challenges.

4.1 Meta-Modelling for Resilience Along the Extended Supply Chain

Nearly all case study participants note that SC visibility decreases steadily due to increased process separation by more business partners. Rising environmental uncertainties and business dynamics lead to greater adversities, with roots and effects spread across SC domains. Therefore, improving SC resilience (SCR) and SC agility are top priorities in many man-

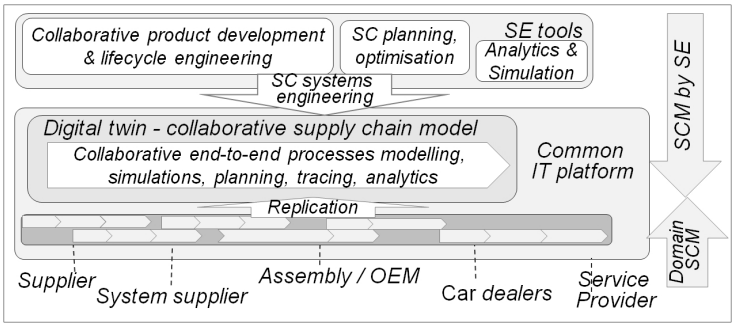


Fig. 13: Meta-modelling resilient SC networks—an end-to-end process perspective (Nuerk, 2024)

ufacturing sectors. The literature recognizes SCR as crucial for handling volatile, uncertain, complex, and ambiguous (VUCA) business situations, focusing on adaptiveness, responsiveness to disruptions, SC risk management, and performance management. However, all participants and industry initiatives, such as Catena-X for automotive, believe current SCR challenges must be addressed collaboratively and holistically across ecosystems, where approaches are currently lacking. SCR is significantly influenced by macroeconomic factors, often impacting locations different from the roots.

Traditionally, SC experts specialize in business functions like procurement, production, and sales. A holistic, cross-domain view of the multiple-tier supply chain is needed to sustain SCR. Cross-SC-domain knowledge is crucial for dealing with unforeseen vulnerabilities. To achieve overall SC visibility and identify local implications, the study recommends a bottom-up approach for domain-driven SCM by lines of business and a SE-driven top-down, cross-domain approach for modelling meta-structures along the supply chain, as highlighted in Fig. 13. This meta-systems perspective allows SE to identify vulnerabilities and latent structures using complexity engineering, simulation, and evaluation methods, safeguarding the resilience of the entire supply chain.

A systemic view of material and value flow across the supply chain, capacities, and bottlenecks among SC members requires new types of interoperability implemented in industries not yet. High visibility across the end-to-end supply chain enables informed decisions based on timely insights into operational flows between SC partners and deviations from plans, impacting delivery accuracy and SC agility, which presents vital variables of SC resilience. SE can significantly contribute to SC design and evaluation methods for controlling SC systems given SC integration's high variability, complexity, dynamics, and context-dependency. SE can provide SCR and performance continuity with a view of the entire end-to-end processes, keeping the supply chain stable and under control. A digital twin (DTW) can serve as a technical basis, enabling collaborative SC modelling connected to various partners' SCM systems, acting as a single source of truth. A DTW can also act as a common process platform, optimizing SC performance, energy consumption, and CO_2 emissions, synchronizing supply networks, and controlling resource sharing.

4.2 Ambidexterity Engineering of SC Business Models

Performance continuity and resilience in dynamic SC ecosystems depend on the right innovations, system convergence, and balanced ambidexterity between exploration and exploitation, strengthened by SE methods such as complexity engineering. Complexity, as a phenomenon of emergence, presents both an engineering challenge and a value source. Organizations must manage innovation streams and value-generating operations in a balanced way,

integrating external knowledge and designing socio-technical systems considering:

1. *Sequential Ambidexterity:* Exploiting technological innovations while coordinating transition architectures to balance business and environmental changes.
2. *Structural Ambidexterity:* Simultaneously exploring and exploiting innovations, and aligning corporate units, assets, and culture.
3. *Contextual Ambidexterity:* Designing and transforming processes to fit both exploratory and exploiting activities within the context.

Studies on ambidexterity emphasize cultural and structural characteristics. The current study highlights the importance of cross-organizational ambidexterity among supply network partners. Mastering ambidexterity requires SE to interact holistically across all SC business model lifecycle phases, integrating analytics and simulations of product lifecycles, SC optimization, and innovation processes. This supports planning reliability and precise product lifecycle management, which in turn provides valuable data for innovation management. In SC business models, ambidexterity refers to exploitation (enhancing existing capabilities) and exploration (developing new capabilities). Continuous evaluations of value exploration and exploitation effectiveness, as well as capability fitness, are core methods for safeguarding value continuity in digital SC models. Current SCM systems cannot consistently evaluate market adversities across the supply chain.

Ambidexterity engineering between innovation exploration and exploitation must be supported by simulations ideally integrating product development, lifecycle management, SC optimization, and macro-environmental implications. A digital twin can provide a platform for designing integrated processes and data models for simulations using real-time data from sensing, SC operations, and environmental conditions. Evaluating SC business model inputs, outputs, and object dependencies can be modelled using System Dynamics (SD). However, SD lacks granularity, so sub-models are needed to detect faults in detail. Combining two perspectives—a macro-level view from SD and a micro-level view using detailed sub-models—provides a feasible approach.

4.3 Modeling Simulations for SC Business Model Ambidexterity

Increasing complexity and business dynamics necessitate simulations in SC systems to enhance planning reliability and resilience. Simulations analyze SC systems' behaviour in complex conditions, supporting SC planning decisions and safeguarding investment projects. Simulation systems support:

1. Increasing distributed manufacturing networks.
2. Increased need for SC resilience by design and pre-emptive simulations.
3. Rising product complexity and variety.
4. Increased flexibility and customization.
5. Shortening product and service lifespan.
6. Growing quality requirements and cost factors.

These needs lead to shorter development and planning cycles, requiring intelligent strategies for complex technical systems in global companies. Analyzing complex dependencies between linking modules, production facilities, and supply systems is limited to mathematical-analytical methods. Simulation is a recognized method for analyzing and improving value-adding processes in production and supply chains. Case study participants see SE as essential for enabling closed monitoring of overall supply chains. SE requires a mindset across business domains to drive SC performance and resilience by design. SE must model analytics capabilities at the meta-level, providing early warnings of events affecting the supply chain across domains.

SCM application providers must offer modelling capabilities for creating meta-process structures for analytics and alerting. Evaluations of SC business model inputs, outputs, and dependencies can be modelled using SD, and are suitable for analysing economic macro effects and latent SC structures. However, SD lacks detail, so sub-models must be developed

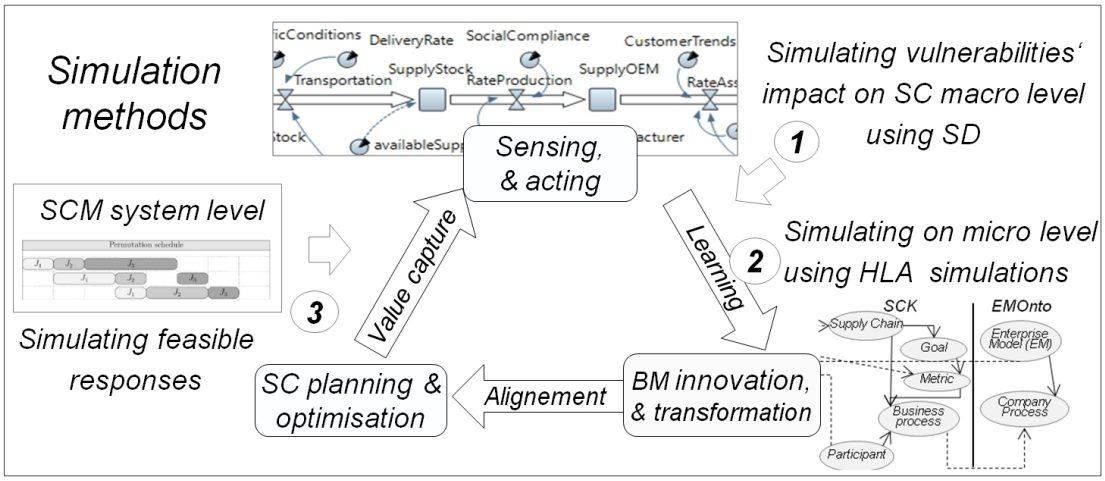


Fig. 14: Simulating local causes of macro effects and discrete responses (Nuerk, 2024)

to identify problems quickly. A combined simulation approach is needed, where the study proposes three levels for simulating supply networks and manufacturing plants:

1. *Macro Simulations* using SD.
2. *Micro Simulations* using agent-based high-level architecture (HLA) federations.
3. *SCM Application-Based Simulations* for detailed engineering change implications on SC planning.

Microscopic SC operations behaviour can be modelled using agent-based methods like HLA Federations. A top-down approach models supply networks based on SC strategies, addressing resilience to macroscopic effects (e.g., SD simulations) and microscopic responses to adverse events (e.g., HLA Federates). A bottom-up approach using agent-based modelling enables the evaluation of operational performance and resilience of critical locations along the supply network. A hierarchical network of agent-based SC operations entities allows simulation-based analysis to identify effective supply network designs to mitigate risks. A hybrid model using agent-based models like networked HLA Federates, which receive macro implications from SD for further simulations, is proposed. Distributed agent-based simulations can be structured using ontology networks like SCOR notation and HLAs are suitable for modelling and simulating complex scenarios across heterogeneous SCM systems.

A federation describes the overall simulation process, with participating systems (federates) linked via HLA middleware by a runtime infrastructure (RTI). HLA supports interoperability, reusability, extensibility, and refinement of existing models, enabling time-critical couplings and message exchanges across agent-based simulation infrastructure. This approach is useful for complex engineering-to-order projects and simulating circular economy use cases, where products can be traced and reused. Evaluating SC business model inputs, outputs, object dependencies, and environmental adversities can be modelled and simulated using SD combined with HLA federates for identifying local implications along the supply chain as shown in Fig. 14.

4.3.1 System Dynamics (SD) and Agent-Based Supply Network Simulations

SD fits for analyzing economic macro effects and latent SC structures but is not granular enough to detect detailed faults. Therefore, agent-based simulations modelled using ontology networks and High-Level Architecture (HLA) Federations are recommended by the SAP case study participants (P_1). Such simulations help understand emergent order in complex SC systems and search for the best

local design for performance, resilience and effectiveness on a local micro-level of the supply chain.

HLA Federates ontologies, linked with SCM SCOR ontology, enable modelling of local system effects, considering crossover effects through HLA runtime infrastructures (RTI). Hence, it can be stated that HLA Federates ontologies linked with SCM SCOR ontology enable the modelling of agent-based simulations about local systems effects considering systems' crossover effects enabled by HLA runtime infrastructures.

Finally, discrete SCM application-based simulations enable detailed analysis of phasing in new products, engineering change management, and phasing out products, providing early insights to safeguard resilience and performance continuity. Discrete, SCM application-based simulations enable detailed implications analysis of phasing-in of new products, engineering change management, and phasing-out products onto the overall SC planning, which provides early insights on necessary activities to safeguard resilience and performance continuity.

Fig. 14 highlights an integrated simulation use case, where expected environmental macro adversities are simulated on their impact on the supply chain using systems dynamics (SD) (no. 1 in Fig. 14) and further simulated using HLA modelling for evaluating their local effect on SC locations (no. 2). Based on these findings, SCM simulation capabilities can be used for exploring workarounds as response alternatives to adversities (no. 3). These can be alternative suppliers, sub-contracting manufacturers, alternative transportation routes, etc. Implementing an SD simulation concept involves:

1. Defining simulation objectives for SC efficiency and resilience.
2. Identifying key variables and relationships influencing the supply network.
3. Developing a conceptual model using SD techniques.
4. Translating the conceptual model into simulation software.
5. Modelling key SC processes and policies.
6. Calibrating and validating the simulation model.
7. Designing scenarios and executing simulations to explore different strategies and assess resilience.

4.3.2 Design, Implement, and Integrate an HLA Simulation Landscape

Designing and implementing a High-Level Architecture (HLA) landscape involves creating a distributed simulation environment that allows collaboration among multiple simulation components. Designing an HLA simulation landscape involves:

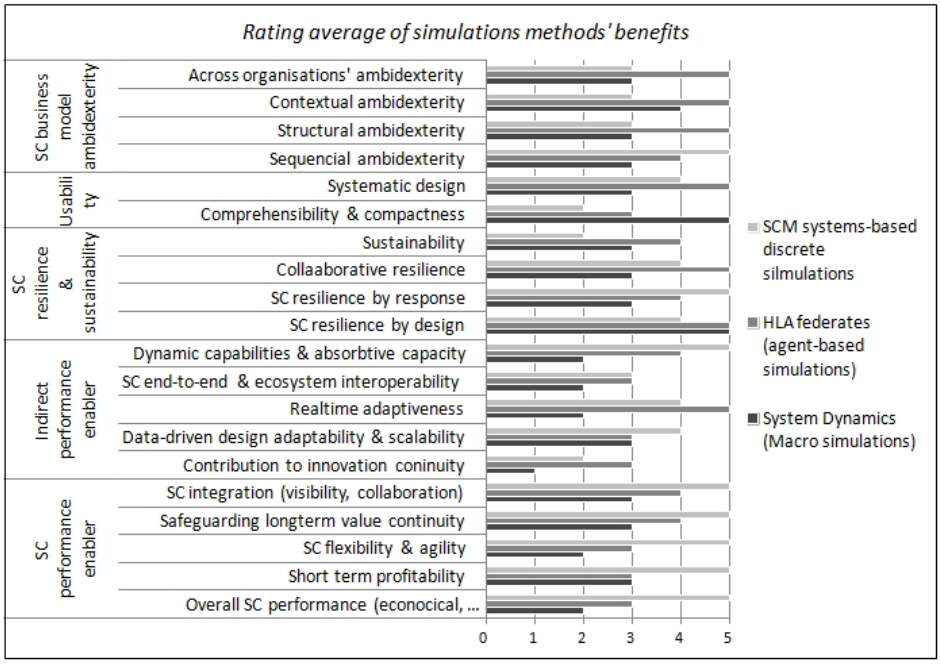
1. Defining simulation objectives and requirements.
2. Selecting an HLA-compliant simulation framework.
3. Defining simulation federates and their interactions.
4. Developing federated implementations.
5. Integrating federates with RTI.
6. Modelling simulation scenarios.
7. Configuring and deploying the simulation federation.
8. Executing and monitoring simulations.
9. Refining and optimizing simulations based on results.

Integrating SD simulation outputs into HLA simulations involves:

1. Defining data exchange requirements.
2. Exporting relevant SD simulation outputs.
3. Designing data interoperability mechanisms.
4. Transforming and integrating data into the HLA simulation.
5. Incorporating data into HLA simulation logic.
6. Validating integration and ensuring data consistency.

4.3.3 Supply Chain Simulations Using Digital Twins and SCM Applications

Business dynamics can be simulated to assess direct impacts on the supply network using SCM application simulation features. Multi-objective optimization and simulations provide insights into worst-case scenarios and help prioritise high-profit orders. Digital twins offer value through visualization, analysis, optimization, and simulations based on real-time data. SE activities for designing resilient supply



Legend to Model Validation: 1 = does not contribute to SC objective; 2 = contributes weakly to SC objective; 3 = contributes to SC objective; 4 = contributes strongly to SC objective; 5 = contributes very strongly to SC objective.

Fig. 15: Validation ratings of the benefits through the explored simulation methods (Nuerk, 2024)

chains include reviewing SC process design, balancing redundancies and economic performance, evaluating risks, and developing ML use cases (P_1, P_2).

4.3.4 Validation of the Explored Simulation Methods

The validation results of simulation methods (Fig. 15) highlight the benefits of SCM application-based simulations for identifying workarounds and optimising manufacturing schedules. However, HLA federates and SD simulations provide greater insights into SC business model ambidexterity. Combining these methods offers long-term effectiveness, agility, and responsiveness to business changes.

4.4 Evaluating the Emergence and Convergence of SC Business Models

Supply chain performance by operational SC processes is measured by key performance indicators (KPIs), with the SCOR standard providing useful hierarchical references. State-of-the-art SC metrics include KPIs for costs, delivery reliability, fulfilment rates, inventory levels, and more. Companies select KPIs based on specific needs, setting timeframes and thresholds to receive alerts for significant deviations. The study shows that performance evaluations using KPIs, value exploration and exploitation effectiveness (emergence), and capability fit (convergence) give a holistic business overview. This approach provides detailed insights into current performance, value exploitation, and capability fitness and enables informed predictions of future performance and value developments.

According to dynamic capability theory, continuous capability alignment is essential, and complex adaptive systems theory suggests that innovation potentials emerge with the creation of new order. Therefore, continuously evaluating value exploration, exploitation effectiveness, and capability fitness are core methods for value continuity. Case studies using sample companies showed that these methods offered rich insights and qualitative findings, particu-

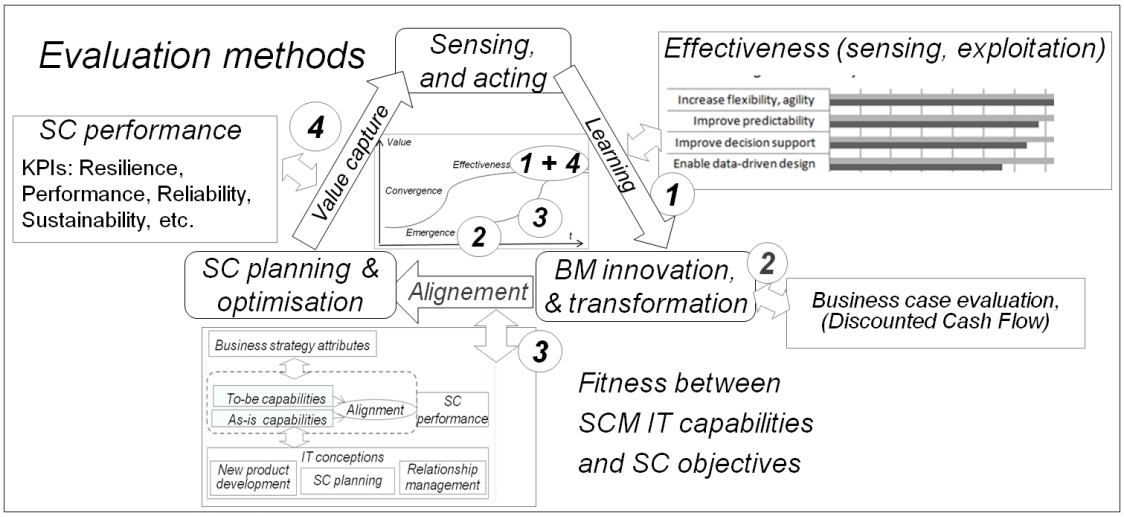


Fig. 16: Monitoring SC performance and evaluating value exploration and exploitation simultaneously to sustain profitability continuity (Nuerk, 2024)

larly in assessing the relationships between SC objectives and SCM IT capabilities and the effectiveness of value sensing and exploitation. To safeguard digital SC models' value continuity, the study proposes ongoing activities: evaluating the effectiveness between value enabler sensing and exploitation (Fig. 16, no. 2), evaluating capabilities' fitness levels (no. 3), and SC performance measurements using KPIs (no. 1). Assessing SCM IT capabilities supports enterprise convergence by providing alignment information. A systems approach, consistent with configurational theory, evaluates fitness levels, considering SC objectives and SCM IT capabilities, enabling a holistic system view. Misfit levels are calculated using the Euclidean distance. Such evaluations help in developing useful artefacts to prepare for economic change.

Investments in artefacts need economic proof, like the Discounted Cash Flow (DCF) method, to ensure monetary effectiveness. This approach also assesses the effectiveness of value sensing and exploitation by business model components, improving innovation productivity. It helps SE understand innovation processes during capability and product lifecycles and offers insight into value-enabling promoters and conditions.

4.4.1 Evaluating the Effectiveness of Value Sensing and Exploitation (Emergence)

A company's ability to use external knowledge for future innovations depends on existing related knowledge. Hence, a strong connection between innovation strategy, knowledge management, and market-sensing capabilities boosts innovativeness and market responsiveness. Collecting value signals and regular lessons learned contribute to the required pre-knowledge. Fig. 17 shows the relationship between value sourcing types and business model components where value opportunities can be adopted. Pairwise evaluations using a Likert scale can express estimated potentials for focused actions. Repetitive evaluations contribute to understanding innovation emergence and monitoring value during lifecycles. These evaluations provide insights into innovation potentials and value-enabling sensing patterns. Observing these patterns offers insights into organization-specific value processes and their conditions.

The case study participants concluded that value sensing improves awareness of signals' value from transforming into value propositions or business process benefits. Evaluating sensed value potentials and prioritizing BM components is crucial for innovation and ambidex-

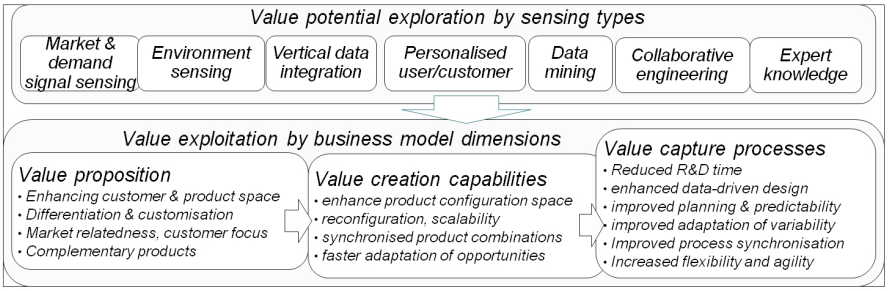
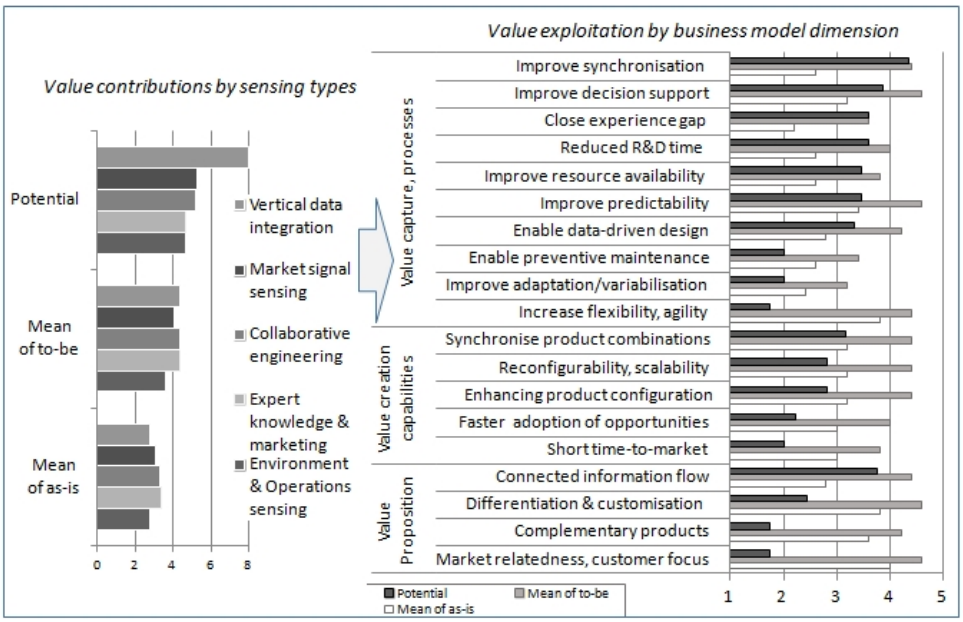


Fig. 17: Relationships of sensed value enablers and value contributors (Nuerk, 2024)



Legend: 1 = does not contribute to value generation; 2 = contributes weakly to value generation; 3 = contributes to value generation; 4 = contributes strongly to value generation; 5 = contributes very strongly to value generation.

Fig. 18: Evaluation result of value contribution by sensing types (exploration) and value exploitation by business model dimensions (a business division of sample company A) (Nuerk, 2024)

terity engineering. The approach requires the consultation of a broad variance of involved stakeholders for qualitative Likert scale assessments, supplemented by quantitative metrics. This holistic evaluation approach offers a comprehensive view of value sensing, exploitation, and innovation productivity benefiting SE and stakeholder collaboration. Findings improve understanding of emergence processes and convergence deficiencies in exploiting expected value, informing the development of artefacts and transformation roadmaps. Case study participants affirmed the value enabler evaluation as a high-priority, continuous lessons-learned activity in innovation management (P_1–P_7).

Hence, evaluating sensed signals and related exploited business value, as a ratio between innovation capacities and potentials, significantly benefits product and capability innovation (P_3, P_7–P_9). Fig. 18 summarises value potentials by sensing type, as evaluated with company A (P_7). Means calculation expresses as-is and to-be value potentials, while the Euclidean distance expresses the gap as remaining value potentials. This provides a holistic view of where value is sensed, and exhausted, and

where further activities can target remaining potentials. It also reveals where expectations were not met or exceeded. Iterative evaluation localizes value drivers and maps them to value propositions (VP), enriching capability matrices in lines of business (LoB) domains. The method gives an overview of the sensed value and exhausted value in the business model, identifying remaining value potentials for a focused roadmap of further activities. It also improves transparency on unmet or exceeded value expectations. This evaluation method is affirmed by industrial case study participants and SAP SE as a high-priority, continuous lessons-learned activity in innovation and transformation management (P_1, P_3, P_7). Such evaluations enhance the transparency of innovation potentials and awareness, providing insights into value-enabling sensing patterns.

Additionally, collecting value signals in a repository and learning from adopting these opportunities to value-generating business model dimensions can lead to pre-knowledge. Repetitive evaluations contribute to understanding innovation emergence and monitoring value, providing insights into organizational- and context-specific value emergence processes and promoter conditions. Evaluating relationships between innovation potentials and capacities helps balance exploration and exploitation efforts, crucial for SC business model ambidexterity engineering. The tested method reveals which sensing sources contribute to value levels, how BM components release value, and which conditions promote value enablers.

4.4.2 Quantitative Metrics and Linking with Qualitative Assessment

Innovation performance is evaluated using quantitative and qualitative measures to capture the effectiveness of innovation efforts. Common methods and metrics are detailed in Tab. 5 in the Annex. These assessments consider the impact of innovation on financial outcomes, market competitiveness, customer satisfaction, operational efficiency, and strategic alignment. Metrics for such evaluations are provided in Tab. 6. Linking KPI performance evaluations with Likert scale evaluations integrates quantitative metrics with qualitative assessments, offering a comprehensive view. Tab. 8 outlines activities for effectively linking these systems, combining quantitative measures with qualitative insights. This comprehensive approach allows organizations to demonstrate their ability to create value, drive growth, and achieve strategic objectives through innovation.

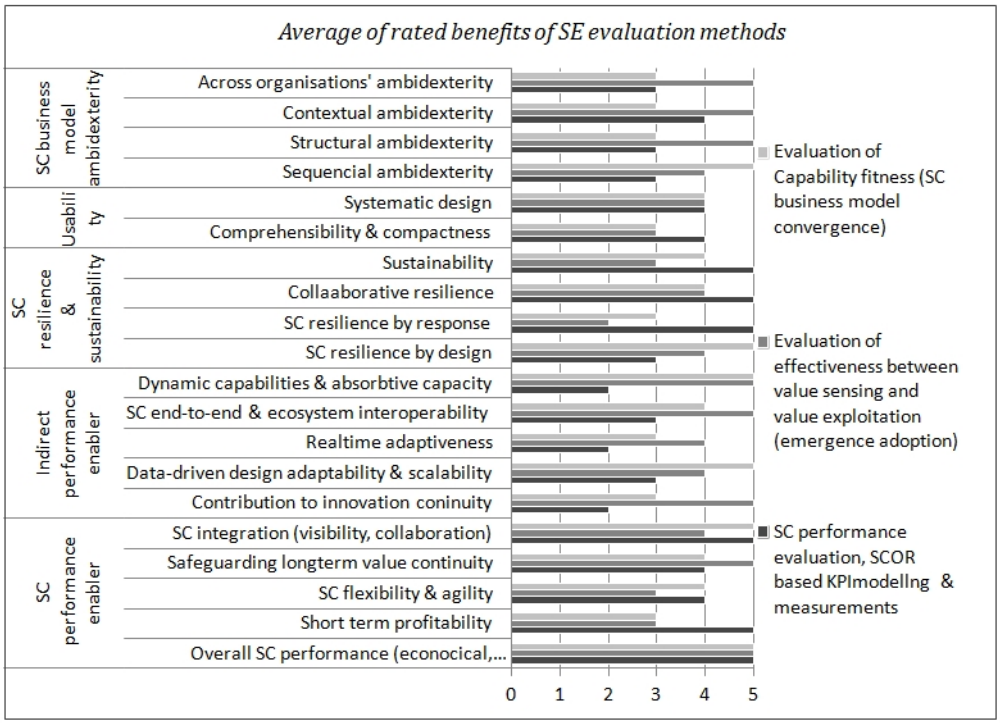
4.4.3 Capability Fit Evaluation for SC Business Model Convergence

Fit is defined as consistency across corporate design and context dimensions. A 2019 study developed a model to measure the fitness of SCM IT capabilities to the prevailing business model strategy, adapted to Industry 4.0 and SC objectives, and applied in sample company B. The model evaluates the as-is levels of SCM IT capabilities supporting SC objectives and the ideal to-be levels, identifying misfit levels and necessary alignment measures. The results align with SAP expert findings on SC collaboration gaps affecting agility and resilience. This evaluation confirms gaps in SC visibility as a root cause of limited resilience. The approach combines a holistic and detailed system view in context to evaluate needed capability levels for changing business situations and the development of dynamic capabilities using artefacts. This evaluation approach is suggested for assessing capability levels to support SC objectives, forming part of the SE-driven SC engineering and transformation model for strategic alignment and convergence.

4.4.4 Validation of Explored Evaluation Methods

Integrated evaluations of SC performance, the effectiveness of innovation adaptation, and capability fitness are the main components of analyzing the business model's ambidexterity.

Fig. 19 shows that participants rated ongoing KPI-based assessments to manage short-term SC performance and profitability as high. However, long-term performance requires business model ambidexterity and SC visibility for agility and responsiveness to unforeseen events. The case study research indicated that the evaluation approaches identify necessary SCM IT capabilities and their levels for ideal SC performance. These methods also enable the development of dynamic capabilities, fostering



Legend: 1 = no contribution; 2 = weak contribution; 3 = contributes; 4 = strong contribution; 5 = very strong contribution.

Fig. 19: Validation rating of the explored SE evaluation methods' benefits (Nuerk, 2024)

value emergence from innovations and convergence by implementing appropriate SCM IT capabilities. Ongoing evaluations and simulations create qualitative knowledge for responding to macro and micro implications.

4.5 The Study Contribution to Ambidextrous SC Business Models

According to dynamic capability theory, capability alignment must be continuous. Complex adaptive systems theory suggests that enterprise innovation potentials emerge with the creation of new order. Therefore, continuously evaluating value exploration, exploitation effectiveness, and capability fitness is crucial for value continuity. To safeguard digital SC models' value continuity, the study proposes the following ongoing activities:

1. Evaluation of Effectiveness between Value Enabler Sensing and Value Exploitation (Fig. 20, no. 2)
2. Evaluation of Capabilities' Fit Levels (Fig. 20, no. 5)
3. SC Performance Measurements Using KPIs (Fig. 20, no. 7)

Evaluating SCM IT capabilities' fitness levels supports enterprise convergence by providing information for value-focused alignment activities. This systems approach is consistent with configurational theory and has been implemented using a profile deviation approach. 'Fit' is defined as consistency across multiple corporate design and context dimensions and evaluated by a holistic and detailed system view. This approach was used to measure the fit of a highly innovative sample company's SCM IT capabilities to its business strategy. Fit and misfit are measured using Likert scales and calculated by Euclidean distance. These

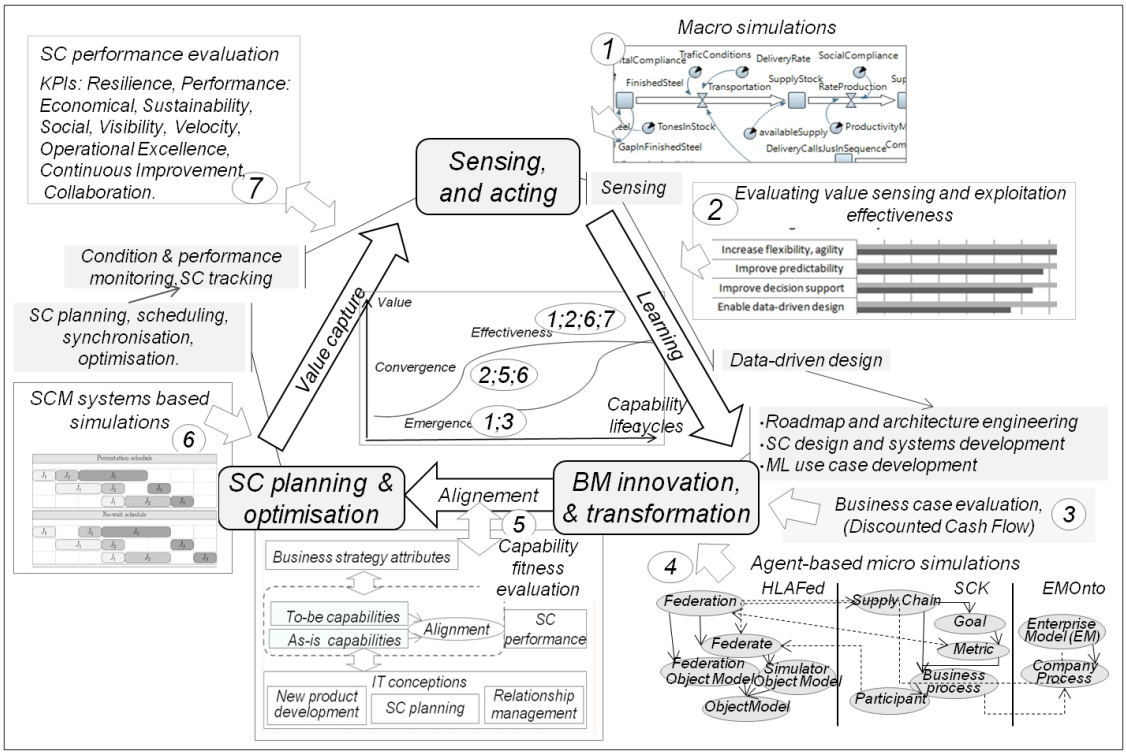


Fig. 20: Simulation and evaluation methods for ambidexterity of SC business models (Nuerk, 2024)

evaluations can develop artefacts for economic change preparation.

Continuous evaluation of value sensing sources' effectiveness and the exploited value by business model components provides insights into emergence drivers for value possibilities and transformation methods. For ambidexterity, investments in artefacts need economic proof, using methods like the Discounted Cash Flow (DCF) to demonstrate monetary effectiveness over time. Pairwise assessment of sensing and exploitation value by business model components allows a detailed evaluation of how value opportunities are identified and adopted into business value.

Value-generating relationships between sensing types and exploiting capacities have been assessed for effectiveness, providing transparency between value sources and actual exploitation capabilities. This evaluation improves innovation productivity and creates knowledge on innovation emergence and convergence during capability and product lifecycles. It also offers insights into value-enabling promoters and conditions, affirmed by participants as a high-priority, continuous lessons-learned activity. Ambidextrous objectives in SC business models focus on balancing exploration and exploitation within the supply chain, enhancing agility, resilience, and innovation while optimizing operational efficiency. Tab. 7 in the Annex outlines key ambidexterity dimensions, main challenges, and how this study proposes to address them.

5 CONCLUSION

Based on multiple case studies, this research identified key methods for reaching ambidexterity in supply chain business models, identifying vulnerabilities from increasing business dynamics and environmental uncertainties. The study proposes SE-driven metamodelling for resilience engineering in end-to-end supply chains and develops a simulation and evaluation methodology for SC business models.

Using common platforms like digital twins holistically enhances the monitoring and control of SC processes, complementing traditional SCM with a top-down SE approach for improving resilience across multi-tier supply chains. Collaborative meta-modelling across ecosystems using digital twins enables the development of cycle-business models, improves transparency of multi-tier supply chains, and enables holistic evaluation of performance and capability fitness and the effectiveness between value exploration and exploitation. Moreover, it supports modelling simulations of macro-environmental events for identifying appropriate responses to micro-level adversities and the most profitable plans that can be synchronized among SC members. Combining System Dynamics, HLA Federates and SCM application-based simulation methods drives the designing of innovative, resilient, and effective SC systems by exploring SC ecosystem contexts and the effects of macro conditions on micro levels.

SE is vital for maximizing the value of digital SC business models and ensuring resilience. Agent-based simulations help understand complex SC systems, improve transparency, and create profitable plans across SC members. The evaluation methods help to identify enablers of emergence and performance and their promoters and preventers. The methods improve collaborative resilience, align capabilities to market needs, and optimize processes through holistic evaluation. The study's methods enable organizations to better exploit supply chain value potentials by:

1. *Improving collaborative end-to-end process resilience* through increased visibility and agility enabled by metamodelling.
2. *Driving cycle business development* by metamodelling multi-tier supply chains driving collaborative product development, life cycle management, engineering change management, SC planning and optimization, and reuse.
3. *Enabling agile capability alignment* responsive to market demands and contextual needs.
4. *SC business model ambidexterity:* Optimising the emergence and convergence processes through holistic simulation and evaluation methods.

The SE methodology delivered by the research is validated to be compact, comprehensive, scalable, and adaptable. The qualitative evaluation methods for SC business model ambidexterity were underpinned by various quantitative metrics as provided in the appendix. Further research on detailed findings and patterns between qualitative and quantitative metrics from long-term studies is recommended. Such findings can enrich the SE framework leading to AI-based analytics use cases for ambidexterity engineering of SC business models.

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7 ANNEX

Tab. 4: The case study participants and their area of contribution

Partic.	Qualification	Roles of the participants	Area of contribution	Company
P1	Dr.-Ing.	Chef developer & development team lead of SAP Industry 4.0 Application	Semi-structured interviews and expert interviews. Review of the model and research theory; ML use cases for SCM. Industry 4.0 developments, and initiatives; Evaluation and validation of the overall model.	SAP SE; SAP Deutschland AG
P2	Diplom-Informatiker	Member of Industry 4.0 product development team		
P3	Dr.-Ing.	Business Enterprise Transformation Principal and Project Manager	Semi-structured interviews and expert interviews. SCM AI and ML capabilities and use cases. Industry 4.0 initiatives. Evaluation and validation of the overall model and validation of approaches.	
P4	Diplom-Informatiker	Chef developer and department manager of SAP SCM APO		
P5	Dr. rer. pol.	SCM Chief Expert Consultant for S&OP, IBP Optimization and Manufacturing Scheduling and optimization	Scheduling and Optimization and solution approaches for manufacturing and process industry. Opportunities from digitalization capabilities. Model evaluation on planning and optimization	
P6	Diplom-Wirt.–ingenieur	Chef Product Manager for SAP SCM APO, IBP; and Solution Architect	Focus group discussions about maturity levels of SCM domains and strategies and related KPIs	
P7	B.A. Business Administration & Betriebswirt (VWA)	SCM Expert for Automotive, OEM, automotive whole sales and automotive supplier; former SCM expert at an automotive supplier, and an automotive wholesaler	Value opportunities along the supply chain and across automotive ecosystems and transformation obstacles. ML use case in SC planning and replenishment. Evaluation of the overall model regarding SCM digitalization and innovation.	Company A
P8	Diplom-Wirtschafts-informatiker	IT Project Manager and SW Development Expert at Siemens AG, Area: Application Systems for R&D, PLM, & Manufacturing	The benefit of SE and effectiveness in innovation, transformation and reusability in big organizations. Requirements engineering and MBSE as an enabler of a common view	Company C
P9	Professor of Engineering Science	Chief IT Strategist; SCM process expert at a high-end product steel producer	Value contribution of digitalization capabilities to SC processes. Contributions of SE in industrial digitalization, Evaluation of capability alignment.	Company B
P10	PhD in computer science	Senior Director Product Management -Predictive ML; and Senior Director, Analytics and ML	SAP S/4HANA Predictive Machine Learning. Python API and ML library for S/4HANA; Possibilities and capabilities.	SAP SE
P11	Diplom-Ingenieur	Director of SAP Digital Supply Chain (Presentation and discussion)	Machine Learning and Automation in SAP IBP, capabilities, and use cases.	
P12	Dr.-Ing. IT	Technical Evangelist, Microsoft Germany, and SAP	Deep Learning on Azure. Capabilities of Azure and how to use and embed.	Microsoft; SAP SE
P13	Informatiker; PhD in Mathematics	CTO of IBM Global Technology Services (retired) and SAP (Presentation and discussion)	Transforming the IT service lifecycle with AI technology. A data-driven and knowledge-base approach to IT optimization.	IBM; SAP SE
P14	PhD in Informatics	Head of Competence KMI Institute Leipzig & SAP	Rapid and automated Supply and Demand matching. Semantically matching demand with supply.	KMI InfA; SAP SE
P15	PhD in Informatics	Lead Development Architect and expert for ontological alignment	Ontology alignment, semantic matching of demand and supply, and automated schema-matching	SAP SE; Signavio

Source: Nuerk (2024)

Tab. 5: Methods and metrics for expressing innovation performance

Method/metric	Description
R&D investment	Measure the investment in research and development activities. Including personnel, equipment, facilities, and external collaborations. Express R&D investment as a percentage of revenue or as absolute monetary value.
Patents & intellectual property assets	Count the number of patents granted to the organization of IP assets developed, including patents, trademarks, copyrights, and trade secrets. Evaluate the quality and significance of patents based on factors such as citation counts, patent family size, and licensing revenue.
New product development	Track the number of new products introduced to the market over a specific period. Assess the success of new product launches based on factors such as market share, sales growth, customer satisfaction, and profitability.
Time-to-market	Measure the time taken to develop and launch new products or innovations from concept. Express time-to-market as the average development cycle time or the percentage of projects meeting target launch dates.
Market share and penetration	Monitor changes in market share and penetration resulting from innovative products, technologies, or business models. Compare market share metrics before and after the introduction of innovations to assess their impact.
Customer adoption & satisfaction	Survey customers to assess their awareness, adoption, usage, and satisfaction with innovative products or services. Metrics are Net Promoter Score (NPS), customer retention rates, lifetime value, sentiment, and loyalty.
Revenue from New Products	Track the revenue generated from sales of new products or innovations as a percentage of total revenue. Assess the contribution of new products to overall revenue growth and profitability.
Employee engagement and creativity	Measure employee engagement in innovation activities through surveys, feedback mechanisms, and participation rates in innovation programs. Recognize and reward employees for their contributions to innovation, creativity, and problem-solving.
Partnerships & collaborations	The number of strategic partnerships, alliances, and collaborations established to drive innovation. Evaluating the impact of partnerships on access to new markets, technologies, resources, and knowledge.
Innovation Culture and Climate	Assess the organizational culture and climate for innovation through employee surveys, leadership assessments, and cultural audits. Measure factors such as risk tolerance, openness to new ideas, tolerance for failure, and support for experimentation.
Social and environmental impact	Evaluate the social and environmental impact of innovations using metrics such as carbon footprint reduction, resource efficiency, social equity, and community engagement. Express impact metrics in terms of sustainability goals, and social responsibility initiatives.
Innovation awards and recognition	Participate in industry awards programs and competitions to gain recognition for innovative products, technologies, or initiatives. Showcase awards and accolades received for innovation performance as external validation of organizational achievements.

Source: Nuerk (2024)

Tab. 6: Value contribution evaluation approaches and metrics

Approach	KPIs for the evaluation approach
Financial metrics	(1) Revenue Growth: Measure the increase in revenue attributed to innovative products, services, or business models. (2) Profitability: Assess the impact of innovations on profitability through metrics such as gross margin, operating margin, and net income. (3) Calculate the return on investment from innovation projects by comparing the financial benefits (e.g., revenue, cost savings) with the investment costs (e.g. R&D expenses, capital expenditures). (4) Cost Reduction: Evaluate the cost savings or efficiency gains achieved through innovations in processes, technologies, or resource utilization.
Market metrics	(1) Market Share: Monitor changes in market share resulting from successful innovations that capture new customers or displace competitors. (2) Customer Acquisition and Retention: Assess the ability of innovations to attract new customers, increase customer loyalty, and reduce customer churn rates. (3) Brand Equity: Measure the impact of innovations on brand perception, brand awareness, and brand loyalty among target customers.
Customer metrics	(1) Customer Satisfaction: Evaluate customer satisfaction levels with innovative products, services, or experiences using surveys, feedback mechanisms, and customer ratings. (2) Customer Lifetime Value. (3) Customer Loyalty: Assess the loyalty of customers who engage with offerings through metrics such as Net Promoter Score and repeat purchase rates.
Operational metrics	(1) Process Efficiency: Measure improvements in operational efficiency, productivity, and cycle times resulting from innovations in processes, workflows, or automation. (2) Resource Utilization: Evaluate the optimal use of resources, including human capital, equipment, and materials, achieved through innovative practices or technologies. (3) Quality and Reliability: Assess the impact of innovations on product quality, reliability, defect rates, and customer satisfaction with product performance.
Strategic metrics	(1) Alignment with Strategic Objectives: Evaluate the extent to which innovations align with organizational goals, priorities, and strategic initiatives. (2) Competitive Advantage: Assess the competitive advantage gained from innovations in terms of differentiation, market positioning, and barriers to entry for competitors. (3) Long-Term Sustainability: Consider the long-term sustainability and resilience of innovations in addressing emerging market trends, technological disruptions, and regulatory changes.
Social and environmental impact	(1) Social Responsibility: Evaluate the social impact of innovations in terms of job creation, community development, and societal well-being. (2) Environmental Sustainability: Assess the environmental impact of innovations on resource conservation, pollution reduction, and carbon footprint mitigation.
Qualitative assessment	(1) Stakeholder Feedback: Gather qualitative feedback from stakeholders, including customers, employees, investors, and partners, to understand their perceptions of the value created by innovations. (2) Case Studies and Success Stories: Document and share case studies, success stories, and testimonials that highlight the tangible and intangible benefits of innovations for stakeholders.

Source: Nuerk (2024)

Tab. 7: Ambidexterity dimensions and the study contributions to mastering those (Nuerk, 2024)

Dimension	Challenge to balance	Study contribution to respond to the challenge
Efficiency vs. flexibility	Balancing efficiency in operations with the necessity to adapt and flexible response to changing market demands & disruptions. This involves process optimization for cost-effectiveness while agility adjusts to new circumstances.	The study delivers a holistic simulation and evaluation framework for agile response to market and context changes. It enables the identification of adversities in time and the most suitable response. Collaborative SC resilience engineering enables high adaptiveness and efficiency. The evaluation methods and simulation methods enable the designing of effective capabilities and dynamic capabilities for fast and flexible responses to business change.
Strategic alignment	Ensuring alignment between strategies and SC models with organizational goals, enabling synergy between exploitation and exploration.	The study's evaluation method deliverables support value-oriented and focused developments of transformation roadmaps and scoping of transformation and capability alignment activities. The simulation methods enable focused design, transformation processes, and capabilities alignment, for the agile flexible, and responsive design of SCM IT infrastructure. Finally, the evaluation methods provided by the study enable the effective development of dynamic capabilities by SE-driven capability engineering and strategic capability alignment.
Adaptive capacity	The ability to quickly respond to changes in markets, customer preferences, or disruptions by adjusting SC capabilities.	
Technological exploration and exploitation	*Technological exploration:* drive innovation and adapt to changing market demands. This includes activities such as R&D and prototyping exploring emerging technologies. *Technological exploitation:* leveraging existing capabilities to optimize operations, enhance productivity, and deliver value to customers. This involves process optimization and continuous improvement initiatives to exploit the full potential of established technologies and practices.	*A holistic view design, transformation, evaluations, and simulations:* The SE model delivered by the study enables holistic engineering, evaluation, and simulations along the life cycles and respective technology curves of the SC business model, capabilities, products, and services of a company. *A holistic view on all phases of lifecycles:* The model provides an integrated view of sensing innovations, their transformation and convergence processes, and their optimization and value exploitation. *Optimized emergence processes (value exploration):* Practising the evaluation of sensing and value exploitation developed by the study provides deep insights into the emergence of value enablers and value exploitation processes by the business model components. *Optimized convergence (value exploitation):* Capability fit evaluations as demonstrated by the study enable highly effective transformation roadmaps and optimized value exploitation.
Business model innovation (BMI) vs. operational efficiency	*In Industry 4.0, BMI* involves experimenting with novel approaches such as product-as-a-service, platform-based business models, and ecosystem partnerships. *Operational efficiency* emphasizes optimizing internal processes to enhance productivity, reduce costs, and improve agility. This includes lean manufacturing, just-in-time production, and demand-driven logistics to streamline operations and increase competitiveness.	The evaluation method delivered by the study enables the identification of value potentials and conditions that foster emergence and help to create knowledge to improve innovation productivity. The digital twin-based SC model facilitates virtual testing and prototyping, reducing the time and cost associated with physical experiments and accelerating the development of new solutions. By optimizing processes and reducing downtime through predictive maintenance, digital twins contribute to significant cost savings. They help in resource optimization by providing detailed insights into asset utilization, leading to more efficient use of resources and reduced waste. DTWs provide a shared platform for collaboration among organizations. This shared visibility encourages innovation and continuous improvement.
Innovative product and service development	Explore new product & service offerings that address evolving customer needs & market trends, while exploiting existing capabilities for profit & service levels.	Collaborative product development and life cycle engineering supported by smart cycle business models were enabled by digital twin-based meta-modelling and simulations. Vertical integration for data collection from products in use will provide fast insights into product strengths and necessary improvements.
SC resilience and risk management	Managing risks associated with SC disruptions, such as natural disasters, or supplier failures, while also fostering innovation and experimentation to stay competitive and seize new opportunities.	A comprehensive proposal and concept have been delivered by the study enabling SC ecosystem partners to master the urgent topic of increased SC visibility by collaborative SC resilience processes. A robust and holistic SC meta-modelling concept including holistic evaluations and simulations has been worked out and empirically evaluated and validated by case studies.

Source: Nuerk (2024)

Tab. 8: Activities for linking quantitative KPI measures with qualitative measurements

Activity	Description
Define KPIs and Likert scale metrics	Identify the relevant KPIs to assess performance. These could include metrics such as productivity, efficiency, quality, customer satisfaction, or financial performance. Define the Likert scale metrics or criteria that will be used to assess performance qualitatively.
Establish weighting and importance	Assign importance scores to each KPI and Likert scale metric based on their relative significance to the overall performance evaluation. Determine the relative contribution of KPIs and Likert scale metrics to the overall performance score or evaluation criteria.
Collect data	Collect data for both KPIs and Likert scale metrics through several sources, for instance, performance reports, surveys, feedback reports, and direct observation. Ensure that data collection methods are consistent, and aligned with the defined KPIs and Likert scale criteria.
Normalise data	Normalize the data collected for KPIs and Likert scale metrics to ensure that they are on a consistent scale and can be compared directly. Convert KPI measurements into a standardized format, such as percentages, ratios, or indices, if necessary. Standardize Likert scale responses into numerical values (e.g., 1 to 5) to facilitate quantitative analysis and comparison.
Aggregate scores	Aggregate individual scores or measurements for each KPI and Likert scale metric across periods, projects, or organizational units. Calculate composite scores or weighted averages for KPIs and Likert scale metrics based on their respective weights and importance scores.
Integrate data	Combine quantitative KPI scores with qualitative Likert scale assessments to create a holistic performance profile.
Analyse results	Analyze the data for needed corrections and possible optimization. Benchmark KPI-based scores with Likert scale evaluations to identify correlations, discrepancies, and areas of alignment between quantitative and qualitative assessments.
Provide feedback and recommendations	Provide feedback to stakeholders based on the integrated performance evaluation results. Offer recommendations for improving performance based on insights from both KPIs and Likert scale assessments, focusing on areas of strength and opportunities for development.
Iterate and refine the evaluation Process	Iterate on the performance evaluation process based on feedback from stakeholders, changes in organizational priorities, and evolving performance objectives. Refine the weighting, criteria, and integration methods for linking KPI-based evaluations with Likert scale assessments to enhance the effectiveness and relevance of the evaluation system over time.

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3D GEOSPATIAL DATA VISUALIZATION IN VR

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ABSTRACT

The use of Virtual Reality (VR) to visualize data is increasingly common in various fields, from medical science to education. However, visualization of geospatial data in VR is still not handled well. GIS data comes in various formats and converting them to 3D can be challenging. The choice of a format capable of streaming large amounts of spatial data in the VR scene is crucial. However, the challenge lies in ensuring the reusability of the presented scenes with different GIS data. Most applications (including the 3D scene models) are created for a single use case and do not allow for simple interchangeability of presented data. This article proposes a reusable architecture of a general-purpose web service for processing and visualizing spatial data in VR using 3D Tiles as the chosen format. The goal of the architecture is to allow fast VR scene generation from GIS data. The critical aspect is the conversion of standard GIS format to 3D Tiles. Several conversion tools were tested and compared using publicly available point and polygon feature layers in order to choose which can be used in the proposed architecture.

KEY WORDS

virtual reality, spatial data, 3D Tiles, data conversion

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1 INTRODUCTION

Visualization of geospatial data within Geographic Information Systems (GIS) is a common task in various applications. The most frequent method is to visualize the data in 2D using widely used software like the open-source application QGIS or ESRI's ArcGIS Pro. Visualization of geospatial data in 3D is also common, referred to as 3D GIS (Boulos et al., 2017). 3D GIS is primarily a visualization tool that concentrates on topological models and frameworks for portraying spatial relationships (Antoniou et al., 2020). The subsequent level of visualization entails the utilization of Virtual Reality (VR). The fusion of VR and GIS is referred to as VR GIS (Virtual Reality Geographic Information System) (Lv et al., 2016). Using VR with geospatial data offers users a heightened level of immersiveness that is lacking in conventional GIS applications. Research indicates that immersive virtual reality (VR) provides users with a higher level of embodiment compared to traditional 3D GIS (Bagher et al., 2022). VR can reduce distractions through immersive experiences and offer more space for users with its 360-degree capabilities (Spur et al., 2020; Wang et al., 2020). Additionally, it can improve spatial analysis and information query abilities (Zuo, 2020).

To create a VR visualization of GIS data, two commonly used approaches are game engines (Du et al., 2018; Halik, 2018) and WebXR technologies (Sermet and Demir, 2022). However, all VR GIS applications share a common challenge – the production of 3D geospatial data for visualization in VR. Unlike traditional GIS applications that only require the use of 2D information, VR GIS necessitates a large amount of data in all three dimensions. This presents a significant challenge to address as the source data is often only available in conventional GIS formats, like Shapefile or GeoJSON, or in three-dimensional formats, such as CityGML (Rahman et al., 2019), that are not optimized for efficient visualizations, but rather just for the representation of three-dimensional models. As a result, to create VR GIS, the data must be converted into a format that is optimized for the streaming of large three-dimensional geospatial data. The two most commonly used formats today are 3D Tiles from Cesium and Esri Indexed 3D Scene Layer (i3S) (Würstle et al., 2022). Both Cesium and Esri offer software development kits (SDKs) for creating virtual reality (VR) applications using Unity or Unreal Engine.

Nevertheless, Unity and UE are only visualization tools and must be provided with 3D data (most commonly in the form of standard 3D model format). The most common approaches create the 3D scene models in specialized software and then import them to game engines for visualization. This poses a challenge in situations, where the underlying data often change and the entire scene must be recreated from the beginning. This article outlines the architecture of the VRGIS application for visualizing geospatial data without the need for the intermediate step (i.e., the 3D model creation in specialized software manually). The application's primary objective is to translate standard GIS formats and present them as 3D visualizations in VR, thus allowing to create the scene from new data easily. The main format used for visualization in the proposed application is 3D Tiles. The 3D Tiles format was chosen because it can be easily created using many available converters, unlike the i3S which can be created primarily only using ESRI software.

The article is structured as follows: Section 2 presents a literature review of approaches to visualizing geospatial data in VR, including commonly used spatial data visualization and streaming formats for virtual reality. Section 3 describes the proposed architecture of the system for geospatial data visualization in VR. Section 4 outlines the crucial part of the application, the data conversion from standard GIS formats to formats suitable for VR visualization. In section 4, the tests were conducted on the available tools for converting geospatial data from GeoJSON to 3D Tiles. Finally, Section 5 discusses the proposed architecture and the selected technologies.

2 LITERATURE REVIEW

This chapter first reviews the use of various geospatial data sources for different visualization purposes. The second part outlines the technical details of data formats suitable for storing and transfer of geospatial data.

2.1 Use Cases for Geospatial Data in VR

The visualization of spatial data in VR is an established field, with numerous examples available. For instance, the PeakLensVR application developed by La Salandra et al. (2019) facilitates the capture of panoramic images using mobile devices, which can then be augmented with data from OpenStreetMaps. Meanwhile, Wang et al. (2019) utilizes 360-degree panoramic images to enhance a system designed to assist with flood risk management through VR visualizations. To increase the visualization element, the addition of cars and trees was implemented (León et al., 2023). The study employs virtual reality (VR) to evaluate the selection of evacuation shelters during emergencies, specifically tsunamis. The application was developed to examine the preference for certain types of buildings during emergency situations. Another application of VR is in aiding the urban decision-making process for the Rafah planning authorities (El Halabi et al., 2019). Data is prepared through traditional GIS, imported to Esri City Engine, and visualized using the 360 VR Experience. The findings suggest that virtual reality (VR) can enhance comprehension amongst planners and other stakeholders. Nonetheless, it has been noted that editing virtual models can be challenging.

Another example is presented in Lindquist and Campbell-Arvai (2021). The Land.Info software was designed to aid in co-designing vacant lots with 3D visualization. The study details the development of a series of virtual environment prototypes, each of which was tested in a series of workshops with the public with the goal of increasing stakeholder engagement. Yang et al. (2018) explored various methods of rendering globes in virtual reality. The exocentric globe, flat map, egocentric globe, and curved map were all tested. The results indicate that the exocentric globe is typically the optimal choice for visualizing the globe in virtual reality (VR). Establishing a spatial presence is a crucial aspect of visualization. The user must recognize the virtual environment as their primary space (Hruby et al., 2018). VR can be used to visualize not only the globe but also traditional 2D maps (Spur et al., 2020). The authors sought to determine the optimal method for visualizing a two-dimensional (2D) map in virtual reality (VR). They proposed a three-dimensional (3D) stack of 2D maps. The projection of a 2D map in VR can be found in (Letić et al., 2018).

Indoor building presentations are also commonplace. The 4D immersive presentation of a virtual museum was developed by (Kersten et al., 2017). The authors reconstructed the museum's 3D model through terrestrial laser scanning. Additional modeling was required for the model to meet the necessary requirements. The VR environment was created using the Unreal Engine (Choromański et al., 2019). Campanaro and Landeschi (2022) fused VR technology with eye-tracking to monitor user visual attention within the Pompeian house. The 3D model of the house was imported into the Unity engine, while the eye-tracking data were analyzed in ArcGIS Pro. BIM is one of the many areas where the proposed research could be utilized.

Large-scale areas can also be visualized through virtual reality (VR), as demonstrated by the work of (Halik, 2018). They produced a 3D representation of a built-up area in Poland, converting the original vector data to the fbx format and visualizing it in the Unity engine. Although the conversion to 3D model formats is widespread, it can result in the loss of attribute and spatial information. Antoniou et al. (2020) used UAV-based photogrammetry to create a high-resolution 3D model of the Metaxa Mine in Greece. The 3D model was subsequently imported into GeoVR software for

advanced GIS analysis. Vanden Broucke and Deligiannis (2019) created a VR application for visualizing heterogeneous, smart city data of Brussels. A comparison was made between the VR application and more conventional web platforms, with the results indicating a decrease in frustration levels when exploring the city.

Sermet and Demir (2022) created the GeospatialVR which is an open-source collaborative virtual reality framework. The framework goal is to generate the virtual reality scene in real time from common data sources using terrain data, elevation mode, and many more. The data is visualized from the Bird's eye view and allows users to collaborate and see other users' positions in the scene. To enhance the visualization, the animation of elements such as water flow or fire are used.

2.2 Formats for Visualization of Geospatial Data in VR

Geospatial data is typically visualized using standard 3D formats, such as fbx or obj, due to their compatibility with game engines. However, these formats are unsuitable for streaming large amounts of data. The two most commonly used formats for streaming geospatial data are 3D Tiles and I3S.

I3S is an open standard developed by Esri for storing and streaming large 3D geospatial data. It supports various types of data, including 3D models, BIM data, photogrammetry, point features, and point clouds. The standard is designed to be cross-platform and scalable. It defines a REST API for accessing the data. Additionally, the data can be stored in a `.slpk` file. The Open Geospatial Consortium (OGC) adopted the specification as a community standard in 2017. Since then, Esri has released several versions of the standard (Belayneh, 2022; Esri, 2024; Open Geospatial Consortium, 2023).

Another option is the 3D Tiles format, which is an open standard with the same purpose as I3S. Cesium introduced it in 2015, and it supports photogrammetry, 3D models, and point clouds. A single 3D Tiles dataset is called a tileset. The tileset is composed of tiles that are arranged hierarchically into a spatial data structure. The children of a tile fit into its bounding volume. Bounding volume can be an oriented bounding box, a bounding sphere, or a geographic region defined by minimum and maximum latitudes, longitudes, and heights. Bounding volume hierarchy can be defined explicitly by providing bounding volumes for every tile or it can be defined implicitly using common spatial division structures such as quadtrees or octrees. Implicit tiling enables random access to the tiles. The 3D content of 3D Tiles is stored in an open glTF standard, commonly known as the 'JPEG of 3D'. 3D Tiles enables the attachment of metadata (feature table in GIS) to various parts of a dataset, such as a texel or tile (CesiumGS, 2024a). The OGC accepted this standard in 2019 (Open Geospatial Consortium, 2019). The standard is supplemented by the Quantized Mesh standard for visualizing terrain data (CesiumGS, 2024b).

3 THE PROPOSED SYSTEM ARCHITECTURE FOR SPATIAL DATA VISUALIZATION IN VR

In order to visualize geospatial data in VR, we propose a system architecture (see Fig. 1). The architecture was designed based on the review performed in Section 2 and consists of three main parts: a) backend service for storing and processing spatial data, b) frontend application for managing spatial data and preparing scenarios for various use cases, and c) client application for displaying the data in VR headsets. Unlike traditional approaches where the main focus is on the visualization part (La Salandra et al., 2019; Lindquist and Campbell-Arvai, 2021), our architecture is designed to cover all aspects of the visualization pipeline. The purpose of the architecture is to enable the users to upload prepared files in a

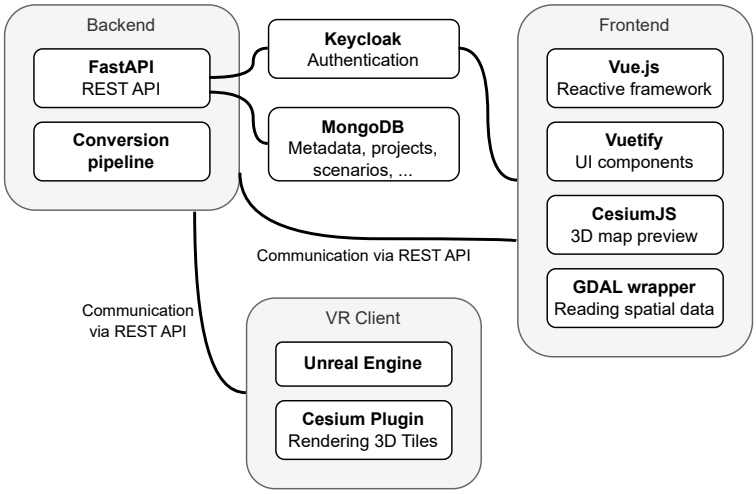

Fig. 1: A diagram of the system's architecture along with the used technologies for each part

standard GIS format. The upload is done using a front-end web application. The GIS data is converted to 3D Tiles at the backend and based on the provided user scene definition, a VR scene configuration is sent to the visualization part (Unreal engine). This is in contrast to approaches such as Kersten et al. (2017) and El Halabi et al. (2019) where a single-purpose scene is created. This approach has also an added advantage in the possibility to easily add other elements to the scene, such as trees or cars. This can be very beneficial to user experience as mentioned in León et al. (2023) and Lindquist and Campbell-Arvai (2021).

3.1 Backend Service for Storing and Processing Spatial Data

A crucial aspect of the backend is the conversion of spatial data to 3D Tiles. As most libraries for this task are written in Python, it is beneficial to implement the entire backend in Python. FastAPI, a commonly used framework for building API services, was used.

Spatial data are typically large textual or binary files and are stored using a standard file system. Metadata about assets, camera positions, or scenarios will be saved in MongoDB. The data structure is simple with few relations. Horizontal scaling of NoSQL databases may be beneficial when deploying our solution for multiple worldwide purposes. Additionally, user management and authentication will be outsourced to an open-source service Keycloak.

3.2 Frontend Application for Managing Spatial Data and Preparing Scenarios for Various Use Cases

The frontend application is intended for administrators to upload spatial data assets, convert them into spatial data, combine them using layers, and define projects with scenarios based on these data.

To ensure long-term stability, Typescript will be used as our proposed solution. The reactive framework Vue.js, currently in version 3, will also be used. Vuetify offers a collection of reusable UI components that simplify the implementation of user interfaces. The frontend application will be connected to Keycloak to manage authentication and access rights.

Additionally, libraries such as CesiumJS will be utilized to provide 3D previews of assets that users are working with. Furthermore, the GDAL wrapper for Javascript (`https://github.com/azavea/loam`) enables access to spatial data files directly in the browser.

3.3 Client Application for Displaying the Data in VR Headsets

The application for displaying spatial data to the user is created within the Unreal Engine version 5.3, which brings a wide range of supported platforms. The client application will be optimized for Meta Quest Pro VR glasses.

Within the UE, a plugin called Cesium for Unreal is used to display 3D Tiles. This plugin is connected to the Cesium Ion platform, from where it is possible to use a large number of freely available pre-prepared data (Imagery, Terrains, 3D buildings, etc.), or use your own content generated by the conversion from standard GIS format on the backend.

Spatial data will be rendered according to the data provided during the client application communication with the backend service. A standard JSON format is used. This file contains the definition of scenarios (i.e., the 3D scene) and the layers in them. Furthermore, this file contains additional information about individual layers. Layers can be of two types, namely layers located on the backend of the application and layers located on the Cesium Ion platform. According to the individual scenarios, layers will be imported into the application, so that the user can work within individual scenarios or move freely between them.

4 GIS DATA CONVERSION TO 3D TILES EVALUATION

As mentioned earlier, the crucial aspect of the backend is data conversion from a standard GIS format to 3D Tiles To test the possibility of effective conversion of GIS data from GeoJSON to 3D Tiles, two datasets were selected from the official GIS portal of the city of Brno. The two datasets represent common conversion and visualization scenarios: a) *points* layer with single objects, b) *polygon* layer representing box models of buildings. *Point* and *polygon* layers were chosen as the most used ones. Other types, like *line* layers, are not considered in this research as almost everything can be represented as point and polygons (e.g. lines can be represented as thin polygons).

Each dataset was converted using one or more publicly available tools for 3D Tiles conversion. The results were visually inspected using CesiumJS with the 3D Tiles inspector widget enabled and validated using the Cesium 3D Tiles validator[1]. The initial dataset[2] consists of a point layer displaying the location of 41,704 streetlamps in Brno. The second dataset[3] is a polygon layer containing 127,601 building bases. The first dataset is converted into a 3D Tiles layer that contains individual 3D models positioned at the points' locations. The second dataset is converted into a box representation of the building bases stored in the polygon layer.

The conversions were tested on a PC with an AMD Ryzen 7 3700X (16) running at 3.599 GHz, an NVIDIA GeForce RTX 2080, 32 GB of RAM, and the Ubuntu 22.04.3 LTS x86_64 operating system.

4.1 Point Layer Conversion to 3D Tiles

The streetlamp dataset in Brno was converted into instanced 3D models of 3D Tiles using `i3dm.export`[4]. This tool is currently the only available option for converting point features into instanced 3D models. It exports the `i3dm` and `tileset.json` from the PostGIS table and is mostly developed and maintained by a single individual. See the whole pipeline in Fig. 2.

Each lamp object is represented by a single glTF model. The 3D model instances were ac-

[1] `https://github.com/CesiumGS/3d-tiles-validator`
[2] Street lights [Stožáry veřejného osvětlení], `https://data.brno.cz`
[3] Buildings research in Brno [Průzkum budov v Brně] 2018–2020, `https://data.brno.cz`
[4] `https://github.com/Geodan/i3dm.export`

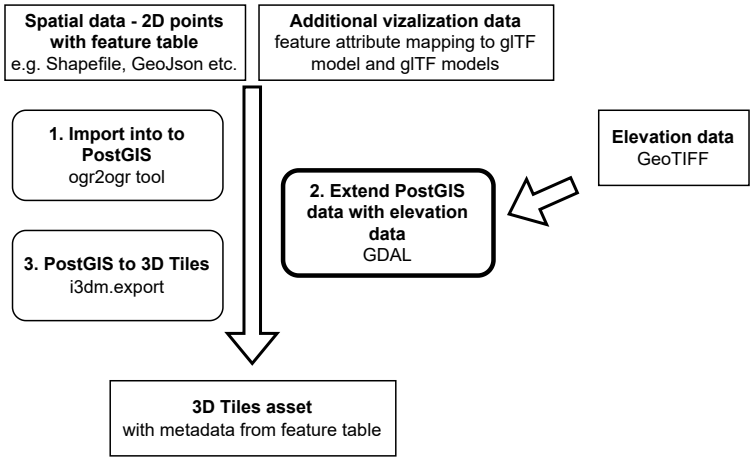

Fig. 2: The proposed pipeline for processing point spatial data

curately placed at their corresponding latitude and longitude coordinates on the globe. It is worth noting that the `i3dm.export` experimentally supports the EXT_mesh_gpu_instancing extension from 3D Tiles 1.1. Furthermore, it also supports export using `.i3dm` or `.cmpt` extensions, which have already been deprecated in the 3D Tiles specification.

The conversion of the test point features took a few seconds. The data size resulting from the model was approximately 10 MB, which is significantly smaller than the model size (128 kB) multiplied by approximately 40,000. Additionally, the size could be further reduced by using an external model option. After conversion, the data was tested using the Cesium 3D Tiles validator and no errors were found.

4.2 Polygon Layer Conversion to 3D Tiles

Four open-source tools were selected to test the generation of 3D Tiles from a polygon layer: `pg2b3dm`[5], `fanvanzh/3dtiles`[6], `py3dtilers`[7], and `viz-3dtiles`[8]. Since all the solutions had issues such as missing documentation, we conducted tests to determine their suitability for our purposes. The four selected tools were the only ones that demonstrated at least some potential. Other tools were either outdated or incomplete and were therefore excluded from this study.

The tools were evaluated based on their features, interpretation of the bounding volume, usage of glTF, and visual representation of element location using CesiumJS. The results of the evaluation are presented in Tab. 1.

The `pg3b3dm` tool is used to convert PostGIS 3D geometries to 3D Tiles. The tool `tesselate_buildings`, created by the same author, is used to create 3D geometries from 2D polygons. The conversion process and its options are explained in the documentation (Geodan, 2024). The conversion steps are as follows: use the `ogr2ogr` tool (from the GDAL package) to convert from GeoJSON (or any 2D polygon format that is supported by GDAL) to a PostGIS table, use `tesselate_buildings` to create 3D geometries, and finally create 3D Tiles from the 3D geometries with `pg2b3dm`. The tool relies on widely used PostGIS and GDAL. It offers implicit tiling and supports glTF content from 3D Tiles 1.1. However,

[5] `https://github.com/Geodan/pg2b3dm`
[6] `https://github.com/fanvanzh/3dtiles`
[7] `https://github.com/VCityTeam/py3dtilers`
[8] `https://github.com/PermafrostDiscoveryGateway/viz-3dtiles`

Tab. 1: Polygon layer to 3D Tiles conversion tools test results

	`pg2b3dm`	`fanvanzh/3dtiles`	`py3dtilers`	`viz-3dtiles`
Position on the globe in CesiumJS	Correct	Correct	Incorrect	Incorrect
Per feature height	Yes	Yes	Yes	No
Per feature altitude	No	No[9]	Yes	No[10]
Per feature color	Yes	No	Yes	No
Bounding volume	Region	Region	Box	Box
Supports metadata	Yes	Yes	Yes	Yes
GPU Draw calls per tile	Few	Hundreds	Few	Few
glTF as content	Yes, optional	No	No	No
Divides data into tiles	Yes	Yes	Yes	No
Implicit tiling	Quadtree	–	–	–
3D Tiles Validator	Errors when glTF as content enabled	Errors	Errors	Errors
Conversion duration	1m 47s	12s	5m 20s	1m 40s
Programming language	C#	C++	Python	Python
Github stars	272	1.7k	141	4
Number of main code contributors	Single	Single	Single	Few

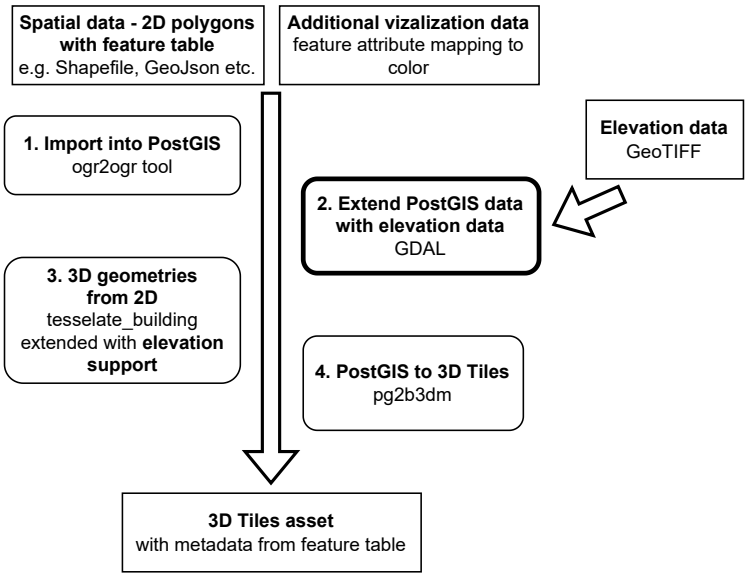

Fig. 3: The proposed pipeline for processing polygon spatial data

the glTF content option does not support feature metadata, and per-feature altitude is also not yet supported. See the whole pipeline in Fig. 3.

The second tested was `fanvanzh/3dtiles` tool. The `fanvanzh/3dtiles` tool has limited documentation compared to other similar tools, which can make it difficult to understand. Addi-

[9] `https://github.com/fanvanzh/3dtiles/issues/256`
[10] `https://github.com/PermafrostDiscoveryGateway/viz-3dtiles/issues/18`

tionally, it only accepts shapefiles for polygon conversion and lacks the option to set feature altitude. While the conversion process is fast, the resulting 3D Tiles tileset has poor rendering performance in CesiumJS due to hundreds of draw calls per tile.

The third tool tested was `py3dTilers`. It is well-documented. The resulting tileset is rendered in CesiumJS, with the latitude and longitude coordinates swapped.

The last tested tool was `Viz-3dtiles`. The forked version of `py3dtiles` was used, but the authors did not contribute changes to the upstream repository. This version shares the same issue as `py3dtiles` with swapped coordinates. When visualizing in CesiumJS, the geometry appeared jittery when the camera was moved. Unfortunately, there is no documentation available on how this version works. Additionally, only a single tile was created, resulting in a 120 MB `b3dm` file containing all the geometry.

5 DISCUSSION AND CONCLUSION

The visualization of geospatial data in VR is a common problem. One of the challenges is to effectively visualize large amounts of GIS data in the form of 3D models. Common approaches use standard 3D model formats (e.g., fbx) created for specific scenarios or scenes. However, these approaches lack the ability to easily switch models or scenes and are mainly used for single-purpose applications. Another challenge is that the standard 3D model formats are missing the location information and cannot be easily combined with any geospatial data. In this paper, we presented a system architecture for the universal visualization of large amounts of GIS data in VR. The proposed architecture can be used for any use case where the data or the focus of the scene can change and thus, in a traditional scenario, the scene and all objects would have to be recreated manually.

The main challenge is the generation of 3D data. The 3D Tiles format was chosen for its versatility. The i3S format was not chosen because of the vendor lock. Several tools for converting spatial data into the 3D Tiles format were tested. Out of the tested tools, the pg2b3dm was chosen. The main reason is the support of many features (implicit tiling, glTF content) from the latest 3D Tiles version 1.1. It is also easy to understand and can be extended to support elevation per feature. If the input data is missing elevation information, it is necessary to retrieve the elevation from a terrain model to be used in the visualization.

For importing data into PostGIS, the Ogr2ogr documentation suggests increasing the number of INSERT statements in transactions when populating a database with a lot of data.[11] The external model option can be used to save even more disk space, the only drawback being that the glTF model must be available from a web server along with the 3D tiles data. To support visualization of terrain, the elevation property of the given terrain would need to be queried for each feature in GeoJSON during the format conversion. It is important to remember that 3D Tiles can be used for all types of 3D spatial content, and extruded 2D polygons are only of one type.

This pipeline for processing 3D spatial data was wrapped into a web service based on commonly used technologies like FastAPI, Vue.js, and Typescript. Users may use this application to upload their geospatial data, convert them into an efficient format, and prepare a customized visualization in a user-friendly way via GUI. The web service is accompanied by a VR client implemented in Unreal Engine to visualize the provided data.

Our approach's primary contribution is the on-the-fly generation of VR scenes from large GIS datasets. Unlike common approaches that create and use a single-purpose application with a VR scene, our system allows for easy exchange of scene layers when visualizing new data.

[11] `https://gdal.org/programs/ogr2ogr.html#performance-hints`

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