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	专业：管理科学与工程
	职称：副教授

业绩成果材料

（申报人的业绩成果材料包括论文、科研项目、获奖以及其他成果等）

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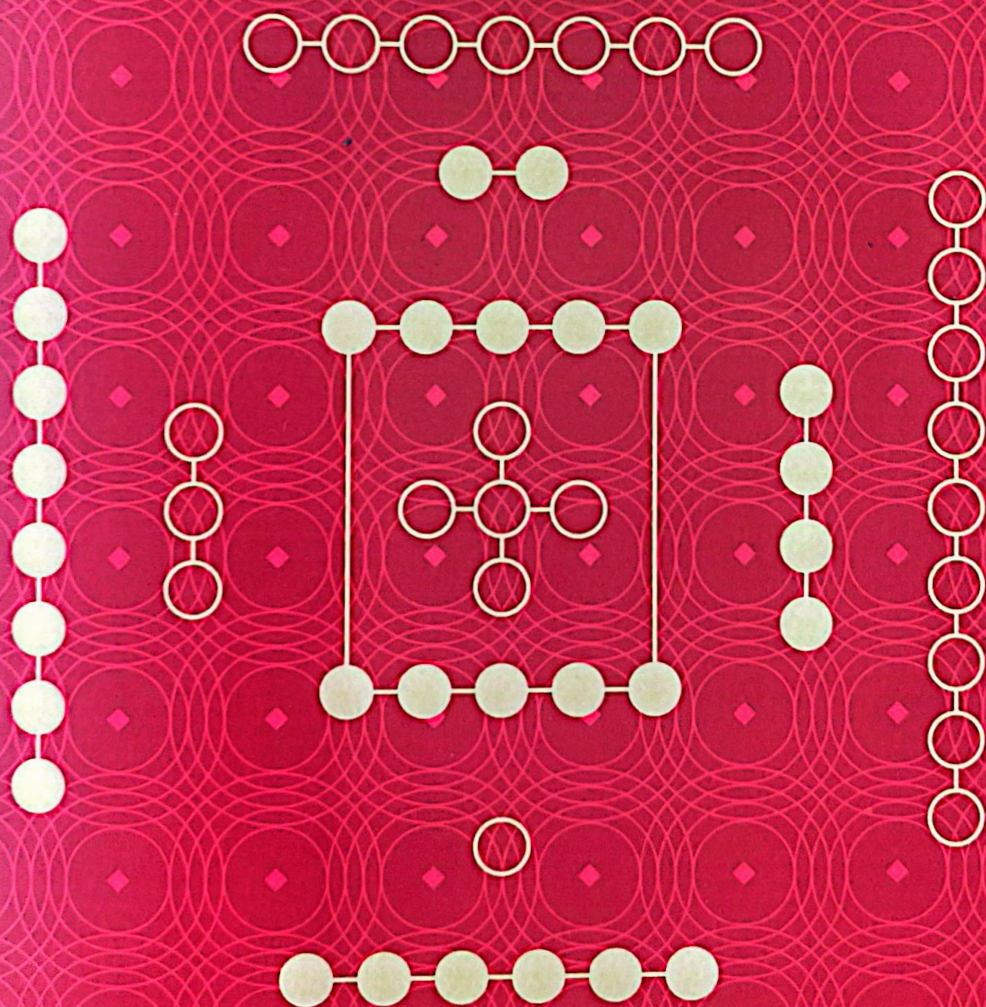
教学研究业绩

经典研究方法系列

管理学研究方法 与论文写作

第2版

杨学儒 董保宝 叶文平 ©主编



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——经典研究方法系列——

管理学研究方法 与论文写作

第2版

杨学儒 董保宝 叶文平 ◎主编

 机械工业出版社
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本书循着管理学研究的基本过程,系统地阐述了研究方法的基本概念、主导逻辑、适用情境和实用范例等。本书围绕论文的摘要、引言、文献综述、理论模型与研究假设、研究方法、数据收集与分析、结论与讨论,以及论文投稿、回复评审意见和发表后管理等,不仅总结了详尽的撰写方法、写作技巧和注意事项等,还提供了“手把手”带着读者“干中学”的范例,有助于读者在研究实践中掌握研究方法,提升研究能力,训练学术论文撰写和报告技能,顺利完成研究论文、学位论文的研究和撰写工作。

本书是一本管理学研究方法入门书,适合高等院校和科研院所管理学、心理学、教育学与社会学等领域的高年级本科生、低年级研究生和研究者阅读。



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《管理学研究方法与论文写作》自2019年下半年出版以来，得到了大量研究生、本科生和任课教师的喜爱、支持和鼓励，每年皆多次加印。近年来，作者团队不断收到学生、教师和同行的各种建议和意见，第1版教材的不完美之处需要通过第2版来加以提升；加之近年来管理学流行的研究方法快速迭代，教材修订必要而紧迫。

2024年，我们经过多次讨论，确定了本次修订的两个原则：一是进一步吸收国内外研究的一些主流方法，从而更好地达成本书的初心——帮助读者快速了解研究概况及选择合适的方法开始一个有意义的研究，换言之，本书首先应是管理学研究新涉入者的“入门指南”；二是吸收战斗在一线的青年学者的智慧，邀请四位优秀学者撰写了部分新增内容。在此，特别感谢他们在“4.3 文献筛选与归类”（蔡文盛博士）、“4.4 文献归纳与述评”（蔡文盛博士）、“6.8 大数据及Python工具的应用”（彭秋萍副教授）、“6.9 QCA定性比较分析法”（彭秋萍副教授）、“8.10 潜变量建模与Mplus应用”（徐光毅博士）和“8.11 内生性问题及其修正方法”（王宇教授）等重写或新增内容方面做出的卓越贡献。

本书的第2版在结构上与第1版保持一致。第1版出版以来，据不完全统计，有上百所高校教师在研究方法或专业论文写作等相关课程中采用本书作为指定教材或主要参考书。由于课程学时差异，特别是是否开设了配套的实验课，任课教师和学生对本书的结构安排提出了不同的建议。我们希望借此机会说明的是：理解、掌握和提升管理学研究方法与论文写作能力，需要“干中学”。因此，建议正式教学安排采用“理论课+实验课”的方式开展，即在学习了第2章后，每组或每名学生围绕一个具体的研究选题，将每章学习与实验练习相结合；如果自学，也可类似操作。

华南农业大学冯江洪、吴娟、朱尧等青年学者参与了本书修订，王少壮、江丽虹、史晓珂、郑洁莹、邓达儒、鲍嘉芯等研究生参与了校对工作。在此，对他们表示感谢。

杨学儒 董保宝 叶文平

2025年9月

科研项目

广东省哲学社会科学规划专项小组

粤社科规专通〔2025〕16号

广东省哲学社会科学规划 2025 年度 常规项目、三类研究专项立项通知书

冯江洪同志：

经省委宣传部批准，您申报的广东省哲学社会科学规划 2025 年度常规项目、三类研究专项《退役新能源汽车动力电池回收研究：影响机理与优化路径》获准立项，项目类型为一般项目，批准号为 GD25CSG22，资助经费 3.0 万元，将分两次拨付至项目负责人所在单位账户，第一次拨款 2.7 万元，待通过结项鉴定后再拨付预留经费 0.3 万元。

项目负责人所在单位须承担保证责任。项目负责人及

所在单位须了解和执行以下规定：

1. 课题组须学习并遵守《广东省哲学社会科学规划项目管理办法》（粤宣发〔2024〕5号）《广东省省级财政社会科学研究项目资金的管理监督办法》（粤财规〔2023〕2号）。对于出现违规行为的，省哲学社会科学规划专项小组将依据相关规定进行处理。

2. 批准后的项目经费不再追加，课题组可以不接受。而一经接受，将不能以经费不足为由，擅自变更原设计的最终成果形式和内容。

3. 项目立项后，课题组须按项目申请书所列计划开展研究。研究过程中，如有变更项目负责人、改变成果内容或形式、变更项目管理单位、变更或增补课题组成员、终止项目或撤销项目、延期等重要事项，项目负责人或所在单位必须及时在广东省哲学社会科学规划项目管理平台申请变更，线上报省哲学社会科学规划专项小组审批。

4. 省社科规划项目成果为论文的，在公开发表时必须注明“广东省哲学社会科学规划项目（项目编号）”字样。成果（含阶段成果）为专著、研究报告的，未经省哲学社会科学规划专项小组组织专家鉴定的，出版时不能标明“广东省哲学社会科学规划项目（项目编号）”字样；如成果确实有先出版后鉴定结项的需要，必须先向省哲学社会科学规划专项小组提出书面申请，经批准后才能出版。

并标明“广东省哲学社会科学规划项目（项目编号）”字样；如未经鉴定申请，自行出版并标明“广东省哲学社会科学规划项目（项目编号）”字样，省哲学社会科学规划专项小组不接受项目结项申请并予以撤项处理。

5. 项目负责人及所在单位须在规定时间内向省哲学社会科学规划专项小组提交项目结项材料。规定时间内不提交结项材料的将作撤项处理。结项所需材料、装印要求等具体事项，请登录广东社科规划网站“结项信息”栏目查看。

6. 成果鉴定等级分为优秀、良好、合格和不合格四个等次。通过结项的，将拨付预留经费。不合格即未能通过结项的，课题组需修改后半年内重新申请结项鉴定。仍不能通过的，将作撤项处理，不再拨付预留经费。

7. 被撤项的项目负责人五年内不得申报国家社科基金项目和省哲学社会科学规划项目。

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广东省哲学社会科学规划专项小组

广东省哲学社会科学规划领导小组办公室（代章）

2025年5月14日

课题编号 2024020132

广州市哲学社会科学发展“十四五”规划

2024年度课题立项协议

甲方：广州市社会科学规划领导小组办公室/广州市社会科学界联合会

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二〇二四年八月

一、经专家组评审、社会公示，报广州市社会科学规划领导小组审定，同意将乙方申请的课题《新能源汽车退役动力电池回收资源配置及交易机制研究》立为广州市哲学社会科学发展“十四五”规划 2024 年度共建课题（课题编号：2024GZGJ32）。本课题负责人冯江洪，课题组成员苏柳方、徐光毅。

二、该课题的研究经费由课题负责人所在单位保障或课题负责人自筹。课题完成后，由乙方所在单位科研管理部门组织专家鉴定结项，结项评审结果通报广州市社科规划办。如乙方无故终止课题研究，按广州市社科规划课题管理办法的相关规定进行处理。

三、课题研究和结项要求

- 1.结项条件。最终研究成果为至少 1 篇普刊论文。
- 2.结项时间。2026 年 5 月 31 日前向广州市社科规划办提交结项材料。
- 3.材料整理。需提交结项材料电子版扫描件：①结题报告书；②课题申报书、课题立项协议；③研究成果；④佐证材料。发送以上电子材料至广州市社科规划办邮箱 gzsghb@163.com。具体整理要求参见结项当年广州社科网公布的结项要求。

四、该课题的研究成果发表或出版，应标注“广州市哲学社科规划 2024 年度课题”字样和课题编号。

五、课题组必须遵守《广州市哲学社会科学“十四五”规划课题管理办法》，认真开展课题研究，保证恪守学术规范，不弄虚作假，保证取得预期研究成果。

六、《课题立项协议》一式三份，一份由甲方保存，一份由乙方保存，一份由乙方所在单位科研管理部门保存。

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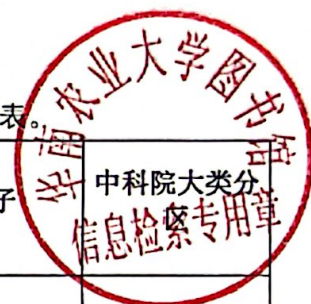
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日期： 2024 年 8 月 6 日

科研论文

检索证明

根据委托人提供的论文材料，委托人华南农业大学经济管理学院 冯江洪(学科类型:人文社科) 8 篇论文收录情况如下表。



序号	论文名称	发表刊物及发表的年月卷期/页码等	作者排名	论文等级	作者文中单位	收录情况	影响因子	中科院大类分
1	An integrated decision framework for resilient sustainable waste electric vehicle battery recycling transfer station site selection	APPLIED ENERGY 出版年: 2024 出版日期: NOV 1 卷期: 373 页码: - 文献号: 123897 文献类型: Article	第一作者	T2 类	华南农业大学 经济管理学院	SCI	IF2-year=11.0 IF5-year=11.2 (2024)	工程技术 1 区 Top 期刊: 是 OA 期刊: 否 (2025)
2	Barriers to electric vehicle battery recycling in a circular economy: An interpretive structural modeling	JOURNAL OF CLEANER PRODUCTION 出版年: 2024 出版日期: SEP 1 卷期: 469 页码: - 文献号: 143224 文献类型: Article	第一作者	T2 类	华南农业大学 经济管理学院	SCI	IF2-year=10.0 IF5-year=10.7 (2024)	环境科学与生态学 1 区 Top 期刊: 是 OA 期刊: 否 标注: Mega-Journal (2025)
3	ChatGPT-enabled two-stage auctions for electric vehicle battery recycling	TRANSPORTATION RESEARCH PART E-LOGISTICS AND TRANSPORTATION REVIEW 出版年: 2024 出版日期: MAR	第一作者	T2 类	华南农业大学 经济管理学院	SSCI	IF2-year=8.8 IF5-year=9.8 (2024)	工程技术 1 区 Top 期刊: 是 OA 期刊: 否 (2025)

		卷期: 183 页码: - 文献号: 103453 文献类型: Article						
4	Moving towards a circular economy: A systematic review of barriers to electric vehicle battery recycling	SUSTAINABLE PRODUCTION AND CONSUMPTION 出版年: 2025 出版日期: MAR 卷期: 54 页码: 241-260 文献类型: Review	第一作者	T2 类	华南农业大学 经济管理学院	SSCI	IF2-year=9.6 IF5-year=10.5 (2024)	环境科学与生态学 1 区 Top 期刊: 是 OA 期刊: 否 (2025)
5	A recycling mechanism for used electric vehicle batteries by integrating affine maximizer auction and fuzzy axiomatic design method	ENERGY 出版年: 2025 出版日期: OCT 15 卷期: 334 页码: - 文献号: 137822 文献类型: Article	第一作者	T2 类	华南农业大学 经济管理学院	SCI	IF2-year=9.4 IF5-year=8.8 (2024)	工程技术 1 区 Top 期刊: 是 OA 期刊: 否 标注: Mega-Journal (2025)
6	Self-building or sharing? The strategy analysis of building charging stations	JOURNAL OF ENERGY STORAGE 出版年: 2024 出版日期: NOV 10 卷期: 101 页码: - 文献号: 113906 文献类型: Article	通讯作者	A 类	华南农业大学 经济管理学院	SCI	IF2-year=9.8 IF5-year=10.0 (2024)	工程技术 2 区 Top 期刊: 否 OA 期刊: 否 标注: Mega-Journal (2025)



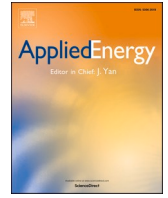
7	Identifying key factors and interrelationships affecting large-scale agricultural biomass production: Insights from interpretive structural modeling	BIOMASS & BIOENERGY 出版年: 2025 出版日期: SEP 卷期: 200 页码: - 文献号: 108013 文献类型: Article	通讯作者	A 类	华南农业大学 经济管理学院	SCI	IF2-year=5.8 IF5-year=5.7 (2024)	生物学 2 区 Top 期刊: 否 OA 期刊: 否 (2025)
8	A meta-auction for on-demand transportation procurement in industry 5.0	TRANSPORTATION RESEARCH PART E-LOGISTICS AND TRANSPORTATION REVIEW 出版年: 2025 出版日期: JAN 卷期: 193 页码: - 文献号: 103842 文献类型: Article	通讯作者	T2 类	华南农业大学 经济管理学院	SSCI	IF2-year=8.8 IF5-year=9.8 (2024)	工程技术 1 区 Top 期刊: 是 OA 期刊: 否 (2025)

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第一作者论文



An integrated decision framework for resilient sustainable waste electric vehicle battery recycling transfer station site selection

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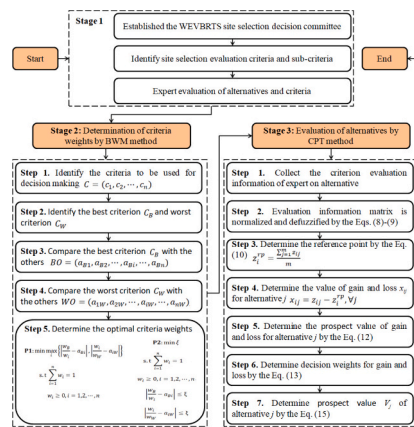
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HIGHLIGHTS

- This paper addresses the issue of battery recycling transfer station site.
- This study identifies a resilience and sustainability evaluation indicator system.
- An analysis framework to locate a battery recycling transfer station is proposed.
- Sensitivity and comparison analyses are provided to verify method validity.
- Several important theoretical implications and managerial insights are provided.

GRAPHICAL ABSTRACT



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ABSTRACT

This study is driven by a company engaged in renewable resource recovery. As the company's battery recycling market continuous continues to grow, the existing recycling facilities are unable to cope with the demand for sorting and storage. As a result, there is an urgent need to identify a suitable electric vehicle battery recycling transfer station (EVBRTS) to alleviate the strain on the recycling plant. The issue of electric vehicle battery recycling location has received scant attention in previous research, with a notable absence of studies focusing on EVBRTS location. Thus, the primary objective of this study is to establish an integrated decision-making framework using the best worst method (BWM) and cumulative prospect theory (CPT) to determine the optimal EVBRTS location. To achieve this goal, a panel of experts representing various sectors was assembled to formulate five primary criteria and fifteen secondary sub-criteria across the economic, social, environmental, technological, and resilience domains, drawing on existing literature and expert insights. The BWM method was employed to determine the criteria weights, followed by a ranking of the alternatives using the CPT approach. Furthermore, an integrated analytical model for the EVBRTS site selection evaluation index system was developed herein. A sensitivity and comparative analysis was carried out to demonstrate the practicality and

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robustness of the proposed method. A notable finding highlighted in this study is the significant impact that the order in which the expert ratings information was aggregated had on the ranking results. Undoubtedly, this study offers a fresh perspective based on resilience and sustainability for battery recycling managers to make informed strategic decisions on site selection, thereby enhancing resilience in the context of EVBRTS site selection.

1. Introduction

Despite challenges like the impact of COVID-19 and supply chain disruptions on the electric vehicles manufacturing and sales over the past three years, the global electric vehicle market is experiencing rapid growth as the automotive industry increasingly shifts towards electrification [39,62]. According to the statistics, global new energy vehicles deliveries increase by approximately 55% to 10.5 million in 2022 compared to 2021, and China, the world's largest electric vehicle manufacturer and the largest electric vehicle market, has increased its sales of electric vehicles by almost 82% in 2022 compared to 2021.¹ Electric vehicles are expected to gain market share as more environmental policies are adopted and demand for green technology increases [44]. While the environmental benefits of electric vehicles are recognized, it is important to address the challenges posed by the electric vehicle batteries. With the rise of electric vehicles, batteries as a critical component of electric vehicles are experiencing a significant growth trend. However, once the remaining capacity of an electric vehicle battery decays beyond a certain point, the battery needs to be replaced [28]. Further research is needed to develop effective strategies for managing the significant volume of end-of-life electric vehicle batteries.

With the rapid growth of electric vehicles, many electric vehicle batteries will reach the end of their life in the coming years [67]. As power batteries contain many heavy metals and other toxic and hazardous substances that are harmful to the ecosystem as well as to public ([82,17]), the benefits of electric vehicles will be reduced if waste batteries are not properly managed. Fortunately, end-of-life electric vehicle batteries can be recycled or disassembled to recover their useful metal components. Battery recycling plays a key role in the transition to a global circular economy, offering significant economic, environmental and social benefits. This process not only facilitates the reuse of finite resources but also helps to reduce negative environmental impacts [30]. More importantly, battery recycling also plays an important role in promoting employment [26]. Battery recycling has a promising future [48]. On the one hand, as the number of retired batteries increases dramatically, economies of scale for battery recycling will become a reality. On the other hand, battery recycling, as the last link in the chain to develop new energy and environmental protection, is strongly supported by various countries in the battery recycling industry [64,71]. While recycling is a viable solution to the scarcity of raw materials for batteries, significant investment is needed to improve and expand the battery recycling infrastructure to alleviate the burden of inadequate facilities.

This work is being driven by a renewable resource recovery company seeking to build a robust battery recycling infrastructure in anticipation of a surge in battery disposal. The primary concern is the strategic location of waste electric vehicle battery recycling transfer station (EVBRTS) to ensure sustainable development. Faced with operational challenges and capacity limitations at the recycling center, the company is seeking to alleviate the pressure by selecting a suitable EVBRTS as part of its expanding battery recycling operations. The transfer station's role is to collect, sort, and store waste batteries, not to dismantle or dispose of them. The strategic selection of EVBRTS sites is critical for effective business management, since failure to make this choice can put business operations at risk. Thus, the importance of EVBRTS site selection cannot be overstated. The focus of this paper is to address this crucial decision-

making process in order to provide a resilient, sustainability-focused site solution for the renewable energy company.

Sustainability is about meeting the needs of the present without compromising the ability of the future [70]. Economic sustainability emphasizes the importance of pursuing economic growth in a manner that is sustainable, prioritizing long-term development over short-term gains. Social sustainability advocates for equitable, inclusive, and stable societal development, ensuring that the needs of the majority are not overshadowed by the interests of a few. Environmental sustainability underscores the necessity of balancing economic benefits with environmental preservation. Evaluation studies often utilize economic, social, and environmental criteria to assess sustainability across various domains [5,54]. Furthermore, EVBRTS site selection is also influenced by technical criteria, and technical criteria should therefore also be considered when siting battery recycling transfer stations. More importantly, given the complex, changing and uncertain external environment, resilience should also be considered when building a sustainable framework [14,60]. For example, when the market environment is very good, whether the capacity of the potential location can meet the market demand; and when the market environment is not good, whether the potential location can cope with the changes in the market. Location resilience refers to the ability of an organization to adapt and respond quickly when faced with uncertainty and risk. This concept highlights the importance of the flexibility and adaptability of the chosen site to make timely and appropriate adjustments to maintain production and supply stability in the face of unforeseeable events, market fluctuations or mismatches between supply and demand. Therefore, it is crucial to consider resilience criteria in EVBRTS site selection. Additionally, due to the absence of precise and integrated analytical framework models for determining the location of EVBRTS, this study utilizes insights from academic literature and expert to develop a comprehensive set of criteria. These criteria cover economic, social, environmental, technical and resilience aspects and aim to fill the gap in the decision-making framework for EVBRTS site selection.

However, the location of EVBRTS presents a complex and challenging scientific problem with many influencing factors. The primary challenge lies in identifying the optimal EVBRTS location amidst various evaluation criteria, including both qualitative and quantitative factors, in order to mitigate decision-making risks. Traditional location allocation optimization models can usually handle quantitative criteria in site selection, but are unable to capture qualitative criteria [16]. Consequently, the traditional mathematical model approach is not applicable to the problem of EVBRTS site herein. However, multi-criteria decision-making (MCDM), which has proven to be a reliable and powerful tool for site selection problems where qualitative and quantitative criteria exist [18,65], has potential advantages in solving evaluation problems with multiple evaluation criteria and complexity, which has led to its widespread use in many fields, such as disaster risk assessment [42], renewable energy rankings [34] and electric vehicle charging station location [15]. In reality, given the differences in the knowledge and experience of the experts, their assessment of qualitative criteria is often subjective and ambiguous, and thus linguistic terms can be used to assess qualitative criteria.

The growth of the battery recycling industry has highlighted the key role of the EVBRTS sites within the recycling network. Despite their growing importance, there is a noticeable lack of literature on EVBRTS sites. This paper seeks to fill this gap by examining the issue of EVBRTS location through the lenses of resilience and sustainability, thereby contributing valuable insights to the existing literature. Specifically, this

¹ <https://www.ev-volumes.com/>

paper aims to answer the following research questions: i) What are the resilient and sustainable evaluation criteria used for EVBRTS location? ii) What MCDM method is employed to derive the significance of the criteria? iii) Which MCDM approach is adopted to obtain the best alternative? iv) How do the parameters in the proposed method have an impact on the sorting results?

To address the aforementioned research questions, this paper outlines four key objectives: i) developing resilient and sustainable evaluation criteria for selecting EVBRTS sites based on academic literature and expert insights; ii) determining the criteria weights using the best-worst method (BWM); iii) establishing alternative rankings through cumulative prospect theory (CPT); and iv) validating the findings through sensitivity analysis. To achieve these research objectives, a hybrid MCDM approach that integrates BWM and CPT methods is proposed. The methodology consists of three main steps: identifying evaluation criteria for EVBRTS sites, constructing an integrated analytical framework model, applying BWM to calculate criteria weights, and determining alternative rankings using the CPT approach.

The contributions we have made are highlighted in the following threefold: i) To the best of our knowledge, the existing literature ignores the EVBRTS problem. After identifying the characteristics of the EVBRTS problem, this paper presents an integrated approach that combines BWM and CPT methods to address the challenges of EVBRTS location. The methodology integrates two effective decision analysis tools, which helps to capture the decision maker's risk preferences under uncertainty and improve the reliability of location decisions. ii) The second contribution of this study is the identification of an evaluation indicator system for determining the location of EVBRTS from the perspective of resilience and sustainability. Additionally, this study has developed a comprehensive analytical framework model for this indicator system, which can provide a valuable reference for the construction of similar systems. Importantly, this paper provides practical methods and experiences to guide future research on similar issues, as well as new ideas and directions for decision-making in the field of battery recycling site selection. iii) The ultimate contribution of this paper is to show, through a comparative study, that the order in which expert evaluation information is aggregated has a significant impact on the results. Furthermore, this study provides some key theoretical and managerial insights that offer valuable inspiration and reference for EVBRTS managers. These insights are important for advancing the science and standardization of electric vehicle battery recycling facilities.

The rest of this work will be structured in the following way: Section 2 provides an overview of the research that is relevant to this paper. Section 3 presents the BWM and CPT methodologies and constructs the EVBRTS sitting decision making analytical framework. Section 4 establishes the EVBRTS system of site selection evaluation criteria. In Section 5, a case study is used to demonstrate the application steps of the integrated methodology. Section 6 presents the sensitivity analysis, the comparative analysis, the advantages of the proposed BWM-CPT method and the managerial implications. Finally, Section 7 summarizes the conclusions, research limitations and future important research directions.

2. Literature review

This section provides a review of the extensive literature in three dimensions: the application of BWM, the application of CPT, and the location of electric vehicle battery recycling facilities.

2.1. Application of best worst method

Since Rezaei first proposed BWM in 2015 [57], the method has received increasing attention from academics and industry and has had a wide range of applications, for instance, company's R&D performance evaluation [61], site of the facility [33], supplier selection [23,58], and circular economy barriers assessment [21]. Ahmadi et al. [3] examined

the issue of social sustainability in the manufacturing supply chains and identified the importance of criteria through the BWM approach, which helps organizations to better manage the social sustainability aspects. Rezaei et al. [59] studied logistics performance index by using BWM, identified the importance of the criteria and provided a reference for policy development for relevant logistics practitioners. Aboutorab et al. [1] developed an approach that integrated Z-numbers and BWM to address the uncertainty in the assessment information. Liang et al. [38] presented a new consistency measure to compensate for the shortcomings of the original and extended BWM, which further strengthens the theoretical foundation of BWM. Wankhede and Vinodh [77] examined the key challenges of applying Industry 4.0 technologies and applied BWM to obtain the importance sorting of the key challenges. Liu et al. [40] extended the BWM into D numbers and proposed the D-BWM to deal with situations where assessment information is incomplete. Xiao et al. [81] extended BWM in the q-rung orthopair fuzzy environment for determining criteria weights in manufacturer selection. Dehshiri et al. [11] used an improved BWM approach to evaluate the criteria for the application of blockchain technology, which bridges the gaps in the fuzzy BWM approach. Aghaloo et al. [2] used fuzzy BWM and geographic information system to construct an assessment methodology for hybrid renewable energy sites. Huang et al. [29] adopted the fuzzy BWM to compute the subjective weights of the criteria.

Recently, publications have extended BWM to various fuzzy environments, such as probabilistic linguistic [47], interval rough numbers [13], interval-valued trapezoidal fuzzy numbers [73], interval-valued number [52], interval type-2 fuzzy environment [68], intervals and interval type-2 fuzzy sets [43], and rough probabilistic linguistic [86], etc. These studies have undoubtedly contributed significantly to the theoretical and applied development of BWM.

2.2. Application of cumulative prospect theory

Since Tversky and Kahneman first proposed the CPT [72], it has been the subject of a great deal of attention. As CPT is a powerful MCDM tool, it has a wide range of applications. For instance, portfolio choice [24], emergency response [41], charging station planning [37], risk analysis [74], and departure time choice [19], etc., Baucells and Heukamp [8] have made an important contribution to the theoretical development of CPT by extending the second-order stochastic dominance condition to it. Yang and Jiang [83] developed a stochastic consumer equilibrium method based on CPT for the route choice model, and numerical results show that the proposed method can better characterize risk preferences. Because of CPT's strength as a reflection of decision-makers' risk appetite, Wu et al. [80] have applied the CPT methodology to renewable energy assessments, providing excellent insights for investors with different risk appetites. Wang et al. [76] suggested a combined approach of deploying quality function deployment and CPT to facilitate product concept selection. Wu et al. [79] applied triangular fuzzy numbers (TFNs) to describe the ambiguity of the assessment information and introduced CPT to evaluate suppliers, showing that decision-makers' psychological behaviour had a significant effect on the sorting results. Zhao et al. [85] introduced CPT to multi-attributive border approximation area comparison (MABAC) in an intuitionistic fuzzy linguistic environment, developed a novel method and validated the reliability of the proposed method with a practical application. Besides, Zhang et al. [84] proposed a method of grey relational analysis based on CPT in a spherical fuzzy set environment, which was demonstrated through a case study of supplier selection for emergency materials. To reduce decision risk, Wang et al. [75] presented an MCDM approach that integrates CPT and ranking relationships and validate the powerful advantages of the method in portfolio selection with real data. Chai et al. [9] extended CPT to deal with the uncertainty and ambiguity of evaluation information in fuzzy sets, and validated the proposed method's effectiveness in a supplier selection case.

The existing literature indicates significant advances in theoretical

and applied research on CPT, highlighting its effectiveness in elucidating individuals' decision-making processes and risk attitudes. Building on this foundation, our study aims to use CPT in the context of site selection for a waste battery recycling transfer station to gain deeper insights into decision makers' risk preferences and uncertainties. Despite the widespread use of CPT in various domains, there is a noticeable lack of studies investigating its utility in the specific domain of EVBRTS. By filling this research gap, our work not only extends the scope of application of the CPT, but also enriches its practical relevance in real-life decision making scenarios.

2.3. Location of facilities in electric vehicle battery recycling

Facility location is a strategic decision for management, influenced by numerous factors such as market demand, transportation infrastructure, labor availability, operational costs, and government regulations [6,10,32,69]. As a critical component of strategic decision-making, facility location must consider the long-term implications and potential risks [7,22]. Selecting the right facility location can result in improved market development, enhanced service capabilities, reduced operating costs, increased efficiency and increased market competitiveness for the company. Recently, literature has been published on the facilities location for electric vehicle batteries recycling. Wei et al. [78] built a multi-objective mathematical model for waste battery recycling center location and proposed a heuristic algorithm with objective ranking method and greedy take-off to solve the optimization model. Hu et al. [27] built a mathematical programming model for electric vehicle battery recycling, which was able to solve the problems of battery recycling center location and vehicle transportation routes, and verified the reliability of the model through case studies. Sherif et al. [63] presented an integrated MCDM methodology to battery recycling station location and constructed 18 sustainability evaluation criteria. Pamucar et al. [50] developed a decision-making analytical framework model for waste battery recycling centers and applied a realistic case study to demonstrate the reliability of the proposed method. Tan et al. [66] developed an integer planning model to determine the optimal location and transport routes for battery recycling plants, taking into account cost minimization and customer satisfaction maximization objectives. Hezam et al. [26] constructed an evaluation system for battery recycling plants on the basis of environmental, economic, social and technical criteria and used the MCDM methodology to obtain the best sorting results. Puviarasu et al. [51] proposed an integrated fuzzy decision making trial and evaluation laboratory (DEMATEL), BWM and technique for order preference by similarity to an ideal solution (TOPSIS) method for the location of battery recycling plants.

Based on the findings of the literature review, the predominant focus in the realm of battery recycling facility location research has been on recycling centers, employing methods such as mathematical optimization models and MCDM approaches. However, as the volume of battery recycling continues to escalate rapidly, recycling plants facing capacity constraints must seek suitable battery recycling transfer stations to alleviate potential operational pressures. Consequently, in contrast to the prevailing literature, this study addresses the critical issue of battery recycling transfer stations site selection. Despite the inherent complexity of determining optimal transfer station locations, scant scholarly attention has been devoted to this specific aspect of the battery recycling process. To fill this research gap and improve the understanding of electric vehicle battery recycling logistics, this study develops a comprehensive MCDM framework integrating BWM and CPT to provide valuable insights for industry practitioners and decision makers.

3. The proposed method for EVBRTS site selection

The aim of this section is to introduce the BWM and CPT methods and to propose an integrated analytical framework model for EVBRTS site selection.

3.1. The best worst method

The BWM method is commonly used to calculate criteria weights, as it enables consistent outcomes to be achieved with minimal comparative information. This section outlines the BWM method for assessing information, following the procedure below.

Step 1. Identification of the criteria to be used in the decision-making process. Assume that the decision maker determines the criteria to be $C = (c_1, c_2, \dots, c_n)$.

Step 2. Identification of the best criterion C_B and the worst criterion C_W . It should be noted that the best criteria are those considered by experts to be the most important, while the worst criteria are the least important. If the expert considers that there are several best or worst criteria, then the choice can be arbitrary [46].

Step 3. The best-to-others (BO) vector is determined by comparing the best criterion C_B with the others, and is given in the following form:

$$BO = (a_{B1}, a_{B2}, \dots, a_{Bi}, \dots, a_{Bn}), \quad (1)$$

where a_{Bj} denotes preferring the best criterion to the other, and $a_{Bi} \geq 1$, $i = 1, 2, \dots, n, i \neq B$.

Step 4. Compare the worst criterion C_W with the others to determine the Worst-to-Others (WO) vector, which is given as follows.

$$WO = (a_{1W}, a_{2W}, \dots, a_{iW}, \dots, a_{nW}), \quad (2)$$

where a_{jW} denotes preferring the worst criterion to the other, and $a_{iW} \geq 1, i = 1, 2, \dots, n, i \neq W$. Note that in steps 3 and 4, a number from 1 to 9 is used to indicate the comparative value of the criteria given by the expert.

Step 5. A mathematical model is developed to determine criteria weights. To obtain criteria weights, we need to ensure that the maximum absolute differences $\left| \frac{w_B}{w_i} - a_{Bi} \right|$ and $\left| \frac{w_i}{w_W} - a_{iW} \right|$ are minimized, and the following mathematical model is developed.

$$P1 : \min \max_i \left\{ \left| \frac{w_B}{w_i} - a_{Bi} \right|, \left| \frac{w_i}{w_W} - a_{iW} \right| \right\} \quad (3)$$

$$\text{s.t. } \sum_{i=1}^n w_i = 1 \quad (4)$$

$$w_i \geq 0, i = 1, 2, \dots, n \quad (5)$$

Indeed, P1 is a non-linear model and to facilitate model solving, ξ is introduced to represent the maximum absolute difference, then we can transform the model P1 into a linear model like this:

$$P2 : \min \xi$$

$$\text{s.t. } \sum_{i=1}^n w_i = 1$$

$$w_i \geq 0, i = 1, 2, \dots, n$$

$$\begin{aligned} \left| \frac{w_B}{w_i} - a_{Bi} \right| &\leq \xi \\ \left| \frac{w_i}{w_W} - a_{iW} \right| &\leq \xi \end{aligned} \quad (6)$$

The criteria weights $w = (w_1, w_2, \dots, w_n)$ can be obtained by solving model P2.

3.2. Cumulative prospect theory

CPT is a psychological theory that sheds light on real-world decision-making and behaviors, describes how individuals make choices in uncertain situations. CPT emphasizes that human decision-making is

impacted by subjective probabilities and how they perceive potential gains and losses. In this paper, we use the CPT method, which captures the risk attitudes of decision makers, for the determination of the optimal EVBRTS location. The steps below are an outline of the process:

Step 1. Assume that there are K ($k = 1, 2, \dots, K$) experts, where the weight of expert k is w^k , and collect the criterion evaluation information of expert k on alternative, expressed by TFNs $(\underline{t}_{ij}^k, t_{ij}^k, \bar{t}_{ij}^k)$. And the evaluation information for expert k is represented by the following matrix $\tilde{T}^k$.

$$\tilde{T}^k = \begin{bmatrix} (\underline{t}_{11}^k, t_{11}^k, \bar{t}_{11}^k), (\underline{t}_{12}^k, t_{12}^k, \bar{t}_{12}^k), \dots, (\underline{t}_{1m}^k, t_{1m}^k, \bar{t}_{1m}^k) \\ (\underline{t}_{21}^k, t_{21}^k, \bar{t}_{21}^k), (\underline{t}_{22}^k, t_{22}^k, \bar{t}_{22}^k), \dots, (\underline{t}_{2m}^k, t_{2m}^k, \bar{t}_{2m}^k) \\ \vdots, \vdots, \vdots \\ (\underline{t}_{n1}^k, t_{n1}^k, \bar{t}_{n1}^k), (\underline{t}_{n2}^k, t_{n2}^k, \bar{t}_{n2}^k), \dots, (\underline{t}_{nm}^k, t_{nm}^k, \bar{t}_{nm}^k) \end{bmatrix}, \quad (7)$$

where i ($i = 1, 2, \dots, n$) denotes the criterion and j ($j = 1, 2, \dots, m$) denotes the alternative. In this paper, as both quantitative and qualitative criteria are involved, we can use crisp value to express the quantitative criteria, which is then converted into the TFNs; while we can apply the linguistic terms to express qualitative criteria, in relation to the corresponding TFNs as shown in Fig. 1. Besides, the interval value (a, b) can be transformed into a TFN $(a, \frac{a+b}{2}, b)$ if the expert's evaluation information is an interval value. If the evaluation information is a crisp value c , then it can be translated into a TFN (c, c, c) .

Step 2. The evaluation information matrix $\tilde{T}^k$ for expert k is normalized. Let $[\tilde{r}_{ij}^k]_{n \times m}$ denote the normalized matrix of $\tilde{T}^k$. Then it can be normalized by the following Eq. (8). In addition, the fuzzy evaluation matrix $[\tilde{r}_{ij}^k]_{n \times m}$ of expert k is defuzzified by Eq. (9). Thus, the matrix of crisp values for expert k is obtained as $T^k = [z_{ij}^k]_{n \times m}$.

$$(\underline{r}_{ij}^k, r_{ij}^k, \bar{r}_{ij}^k) = \begin{cases} \left(\frac{\underline{t}_{ij}^k}{\max_j \underline{t}_{ij}^k}, \frac{t_{ij}^k}{\max_j t_{ij}^k}, \frac{\bar{t}_{ij}^k}{\max_j \bar{t}_{ij}^k} \right), & \text{for benefit criterion} \\ \left(\frac{\min_j \underline{t}_{ij}^k}{\underline{t}_{ij}^k}, \frac{\min_j t_{ij}^k}{t_{ij}^k}, \frac{\min_j \bar{t}_{ij}^k}{\bar{t}_{ij}^k} \right), & \text{for cost criterion} \end{cases} \quad (8)$$

$$z_{ij}^k = \frac{\underline{r}_{ij}^k + 2r_{ij}^k + \bar{r}_{ij}^k}{4} \quad (9)$$

Step 3. Determine reference point. The choice of reference point is crucial for the CPT method. In this paper, we use the average value as the reference point in the CPT method. Thus, we apply the Eq. (10) to calculate the average values, denote RP_i^k .

$$RP_i^k = \frac{\sum_{j=1}^m z_{ij}^k}{m} \quad (10)$$

where m indicates the number of alternatives.

Step 4. Determine gain and loss value. Let x_{ij}^k represent the expert k 's gain or loss value for alternative j . If the difference between the values of the reference point and the evaluation data exceeds zero, this difference represents the gain. Conversely, if the difference obtained by subtracting the value of the reference point from the value of the assessment information is a negative number, then this difference is the loss value. The expressions are as follows.

$$x_{ij}^k = z_{ij}^k - RP_i^k. \quad (11)$$

Step 5. Determine the prospective value $v(x_{ij}^k)$. Let $v^+(x_{ij}^k)$ and $v^-(x_{ij}^k)$ represent decision weights with regard to gain and loss, respectively. Then $v(x_{ij}^k)$ can be obtained by

$$v(x_{ij}^k) = \begin{cases} v^+(x_{ij}^k) = (x_{ij}^k)^\alpha, & \text{if } x_{ij}^k \geq 0 \\ v^-(x_{ij}^k) = -\theta(-x_{ij}^k)^\beta, & \text{if } x_{ij}^k < 0 \end{cases}, \quad (12)$$

where α and β represent the exponential parameters of gain and loss respectively, and $0 \leq \alpha, \beta \leq 1$, while θ denotes the risk aversion parameter of the decision maker, $\theta > 1$.

Step 6. Determine decision weights $\pi(x_{ij}^k)$. Let $\pi^+(x_{ij}^k)$ and $\pi^-(x_{ij}^k)$ represent decision weights with regard to gain and loss, respectively. The decision weights are then determined by the following equation.

$$\pi(x_{ij}^k) = \begin{cases} \pi^+(x_{ij}^k) = \frac{w_i^\eta}{[w_i^\eta + (1 - w_i)^\eta]^{1/\eta}}, & \text{if } x_{ij}^k \geq 0 \\ \pi^-(x_{ij}^k) = \frac{w_i^\delta}{[w_i^\delta + (1 - w_i)^\delta]^{1/\delta}}, & \text{if } x_{ij}^k < 0 \end{cases} \quad (13)$$

where w_i indicates the criterion i 's weight derived by the BWM, η and δ indicate the decision maker's risk preferences for gain and loss, $0 < \eta, \delta < 1$.

Step 7. Determine the expert k 's cumulative prospect value V_j^k of alternative j by Eq. (14). It is worth noting that, to facilitate the calculation, the gain and loss values for each alternative need to be ranked in descending order. Those with subscripts 1 to t are the gain values, while those with subscripts $t+1$ to n are the loss values. Finally, use the Eq. (15) to calculate the weighted cumulative prospect value V_j .

$$V_j^k = \sum_{i=1}^t \pi^+(x_{ij}^k) v^+(x_{ij}^k) + \sum_{i=t+1}^n \pi^-(x_{ij}^k) v^-(x_{ij}^k) \quad (14)$$

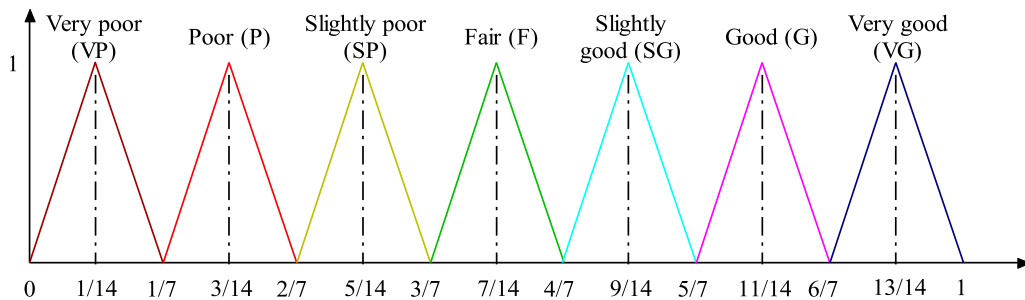


Fig. 1. Linguistic terms corresponding to the TFNs.

$$V_j = \sum_{k=1}^K V_j^k w^k \quad (15)$$

where w^k denote the weight of expert k , and $\sum_{k=1}^K w^k = 1$.

3.3. Decision framework of the EVBRTS site selection

As EVBRTS location has a key role to play in battery recycling in a circular economy, however, the lack of an integrated framework literature on EVBRTS location limits the development of corporate battery recycling operations at scale. This study thus applies BWM and CPT approaches to develop a decision framework for EVBRTS site selection, as shown in Fig. 2. The first step is to identify a list of experts in the various fields and establish an EVBRTS site selection decision group; then a system of evaluation indicators is defined based on academic literature and expert opinion; finally, experts provide information on the evaluation of options and criteria. In the second stage, the BWM can be used to derive criteria weights. In the final stage, the CPT method is used to determine the prospect values of the alternatives and then the best alternative is selected. It should be noted that in the CPT method, the quantitative data collected needs to be transformed, as shown in step 1 of the CPT method description. The adoption of a site decision framework that integrates BWM-CPT methodologies can improve the scientific and accuracy of decision making. On the one hand, quantitative assessment and comprehensive consideration of multiple factors can avoid subjective bias and arbitrary decision-making, ensuring more objective and rational site selection decisions. On the other hand, by developing a decision framework based on the BWM and CPT methods, the efficiency and accuracy of site selection can be improved, providing

scientific guidance to companies and promoting the large-scale development of the battery recycling business. Most importantly, the integrated BWM and CPT methods framework proposed herein can be applied to other similar site problems.

This paper constructs a hybrid MCDM theoretical framework for EVBRTS site selection. The main reasons for using a hybrid MCDM instead of a single MCDM method are as follows. First, hybrid MCDM methods can overcome the limitations of a single MCDM method, consider the decision problem in a more comprehensive and multi-perspective way. Each MCDM method may have its own advantages and limitations, and using a mixture of them can compensate for the shortcomings of a single method to improve the comprehensiveness and accuracy of the decision-making. Second, hybrid MCDM methods can improve the robustness of the decision. Using multiple MCDM methods can increase the robustness of decision making and reduce the dependence on a single method. When different methods produce similar results, it can increase confidence in decision making; when the results are inconsistent, it can help decision makers to consider different factors more fully to make more informed decisions. Third, hybrid MCDM methods can increase credibility of decision making. The credibility and persuasiveness of decisions can be improved by using a mixture of MCDM methods. Different methods may perform better in different ways, and using them in combination can reduce subjectivity and bias, making decisions more objective and credible.

The BWM and CPT methods proposed in this paper are particularly suitable for the site selection of battery recycling transfer stations. In the decision making of battery recycling transfer station location, decision makers need to consider many factors such as accessibility, environmental impact, cost and other attributes, as well as a weighting method that is intuitive and has a visualization process. For this reason, this

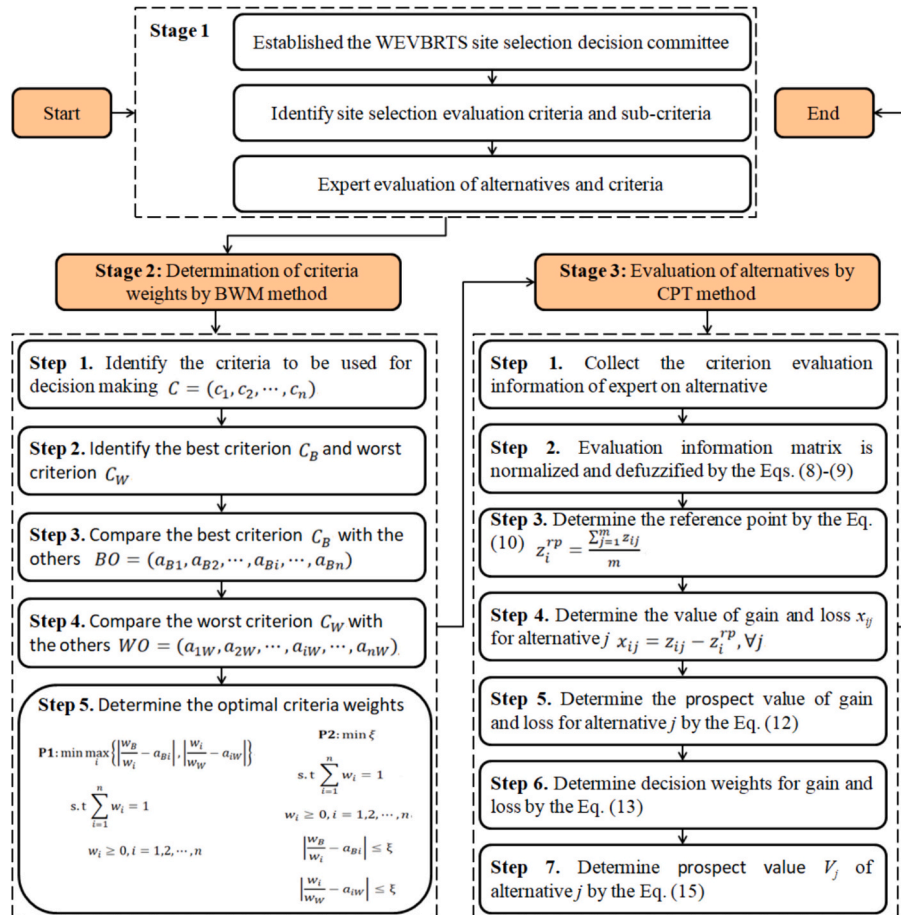


Fig. 2. Decision framework for EVBRTS site selection.

paper finally adopts the BWM method by comparing it with other weighting methods, because the BWM method can help determine the best and worst performance of each alternative in terms of each attribute, and help decision makers understand the advantages and disadvantages of each alternative more clearly, which helps to make a reasonable choice. Moreover, the BWM method can provide decision makers with an intuitive basis for decision making on the location of battery recycling transfer stations, which contributes to the transparency and visualization of the decision-making process. In the process of ranking the alternatives, the battery recycling transfer station location decision maker needs to consider the uncertainty factors and the potential gains and losses of the preference choices, however, among the many ranking methods, the CPT is very suitable because the CPT method combines the probability distributions and the decision maker's preferences to consider the impacts of these uncertainties on the location decision, helping the decision maker to make a more robust decision. On the whole, the BWM and CPT methods are very suitable for resilient and sustainable used EV battery recycling transfer station site selection, which provides scientific and effective decision support for decision makers, and helps to formulate the optimal site selection plan in line with the sustainable development goals and actual situation.

4. Evaluation indicator system

The importance of the evaluation indicator system for site selection cannot be overstated, as the evaluation criteria form the foundation for EVBRTS site selection. It is therefore undeniable that the establishment of a comprehensive and scientifically sound evaluation criteria system for EVBRTS site selection is important. Despite the abundance of evaluation criteria for facility location in the existing literature, there is a noticeable gap in the discussion of the evaluation index system specific to EVBRTS in the context of the circular economy. This gap may be due to the specific characteristics of EVBRTS sites, which are the subject of particular attention and research.

This paper summarizes the following typical characteristics of

EVBRTS site selection: i) Electric vehicle batteries are hazardous, and when sitting a recycling transfer station, it is essential to consider the potential contamination of soil, water, and air; ii) The location of EVBRTS should consider accessibility to transportation routes, utilities, and waste treatment facilities; iii) EVBRTS may face opposition from the local community due to concerns about environmental pollution, safety risks, and potential negative impacts on property values; and iv) Setting up an EVBRTS involves significant costs for land acquisition, construction, equipment and ongoing operation and maintenance, and it is therefore crucial that these costs are carefully weighed against the benefits of recycling electric vehicle batteries when making decisions. Thus, considering the fundamental characteristics of EVBRTS outlined above, this paper establishes site selection criteria for EVBRTS that integrate resilience and sustainability objectives.

This paper constructs an analytical framework for the EVBRTS evaluation index system to further realize the scientificity and validity of the criteria selection, as shown in Fig. 3. Firstly, Company H invited five experts from the engineering department, environmental protection department, operation department, university and finance department to form the EVBRTS site selection decision committee, all of whom have rich working experience and educational background, with basic information as shown in Table 1. Next each expert individually reviewed the relevant literature to screen out potential evaluation criteria and summarize the evaluation criteria provided by the experts. All experts discussed the screened criteria centrally, retaining the relatively important ones. The rationality of the indicator system was evaluated and adjusted through a questionnaire survey, and the EVBRTS evaluation index system was finally established.

Through a rigorous selection of EVBRTS criteria by experts, the structure of evaluation index systems constructed herein is shown in Fig. 4 and contains economic, social, environmental, technical and resilience criteria. A detailed description of the EVBRTS site selection evaluation criteria is shown in Table 2.

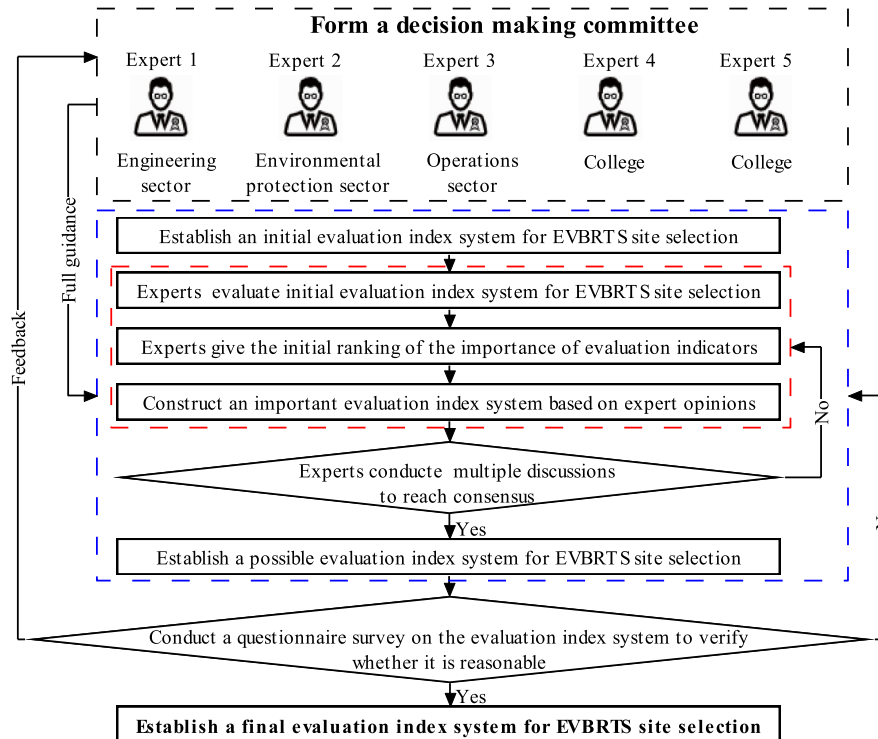


Fig. 3. Analysis framework of the designed evaluation index system.

Table 1
General information about the experts.

Experts	Occupation	Education	Experience (years)	Position	Weight
E1	Industry	Undergraduate	25	Engineering manager	0.15
E2	Industry	Master	28	Environmental manager	0.2
E3	Industry	Master	35	Operation manager	0.2
E4	Academia	PhD	22	Professor	0.2
E5	Academia	PhD	29	Professor	0.25

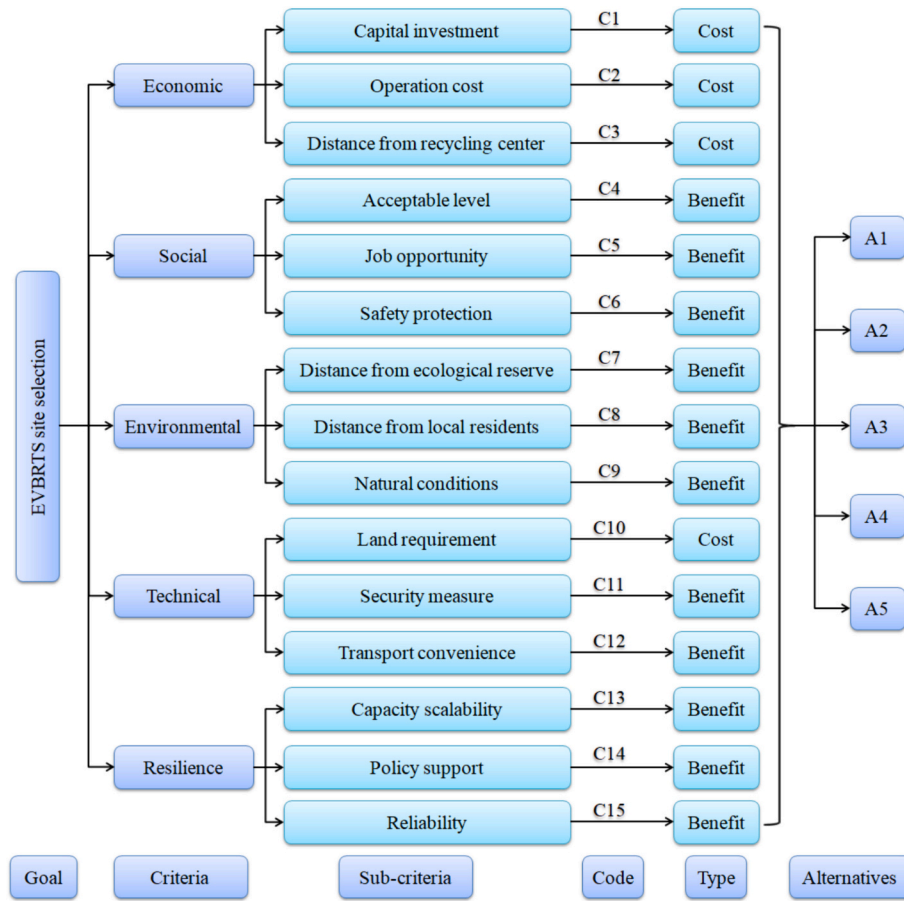


Fig. 4. A three-level decision hierarchy for EVBRTS site selection.

5. Application of the proposed method

This section illustrates the effectiveness of the proposed BWM-CPT method in capturing expert ambiguity and risk attitudes through a case study, and the ease of use of the methodology proposed here through a concrete demonstration of the application process. Potential EVBRTS alternatives were identified through field research with companies, and all alternatives are described in detail in the feasibility report.

5.1. Case description

Driven by the principles of the circular economy and supportive policies, the adoption of new energy vehicles has surged in recent years. However, as the capacity of electric vehicle batteries decreases to the point where they are no longer suitable for use in electric vehicles, a significant volume of used batteries will need to be recycled. The recycling of electric vehicle batteries is of the utmost importance. On one hand, electric vehicle batteries contain hazardous substances and precious metals. Improper disposal or indiscriminate discarding of these

batteries can lead to severe environmental pollution, posing risks of harmful substances infiltrating water sources and the atmosphere. On the other hand, these batteries are rich in valuable materials like lithium, nickel, and cobalt, crucial elements in the production of new batteries. Battery recycling reduces dependence on finite resources and facilitates resource recycling by reusing these scarce resources.

Given the many benefits of electric vehicle battery recycling, there are already many companies in the battery recycling business. A renewable resource company, which is referred to by the pseudonym Company H, plans to locate a suitable EVBRTS site to relieve the pressure of increasing battery recycling volumes. Company H specializes in recycling and technology development of waste lithium-ion batteries, waste electric vehicle batteries, nickel batteries, disposable dry batteries, etc.; battery recycling types include nickel-cadmium, nickel-hydrogen batteries, lithium-ion digital batteries, mobile phone batteries, electric bicycle batteries, new energy electric vehicle batteries, etc. With the increasing scale of business, the recycling centre faces many constraints, such as inventory and sorting operations. Company H therefore decides to build a battery recycling transfer station to acquire part of the business of the recycling plant. The transfer station will be

Table 2
Description of EVBRTS site selection criteria.

Criteria	Sub-criteria	Detailed descriptions	Literatures
Economic	Capital investment	This mainly includes land costs, construction costs, equipment costs, and project capital costs.	Pamucar et al. [50], and Li et al. [36]
	Operation cost	It involves wages, asset depreciation, operation and maintenance costs, etc.	Lee et al. [35], Sherif et al. [63], and Deveci et al. [12]
	Distance from recycling center	The proximity to recycling center saves transport costs as the role of transfer station is to store and sort waste battery without dismantling functions.	Authors contribution
Social	Acceptable level	It focuses on the acceptability of the EVBRTS location to surrounding residents.	Sherif et al. [63], and Mastrocinque et al. [45]
	Job opportunity	It indicates the number of jobs that potential alternative locations could bring to the public.	Lee et al. [35], and Kannan et al. [31]
	Safety protection	As used batteries are hazardous, specialized equipment should be provided to protect employees.	Govindan et al. [20], and Sherif et al. [63]
Environmental	Distance from ecological reserve	Potential locations should be away from farmland, water sources, ecological reserves, etc.	Sherif et al. [63], and He et al. [25]
	Distance from local residents	Potential locations should be as far away from residential areas as possible for safety.	Rahimi et al. [53], and Sherif et al. [63]
	Natural conditions	Transfer station locations should be strategically located in well natural conditions to avoid risks of flooding, cyclones, drought, etc.	Rao et al. [56], and Sherif et al. [63]
Technical	Land requirement	Area of land occupation at potential locations.	Pamucar et al. [50], and Li et al. [36]
	Security measure	Safety measures include fire compliance, response plans to deal with emergencies, etc.	Authors contribution
	Transport convenience	It includes the improvement of the surrounding infrastructure, the convenience of transport, etc.	Feng et al. [16]
Resilience	Capacity scalability	Potential locations should have the ability to readily respond to rising capacity to achieve economies of scale.	Feng et al. [16]
	Policy support	Local government's attitude towards environmental enterprises, financial subsidies, etc.	Pamucar et al. [50]
	Reliability	Reliability of potential location infrastructure and relationships with sellers of used batteries.	Authors contribution

used to store the waste batteries collected, sort them, test their remaining capacity, etc. It will not involve the dismantling of the batteries or their subsequent disposal. To select a suitable location for the EVBRTS, Company H has conducted prior field research on potential five alternatives, which denotes $A_j (j = 1, 2, \dots, 5)$. The key challenge for Company H is thus to select the appropriate method to evaluate the potential alternatives to obtain the optimal site.

5.2. Determining the criteria weights by the BWM

After obtaining the EVBRTS site evaluation index system (shown in Table 3), the five experts gave the best criterion C_B and worst criterion C_W , as shown in Table 4. Then the experts gave the evaluation information BO and WO respectively, which are given in Table A1 and A2 in Appendix.

The obtained values which are given in Table A1 and A2 in Appendix are brought into the model P2 to obtain criteria weight, as shown in Table 5.

Due to the differences in the experience and professional background of the experts, it is necessary to give different weights to the experts, the weights of the experts $w^k (k = 1, 2, \dots, 5)$ given herein are shown in Table 1, and the final criteria weights are determined by the following expression.

$$w_i = \sum_{k=1}^5 w^k w_i^k \quad (16)$$

where w^k indicates the criterion weight derived from expert k . The weighted criteria weights obtained are given in Table 5. In purpose of easy to see the magnitude relationship between the criterion weights, a histogram of the criterion weights was drawn as shown in Fig. 5. As illustrated in Fig. 5, the resilience criteria have the largest weighting of 0.3063, while the social criteria have the smallest weighting of 0.1308, indicating that the decision-making team preferred to achieve resilient sustainable development of the site.

5.3. Determining the optimal sorting by the CPT

Each of the five experts gave an evaluation of the alternatives, as shown in Tables A3-A7 in Appendix. The evaluation information is then transformed into TFNs as described in step 1 of the CPT method. Then the data is normalized by Eq. (8), defuzzified by Eq. (9). Then the average value can be calculated by Eq. (10) and this average value will be used as the reference point. Eq. (11) is next applied to calculate the values of gains and losses for each alternative. Then the prospective values of gains and losses are calculated separately by expression (12), and decision weights for gain and loss are determined by expression (13). It is worth noting that in expression (12) and (13), the parameter

Table 3
EVBRTS site evaluation index system.

Criteria	Sub-criteria	Notation
Economic	Capital investment	C1
	Operation cost	C2
	Distance from recycling center	C3
Social	Acceptable level	C4
	Job opportunity	C5
	Safety protection	C6
Environmental	Distance from ecological reserve	C7
	Distance from local residents	C8
	Natural conditions	C9
Technical	Land requirement	C10
	Security measure	C11
	Transport convenience	C12
Resilience	Capacity scalability	C13
	Policy support	C14
	Reliability	C15

Table 4
Best and worst criterion determined by expert.

Experts	Best criterion	Worst criterion
E1	Capacity scalability	Land requirement
E2	Natural conditions	Job opportunity
E3	Capital investment	Job opportunity
E4	Policy support	Security measure
E5	Capacity scalability	Acceptable level

Table 5
Calculation of the weighting of criteria for each expert assessment.

Criteria	E1	E2	E3	E4	E5	Final weights
C1	0.0943	0.0802	0.2156	0.0991	0.0707	0.1108
C2	0.0943	0.0802	0.0437	0.0594	0.0942	0.0744
C3	0.0708	0.0603	0.0328	0.0743	0.0565	0.0582
C4	0.0404	0.0481	0.0875	0.0425	0.0202	0.0467
C5	0.0472	0.0190	0.0187	0.0495	0.0354	0.0334
C6	0.0708	0.0481	0.0656	0.0425	0.0354	0.0507
C7	0.0404	0.0401	0.0875	0.0372	0.0404	0.0491
C8	0.0404	0.0401	0.0525	0.0372	0.0565	0.0461
C9	0.0404	0.1868	0.0437	0.0594	0.0471	0.0758
C10	0.0203	0.0802	0.0656	0.0425	0.0404	0.0508
C11	0.0404	0.0481	0.0375	0.0212	0.0354	0.0363
C12	0.0404	0.0481	0.0656	0.0743	0.0707	0.0613
C13	0.2325	0.0401	0.0437	0.0743	0.2322	0.1245
C14	0.0708	0.1203	0.0525	0.2441	0.0942	0.1176
C15	0.0566	0.0603	0.0875	0.0425	0.0707	0.0642

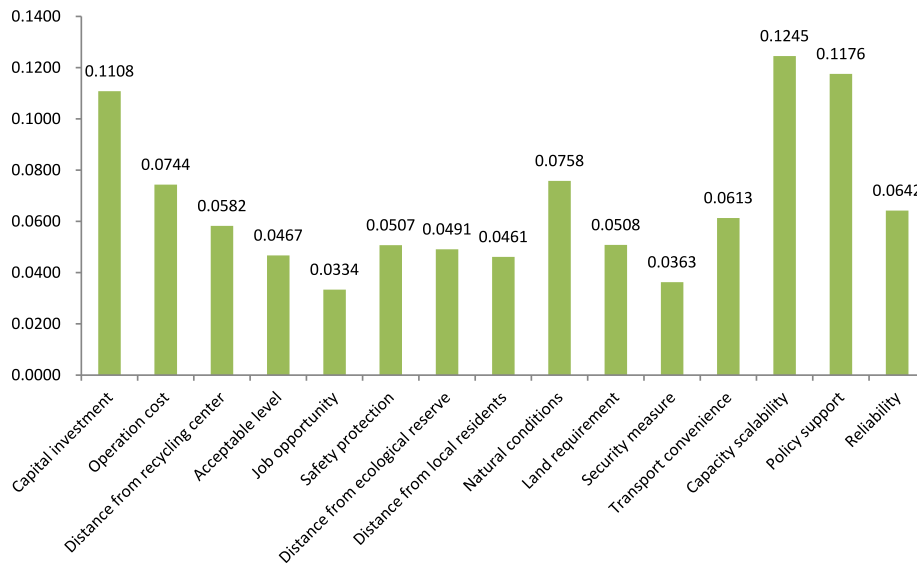


Fig. 5. Criteria weights.

Table 6
The ranking of the alternatives.

Experts	Results	A1	A2	A3	A4	A5
E1	Numerical results	-0.0163	-0.1655	-0.2270	-0.0070	-0.7202
	Sorting results	A4 > A1 > A2 > A3 > A5				
E2	Numerical results	-0.0611	-0.2694	0.1354	-0.3248	-0.6296
	Sorting results	A3 > A1 > A2 > A4 > A5				
E3	Numerical results	-0.2021	-0.3719	-0.0156	-0.1125	-0.4656
	Sorting results	A3 > A4 > A1 > A2 > A5				
E4	Numerical results	-0.1933	-0.2943	-0.5090	0.1268	-0.2680
	Sorting results	A4 > A1 > A5 > A2 > A3				
E5	Numerical results	-0.0400	-0.3798	-0.0874	0.0758	-0.5569
	Sorting results	A4 > A1 > A3 > A2 > A5				
Weighted	Numerical results	-0.1038	-0.3069	-0.1338	-0.0442	-0.5198
	Sorting results	A4 > A1 > A3 > A2 > A5				

$\alpha = \beta = 0.88$, $\theta = 2.25$, $\eta = 0.61$, and $\delta = 0.69$ [80]. Next the prospect values for each alternative were computed by Eq. (14), and finally the weighted cumulative prospect value V_j can be calculated by Eq. (15). The final ranking of the alternatives is presented in Table 6. Therefore, the best location should be alternative A4.

Fig. 6 depicts the performance of each alternative across economic, social, environmental, technical, and resilience criteria. Evidently, each alternative shows different performance levels across these criteria. For example, Alternative A1 excels in the environmental criterion but falls short in the resilience criterion. In contrast, Alternative A3 shows outstanding performance in the economic criterion but lacks in the environmental criterion. Alternative A5 demonstrates the weakest performance in both the economic and environmental criteria, whereas Alternative A4 displays a more balanced performance across economic, social, environmental, technical, and resilience criteria.

6. Analyses and discussions

In this section, the sensitivity and comparative analysis will be used to demonstrate the applicability and stability of the proposed methodology. Besides, the theoretical and management implications are also discussed.

6.1. Sensitivity analysis

To further analyze the affect of parameter changing on the ranking results, this paper performs a sensitivity analysis on the risk attitude

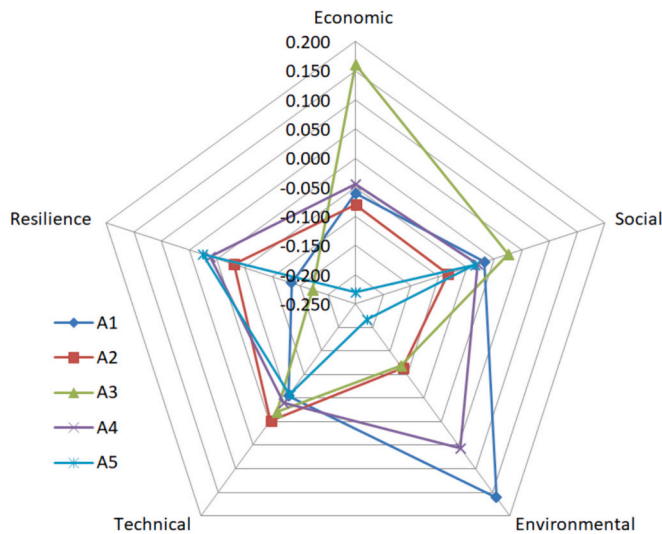


Fig. 6. Performance of each alternative in terms of economic, social, environmental, technical and resilience criteria.

parameters α , β , θ , η and δ , the expert weights, and criteria weights, respectively.

6.1.1. Effect of changes in risk attitude parameter α , β , θ , η and δ on results

In the CPT approach, both the prospect function and the decision weight function contain risk attitude parameters of the decision maker, so it is necessary to discuss these parameters. This section discusses the sensitivity analysis of risk parameters for the following five scenarios. It is worth noting that the analyses in this section are based on the aggregation of expert assessment information following Eq. (9).

Scenario 1: Parameter α is changed from 0.1 to 1 at intervals of 0.1.

Scenario 2: Parameter β is changed from 0.1 to 1 at intervals of 0.1.

Scenario 3: Parameter θ is changed from 1 to 10 at intervals of 1.

Scenario 4: Parameter η is changed from 0.1 to 0.9 at intervals of 0.1.

Scenario 5: Parameter δ is changed from 0.1 to 0.9 at intervals of 0.1.

Fig. 7 shows the results of the calculations for each of the five scenarios above. Apparently, these parameter variations have a significant impact on the sorting results. For example, the results of the alternatives decrease as the parameter α increases, and when the value of parameter α is < 0.9 , the sorting of alternatives does not change; whereas when the value of parameter α is between 0.9 and 1, the sorting of alternatives A3 and A1 changes. Alternative ranking is most sensitively affected by changes in the parameter η . For example, when $\eta = 0.1$, the best sorting is $A1 > A3 > A4 > A2 > A5$, and when $\eta = 0.5$, the optimal sorting is $A4 > A1 > A3 > A2 > A5$. Moreover, the sensitivity of the risk aversion parameter θ to changes in the ranking of alternatives can be found in Fig. 7(c), which demonstrates that risk preference can influence the EVBRTS site selection results. Actually, parameters α and β represent the trends of gains and losses in the value function, respectively; the larger the value of parameters α and β , the greater the likelihood of a risk-seeking attitude; while the lower the value of parameters α and β , the greater the likelihood of a risk-averse attitude.

6.1.2. Impact of changing expert weights

Both the BWM and CPT methods involve the use of expert weights, and in order to evaluate the influence of these weights on the ranking outcomes of the alternatives, a sensitivity analysis is carried out. This study selects several sets of different expert weight combinations, as detailed in Table A8 in the Appendix. The sorting results of the alternatives under various expert weight combinations are presented in Fig. 8. It is clear that adjustments in expert weights have no impact on

the ranking of the top alternative, but they do affect the rankings of the other alternatives. Expert weights play a crucial role in determining the ordering of alternatives, especially when there is little differentiation in performance among them. For instance, consider alternatives A1 and A3 as depicted in Fig. 8. In light of this, decision-makers should allocate varying weights to experts based on their knowledge background and practical experience to ensure a more accurate evaluation of the alternatives.

6.1.3. Impact of changing criteria weights

This section aims to analyze the impact of changes in criteria weights on the results. The following scenarios with different combinations of weights are considered: i) C1 criterion weights change from 0.1073 to 0.0773, C4 criterion weights change from 0.047 to 0.077, while the rest of the criterion weights remain unchanged; ii) C1 criterion weights change from 0.1073 to 0.0773, and C7 criterion weights change from 0.0505 to 0.0805; iii) the C1 criterion weight changed from 0.1073 to 0.0773, the C10 criterion weight changed from 0.052 to 0.082; iv) the C1 criterion weight changed from 0.1073 to 0.0773, the C13 criterion weight changed from 0.1185 to 0.1485. The results are shown in Table 7.

Table 7 illustrates only a few potential combinations, highlighting the varying impacts of different criteria weights on the alternatives. For example, by lowering the C1 criterion weights and increasing the C10 weights, alternative A3 will be superior to A1. Consequently, alterations in criterion weights have the potential to shift the evaluation results of the alternatives, potentially relegating initially top-ranked alternatives due to changes in specific criteria weights, or promoting initially lower-ranked alternatives to the forefront as a result of increased weights for certain criteria. Thus, fluctuations in criterion weights redefine the hierarchy of the alternatives. Changes in criterion weights may introduce bias into decision outcomes, as subjective increases in the weight of a criterion can favor one alternative at the expense of others. To mitigate the impact of criterion weight adjustments on the evaluation of alternatives, decision-makers should strive for objectivity and impartiality when determining criteria weights. It is essential to consider the significance and impact of each criterion, while avoiding subjective biases and interference from vested interests.

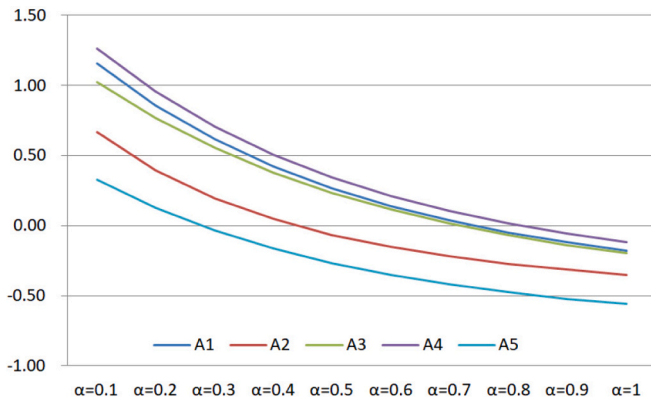
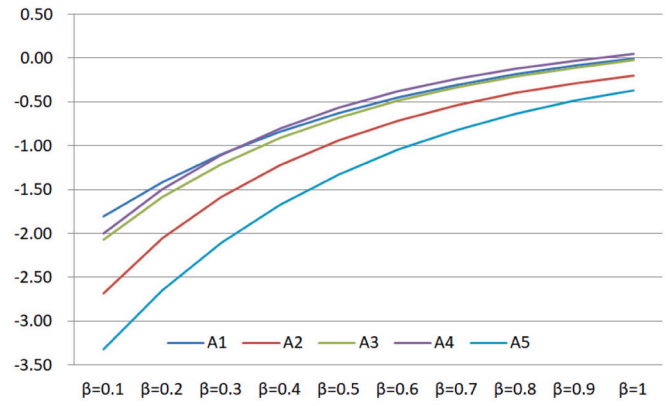
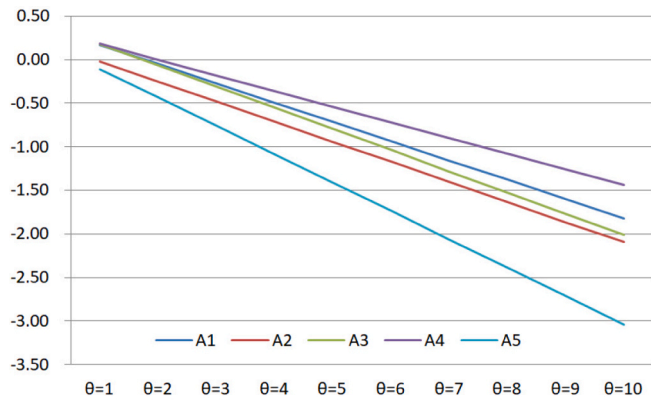
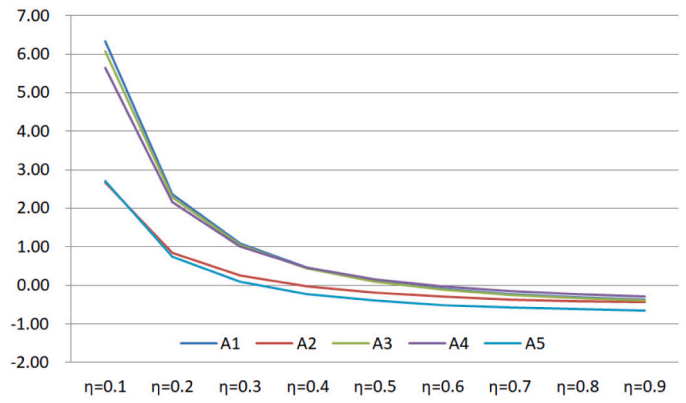
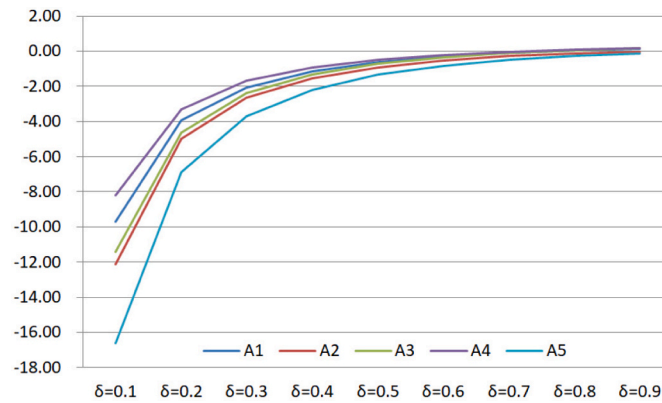
6.2. Comparative analysis

This section delves into the reliability of the proposed method by conducting a comparative analysis with other MCDM methods and exploring different aggregation sequences of expert evaluation information.

6.2.1. Comparison with other MCDM methods

In order to further validate the validity and flexibility of the method presented, the method presented was subject to a comparative analysis with three other well-known MCDM methods, namely TOPSIS [55], MABAC [49], and weighted aggregated sum product assessment (WASPAS) [4] methods. The ranking of alternatives are presented in Table 8.

The TOPSIS, MABAC, WASPAS, and CPT methods each adhere to distinct calculation rules. Nevertheless, they share common ground in identifying the best and worst alternatives. While the ranking of alternatives generated by the TOPSIS and WASPAS methods deviates slightly from the one presented in this paper. TOPSIS calculates the weighted Euclidean distance between alternatives and the positive and negative ideal solutions to determine their rankings, whereas the WASPAS method integrates two renowned MCDM methods—a weighted sum model and a weighted product model. In this study, a weight of 0.5 was assigned to the weighted sum model and another 0.5 to the weighted product model within the WASPAS approach. Conversely, the CPT method incorporates a risk attitude parameter, and alterations in parameter values yield varying rankings. For example, the ranking re-

(a) Sensitivity analysis of parameter α (b) Sensitivity analysis of parameter β (c) Sensitivity analysis of parameter θ (d) Sensitivity analysis of parameter η (e) Sensitivity analysis of parameter δ **Fig. 7.** Effect of changes in risk attitude parameter α , β , θ , η and δ on results.

sults obtained are the same as those obtained by TOPSIS and WASPAS methods when the parameters $\alpha = 0.7$, $\beta = 0.88$, $\theta = 2.25$, $\eta = 0.61$ and $\delta = 0.69$. In essence, the CPT method is more flexible and responsive to various decision-maker risk attitudes, thereby resulting in diverse ranking outcomes. By adjusting the decision maker's risk attitude, the CPT method can potentially generate varying ranking results. On the

other hand, MABAC operates as a compensatory method where attributes are considered independently, factoring in the magnitude of potential losses and gains without explicitly accounting for the decision maker's risk attitude. The effectiveness and compatibility of the proposed method are validated through comparisons with the TOPSIS, WASPAS, and MABAC methodologies.

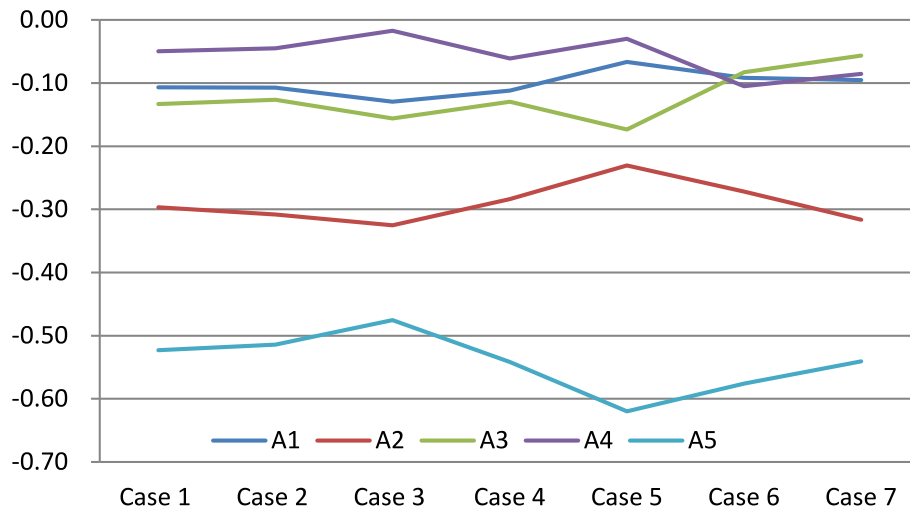


Fig. 8. Impact of changing expert weights.

Table 7

Impact of different combinations of criteria weights on results.

Combinations	Results	A1	A2	A3	A4	A5
(i)	Numerical results	−0.0769	−0.2489	−0.0897	0.0386	−0.4219
	Sorting results	A4 > A1 > A3 > A2 > A5				
(ii)	Numerical results	−0.0583	−0.2481	−0.1313	0.0733	−0.4516
	Sorting results	A4 > A1 > A3 > A2 > A5				
(iii)	Numerical results	−0.0941	−0.2445	−0.0745	0.0437	−0.4439
	Sorting results	A4 > A3 > A1 > A2 > A5				
(iv)	Numerical results	−0.0861	−0.2378	−0.1056	0.0531	−0.4224
	Sorting results	A4 > A1 > A3 > A2 > A5				

Table 8

Comparative results with other MCDM methods.

Methods	Results	A1	A2	A3	A4	A5
TOPSIS	Numerical results	0.5167	0.4256	0.5180	0.5604	0.3032
	Sorting results	A4 > A3 > A1 > A2 > A5				
WASPAS	Numerical results	0.8260	0.8140	0.8443	0.8451	0.7781
	Sorting results	A4 > A3 > A1 > A2 > A5				
MABAC	Numerical results	0.0466	0.0394	0.0454	0.1285	−0.0302
	Sorting results	A4 > A1 > A3 > A2 > A5				
The proposed method	Numerical results	−0.1038	−0.3069	−0.1338	−0.0442	−0.5198
	Sorting results	A4 > A1 > A3 > A2 > A5				

The CPT method considers the decision maker's attitude and preference for risk, which can better describe the psychological process of the decision maker, and can also deal with non-linear preferences and uncertainty, which is more in line with the actual situation of human decision making. The TOPSIS method is simple and easy to understand, and the calculation process is more intuitive, but it does not take into account the decision maker's risk appetite and psychological preference, and may not fully reflect the actual needs of decision makers. WASPAS and MABAC methods have the advantages of simplicity and intuition when dealing with simple multi-criteria decision-making problems, and are suitable for some more direct decision-making situations. The CPT method is relatively more complex, requiring an in-depth understanding of the decision maker's psychological preferences, more cumbersome data collection and processing, as well as a large amount of data and the decision maker's personalized parameter settings, especially when there are high requirements for risk and uncertainty, which will increase the complexity and cost of the calculation.

6.2.2. Comparing various aggregation sequences of experts' evaluation information

This section delves into the impact of different aggregation sequences of experts' assessment information on the alternatives. While both the BWM and CPT methods entail aggregating expert evaluation information, for the sake of simplicity in analysis, this paper focuses solely on the influence of different aggregation sequences of experts' assessment information on the outcomes within the CPT method. As such, three distinct orders of aggregation are explored: sequence 1) the aggregation order employed in this study; sequence 2) aggregation subsequent to Eq. (9); and sequence 3) aggregation following Eq. (7). The results of these sequences are presented in Table 9.

Obviously, different aggregation sequences have different impacts on the alternatives. If the experts' evaluation information is aggregated in the first step, then some of the information may be lost, which brings more risk to the evaluation. As a result, the later the aggregation of experts' information is necessary for the alternatives, so that unnecessary loss of linguistic information can be reduced.

Table 9
Effect of different aggregation sequences on alternatives.

Sequences	Results	A1	A2	A3	A4	A5
Sequence 1	Numerical results	−0.1038	−0.3069	−0.1338	−0.0442	−0.5198
	Sorting results	$A4 \succ A1 \succ A3 \succ A2 \succ A5$				
Sequence 2	Numerical results	−0.0831	−0.2417	−0.0845	0.0439	−0.4391
	Sorting results	$A4 \succ A1 \succ A3 \succ A2 \succ A5$				
Sequence 3	Numerical results	0.1633	0.1318	0.0334	0.1077	−0.1413
	Sorting results	$A1 \succ A2 \succ A4 \succ A3 \succ A5$				

6.3. Advantages of the proposed BWM-CPT method

By means of sensitivity analysis and comparative analysis, the integrated BWM-CPT method presented herein has the below advantages:

First, BWM is relatively simple and intuitive to understand and use. It does not require excessive data support and is sufficient to consider the relative importance of different factors. BWM helps to prioritize criteria by identifying the most and least important criteria, thus providing a holistic picture of the relative importance of these criteria in the decision-making process. BWM takes into account the subjective preferences of decision makers and, by asking them to assess the interrelationships between the best and worst criteria, provides a more accurate understanding of the personal preferences of assessment experts. In addition, BWM is a structured method that ensures transparency in the decision-making process. The explicit weights of the criteria obtained through this method can be easily communicated to stakeholders and results are more consistent and reliable.

Second, the CPT approach describes how human assess potential losses and gains when making decisions. Unlike traditional expected utility theory, CPT emphasizes that human have asymmetric perceptions of and responses to losses and gains, which better explains differences in human's decision-making behaviour. In addition, CPT emphasizes how human consider a target reference point when making decisions, assessing gains and losses based on the reference point rather than absolute utility. In addition, the CPT approach takes into account psychological factors in the decision-making process, such as risk aversion and loss aversion, which on the one hand provides a more realistic reflection of the way decision makers make choices under uncertainty; on the other hand, the CPT approach takes into account a non-linear utility function, which enables it to more accurately reflect decision maker's preferences, which is particularly important when dealing with complex and uncertain decision-making situations.

Third, the proposed method is able to obtain stable results and has a visualization of the calculation process. In the CPT method, decision makers can adjust the risk attitude parameters to obtain stable ranking results. The visualized calculation process is relatively simple and easy to practice. More importantly, in real scenarios, there are often multiple uncertainties and complex situations. By adopting an integrated BWM and CPT approach for informed and robust decision-making results, such complex decision-making environments can be better adapted to improve the validity and reliability of decisions.

6.4. Theoretical implications

Several theoretical implications are highlighted as follows: i) This is the first paper to present an analytical framework model for the EVBRTS site selection evaluation indicator system, which contributes to the identification of resilient sustainability criteria for EVBRTS site selection. Importantly, the analytical framework is an excellent reference for the development of other evaluation criteria systems; ii) This study developed a framework model for the location of battery recycling transfer stations and provided a theoretical and informational basis for the decision-making process of battery recycling managers; and iii) The theoretical validation of this paper highlights the effect of the order in which expert assessment information is aggregated on the ordering of

results, showing that delayed aggregation of expert assessments tends to produce more favourable results, which is attributed to the potential loss of linguistic information during the aggregation process. As a result, this paper provides a solid theoretical foundation for the optimal order of aggregation of expert assessment information in alternative selection.

6.5. Managerial implications

This paper provides battery recycling managers with a decision-making framework for the strategic site selection problem of EVBRTS from a resilience and sustainability perspective, and provides important managerial implications for the EVBRTS site selection, which contributes to the practical application of the proposed methodology.

First, this paper conducts an exploratory study focusing on the location challenges faced by companies operating transfer stations. To identify the optimal EVBRTS site, we develop an evaluation indicator system comprising five criteria and fifteen sub-criteria, meticulously refined through extensive discussions between industry stakeholders and academia. Nonetheless, the dynamic nature of the external environment may require adjustments to these criteria. For example, while traditional site selection analyses emphasize sustainability, evolving market dynamics warrant a focus on site resilience. Therefore, a resilience sustainability assessment indicator system for EVBRTS sites is established herein.

Second, the integrated approach proposed herein reduces the risk for managers associated with site selection decisions. Traditional methods such as TOPSIS, MABAC and WASPAS overlook the risk attitudes of decision-makers and fail to capture the nuances of their psychological behaviour during the decision-making process. In contrast, the CPT method is used in this study to rank alternatives and help decision makers to implement the necessary risk controls to prevent losses. Furthermore, the parameters in the CPT method can be adjusted according to the different attitudes of decision makers towards risk, making the methodology highly flexible and stable.

Last, the sequence in which experts' assessment information is aggregated significantly influences result sorting, as elucidated in the comparison of various orders of aggregated expert evaluation information. Consequently, in practice, managers must recognize that delaying the aggregation of expert assessments can minimize the loss of linguistic information, thereby reducing decision-making risks. While some loss of assessment information is inevitable during aggregation, managers can mitigate this loss by employing suitable methods.

7. Conclusions

The recycling of electric vehicle batteries has attracted increasing attention from academia and industry, aiming to promote sustainable economic, social, and ecological development. With a growing volume of waste electric vehicle batteries, urgent measures are needed to recycle this surplus and mitigate adverse impacts on the ecosystem. This study was initiated by a renewable energy company facing the challenge of expanding its battery recycling business, as the current recycling plant is insufficient to meet demands. Thus, there is an urgent need to establish a suitable battery recycling transfer station to relieve pressure on the recycling facility. To address this requirement, a framework model for

EVBRIS site selection was developed, integrating the BWM-CPT method and establishing a system of site selection evaluation criteria. The BWM method was employed to determine the weight of each criterion, followed by the application of CPT to rank alternatives. Sensitivity and comparison analyses demonstrate that the integrated method developed in this study provides a reliable scientific basis for a robust ranking of alternatives.

The key findings derived from the paper presented herein are as follows: i) the order in which the experts' assessment information is aggregated significantly influences the ranking outcomes. This is due to the fact that there may be a loss of potential information in the aggregation of assessment information from multiple experts. Typically, the assessment information from various experts is aggregated in the final step to reduce the loss of information; ii) criteria weights and decision makers' risk attitudes have an impact on the evaluation results. Decision-makers evaluate potential losses and gains based on reference points, and different risk attitudes lead to varying ranking results. As a result, the CPT method demonstrates greater compatibility compared to other MCDM methods; and iii) the application of the BWM and CPT methods in EVBRIS site selection has stability and robustness, and the evaluation indicator system framework model developed in this study is applicable to the most transfer station location.

In this paper, the BWM and CPT methods are adopted to study the problem of battery recycling transfer stations site selection, and the significance of the study is highlighted in the following ways. 1) The BWM method can help to determine the importance and weight of the location factors and help the decision maker to evaluate the alternatives more comprehensively, while the CPT method takes into account the decision maker's uncertainty about the gains and losses, which can make the location decision more scientific and accurate and improve the success rate of the decision. The application of these methods can improve the scientificity and effectiveness of the decision on the location of the battery recycling transfer station. 2) The study of the location of the battery recycling transfer station can help improve recycling efficiency and resource utilization, reduce the impact of waste batteries on the environment, promote green development, and contribute to environmental protection and sustainable development of society. 3) The study of the location of the battery recycling transfer station embodies the company's awareness of social responsibility and sustainable development. By making scientific location decisions, the Company fully considers environmental, social, economic and resilience factors to achieve the goal of sustainable development and make more contributions to society. 4) This paper provides a theoretical framework based on the MCDM method for the site selection problem in the battery recycling process, which fills the research gap of the existing research ignoring the site selection in the battery recycling process, and contributes to the sustainable development of the battery recycling field.

This paper offers a valuable tool for companies seeking to identify the optimal EVBRIS location; nonetheless, it also presents some limitations. First, the use of clear values to compare criteria in the adopted BWM methodology may ignore the ambiguity inherent in the experts' evaluation of these criteria. Therefore, it would be both interesting and meaningful to explore the inclusion of expert-provided interval values

conforming to a normal distribution to characterize assessment uncertainty in future studies. Second, in the adopted CPT methodology, this paper sets the value of the decision maker's risk attitude parameter based on previous research. However, since each decision maker's risk attitude parameter value may be different, determining how to measure the decision maker's risk attitude through a specific methodology can greatly improve the accuracy of site selection. Third, this study did not consider the possible correlations between the selected criteria. Considering the possible interdependence of the criteria, the use of the DEMATEL method to assess the importance of each of the evaluation indicators in the system would be a worthwhile direction to explore in future studies. Last, future research should focus on updating EVBRIS standards based on practical applications. By integrating geographic information system technology into site selection analysis, researchers can consider factors such as geography, transportation accessibility, and resource distribution to optimize EVBRIS locations. Furthermore, as the body of literature on battery recycling site selection continues to grow, it would be valuable to compile a review article summarizing the key findings and insights in this field. This review article could serve as a comprehensive resource for researchers and practitioners interested in battery recycling sitting issues.

CRediT authorship contribution statement

Jianghong Feng: Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation. **Ping Guo:** Validation, Software, Investigation, Formal analysis. **Gangyan Xu:** Software, Resources, Investigation, Data curation. **Yu Ning:** Visualization, Software, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Appendix

Table A1
BO vectors for five experts.

Criteria	E1	E2	E3	E4	E5
	Capacity scalability	Natural conditions	Capital investment	Policy support	Capacity scalability
Capital investment	3	3	1	3	4
Operation cost	3	3	6	5	3
Distance from recycling center	4	4	8	4	5
Acceptable level	7	5	3	7	9
Job opportunity	6	7	9	6	8
Safety protection	4	5	4	7	8
Distance from ecological reserve	7	6	3	8	7
Distance from local residents	7	6	5	8	5
Natural conditions	7	1	6	5	6
Land requirement	9	3	4	7	7
Security measure	7	5	7	9	8
Transport convenience	7	5	4	4	4
Capacity scalability	1	6	6	4	1
Policy support	4	2	5	1	3
Reliability	5	4	3	7	4

Table A2
WO vectors for five experts.

Criteria	E1	E2	E3	E4	E5
	Land requirement	Job opportunity	Job opportunity	Security measure	Acceptable level
Capital investment	7	7	9	6	6
Operation cost	6	7	3	5	7
Distance from recycling center	5	6	2	6	5
Acceptable level	3	4	7	3	1
Job opportunity	4	3	1	4	2
Safety protection	6	4	5	3	2
Distance from ecological reserve	3	4	6	2	3
Distance from local residents	2	4	5	2	4
Natural conditions	3	9	3	5	4
Land requirement	1	7	6	2	3
Security measure	3	5	3	1	2
Transport convenience	2	4	5	6	6
Capacity scalability	9	4	3	5	9
Policy support	6	8	4	9	6
Reliability	5	5	7	3	5

Table A3
Results of expert E1’s assessment of alternatives.

Criteria	Unit	A1	A2	A3	A4	A5
C1	\$(10 ⁵)	[40,50]	[32,40]	[24,36]	[38,46]	[39,48]
C2	\$(10 ⁴)/year	[20,24]	[17,22]	[10,15]	[18,21]	[20,23]
C3	km	20	34	28	24	39
C4	–	G	VG	G	F	VG
C5	–	SG	G	VG	VG	G
C6	–	G	F	SP	G	F
C7	km	13	11	8	15	9
C8	km	10	5	6	8	4
C9	–	VG	VG	G	SG	G
C10	hm ²	0.31	0.24	0.17	0.26	0.28
C11	–	G	SG	SG	VG	VG
C12	–	VG	G	F	F	G
C13	–	SP	F	G	SG	F
C14	–	VG	G	G	VG	SG
C15	–	SG	VG	SP	G	F

Table A4
Results of expert E2’s assessment of alternatives.

Criteria	Unit	A1	A2	A3	A4	A5
C1	\$(10 ⁵)	[40,50]	[32,40]	[24,36]	[38,46]	[39,48]
C2	\$(10 ⁴)/year	[20,24]	[17,22]	[10,15]	[18,21]	[20,23]
C3	km	20	34	28	24	39
C4	–	SG	F	VG	F	F
C5	–	G	SP	G	F	G
C6	–	SG	F	G	F	G
C7	km	13	11	8	15	9
C8	km	10	5	6	8	4
C9	–	G	G	VG	SP	F
C10	hm ²	0.31	0.24	0.17	0.26	0.28
C11	–	VG	G	G	SG	VG
C12	–	VG	SG	F	G	F
C13	–	F	G	SG	G	G
C14	–	VG	VG	VG	G	SG
C15	–	F	G	F	G	VG

Table A5
Results of expert E3’s assessment of alternatives.

Criteria	Unit	A1	A2	A3	A4	A5
C1	\$(10 ⁵)	[40,50]	[32,40]	[24,36]	[38,46]	[39,48]
C2	\$(10 ⁴)/year	[20,24]	[17,22]	[10,15]	[18,21]	[20,23]
C3	km	20	34	28	24	39
C4	–	SP	G	G	F	SG
C5	–	VG	SP	VG	SG	SG
C6	–	SG	SG	F	G	F
C7	km	13	11	8	15	9
C8	km	10	5	6	8	4
C9	–	G	F	G	F	G
C10	hm ²	0.31	0.24	0.17	0.26	0.28
C11	–	G	F	SG	VG	G
C12	–	G	SG	F	G	SG
C13	–	SP	VG	SP	SG	F
C14	–	G	SG	G	F	G
C15	–	F	SG	G	G	G

Table A6
Results of expert E4’s assessment of alternatives.

Criteria	Unit	A1	A2	A3	A4	A5
C1	\$(10 ⁵)	[40,50]	[32,40]	[24,36]	[38,46]	[39,48]
C2	\$(10 ⁴)/year	[20,24]	[17,22]	[10,15]	[18,21]	[20,23]
C3	km	20	34	28	24	39
C4	–	G	SG	SG	G	G
C5	–	G	F	G	VG	VG
C6	–	SP	VG	SG	G	G
C7	km	13	11	8	15	9
C8	km	10	5	6	8	4
C9	–	G	SG	F	VG	SG
C10	hm ²	0.31	0.24	0.17	0.26	0.28
C11	–	G	G	F	G	VG
C12	–	F	SG	G	F	SG
C13	–	F	VG	SP	F	G
C14	–	G	F	F	VG	VG
C15	–	VG	G	G	G	SG

Table A7
Results of expert E5’s assessment of alternatives.

Criteria	Unit	A1	A2	A3	A4	A5
C1	\$(10 ⁵)	[40,50]	[32,40]	[24,36]	[38,46]	[39,48]
C2	\$(10 ⁴)/year	[20,24]	[17,22]	[10,15]	[18,21]	[20,23]
C3	km	20	34	28	24	39
C4	–	G	SG	G	G	VG

(continued on next page)

Table A7 (continued)

Criteria	Unit	A1	A2	A3	A4	A5
C5	–	VG	VG	G	G	SP
C6	–	G	G	VG	G	SG
C7	km	13	11	8	15	9
C8	km	10	5	6	8	4
C9	–	G	SG	G	G	SG
C10	hm ²	0.31	0.24	0.17	0.26	0.28
C11	–	G	G	SG	F	F
C12	–	F	G	F	G	SG
C13	–	G	SG	G	SG	VG
C14	–	G	G	F	VG	VG
C15	–	SG	F	G	VG	VG

Table A8
Different expert weight combinations.

Cases	E1	E2	E3	E4	E5
Case 1	0.2	0.2	0.2	0.2	0.2
Case 2	0.15	0.2	0.2	0.2	0.25
Case 3	0.1	0.1	0.3	0.25	0.25
Case 4	0.3	0.15	0.3	0.15	0.1
Case 5	0.6	0.1	0.1	0.1	0.1
Case 6	0.3	0.3	0.2	0.1	0.1
Case 7	0.1	0.3	0.2	0.1	0.3

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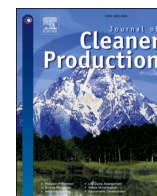
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Barriers to electric vehicle battery recycling in a circular economy: An interpretive structural modeling

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ABSTRACT

An increasing number of electric vehicle batteries will reach the end of their life cycle with the fast growth of electric vehicles. Since the recycling of retired electric vehicles batteries is of great significance in the light of resource utilization, ecological protection, energy saving and economic benefits, the proper management of electric vehicle battery recycling (EVBR) is crucial for achieving sustainable development. However, due to the involvement of multiple stakeholders, there are many potential barriers in the process of EVBR, and analyzing these barriers can significantly help the recycling management of waste electric vehicle batteries towards a circular economy. Although the literature has focused on analyzing obstacles to implementing reverse logistics for electric vehicle lithium battery recycling from a manufacturer's perspective, less attention has been paid to analyzing barriers to EVBR from a multi-stakeholder perspective. This paper thus aims to investigate the barriers to EVBR from a multi-stakeholder point of view, identify the main barriers affecting battery recycling, and analyze the interrelationships and hierarchies between these barriers. Based on expert opinions and literature reviews, this paper identifies twenty major barriers to EVBR and uses interpretive structural modelling (ISM) method to determine the interrelationships and hierarchies between the barriers, and finally classifies the barriers to EVBR into a seven-level structural model. Furthermore, matrixed impacts corises-multiplication appliance classement (MICMAC) analysis is applied to categorize the identified barriers to EVBR, and the twenty barriers are finally classified into three categories, namely dependent barriers, linkage barriers, and driver barriers. This paper discusses theoretical insights, managerial and practical implications, and measures to overcome EVBR barriers based on the results, which show that the lack of more appropriate incentives is a major barrier to EVBR implementation. This paper provides a solid theoretical foundation for the further development of battery recycling policies, and will also help relevant stakeholders and governments to better understand these barriers and adopt effective approaches to address them.

1. Introduction

The transport sector has long been a major carbon emitter (Awan et al., 2022; Feng et al., 2021). However, the world has yet to find an effective solution to carbon emissions, which have been on the decline in developed countries in areas such as industry and construction in the past years (e.g. 2021–2022), but have not changed significantly in the transport sector (IEA, 2023a). Reducing the carbon footprint of the transportation sector is thus crucial to the achievement of carbon neutrality and the transition to a circular economy (Yang et al., 2023). In recent years, electric vehicles have been the focus of much attention from a growing number of academics and industries due to their proven superior performance in terms of carbon emission reduction. Driven by

environmental pressures and policy incentives, electric vehicle development has progressed significantly (Liu et al., 2023; Xu et al., 2023). For example, over the past few years, major countries around the world have developed various incentivized policies to develop electric vehicles, which has been instrumental in their rapid spread (Kester et al., 2018; Zhang et al., 2017). Furthermore, according to electric vehicle sales data, over 10 million electric vehicles were sold worldwide in 2022 (IEA, 2023b). The rapid growth of electric vehicles has undoubtedly made a significant contribution to the reduction of carbon emissions in the transportation sector (Zhang et al., 2022). From the perspective of a circular economy, widespread adoption of electric vehicles and electrifying the transport sector are key measures to achieving carbon reductions in transport (Andwari et al., 2017; Isik et al., 2021; Zhang and

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Hanaoka, 2021).

As the popularity of electric vehicles explodes, another major challenge is managing electric vehicle battery recycling (EVBR) to cope with the large volumes of retired batteries. As we all know, once the waste battery is discarded into the natural environment, it has an incalculable impact on the ecosystem and have an adverse effect on public health (Du et al., 2022). To reduce the ecological pollution caused by batteries, recycling batteries is particularly necessary and important (Yang et al., 2021). Recycling end-of-life electric vehicle batteries thus has the potential to deliver huge economic and environmental benefits (Qiao et al., 2019, 2021; Shafique et al., 2022). However, the current rate of EVBR is not very high (Woollacott, 2021). Moreover, battery recycling is a complex and challenging issue that involves a wide range of stakeholders including manufacturers, consumers, battery technology developers, recyclers, dismantlers, downstream users and policy makers (Dong and Ge, 2022). Consequently, battery recycling is not just the business of recyclers, but involves a wide range of stakeholders, which makes the EVBR a challenging endeavor (Bhuyan et al., 2022). There are a number of problems with EVBR, such as recycling technology and safety, which limit the large-scale recycling of batteries (Kang et al., 2023; Yu et al., 2022). Meanwhile, many academics and industry stakeholders are calling for the development of a comprehensive battery recycling system that takes an interdisciplinary and multi-sectoral approach, including the fields of engineering, economics, environmental science and systems science. The most recent studies have been dedicated to designing EVBR supply chain networks (Sasikumar and Haq, 2011; Tadaros et al., 2022), auctions for battery recycling (Feng et al., 2024; Xu et al., 2022), and battery recycling subsidies (Gu et al., 2017; Li et al., 2020). However, there has been little discussion of the key factors which have an impact on EVBR to date.

To promote EVBR for sustainable development, countries worldwide have formulated EVBR policies and regulations to encourage and regulate battery recycling industry development (King and Boxall, 2019; Ren et al., 2023; Sun et al., 2021; Yang et al., 2022). For instance, the European Union has established a clear battery recycling system to promote a circular economy.¹ China has also formulated a series of battery recycling policies, including encouraging enterprises to carry out battery recycling business and building infrastructure related to battery recycling (Tian et al., 2014). While these policies have been an important driver of battery recycling, however, research to analyze the barriers to EVBR is challenging because of the interdisciplinary characteristics of battery recycling, which requires background knowledge in materials science, logistics, management science, ecology, etc. For example, a recycler may also need expertise in materials science, logistics, etc. to ensure safe battery recycling. On the other hand, EVBR involves stakeholders like regulators, consumers, recyclers, battery engineers and manufacturers, which add to the complexity of the battery recycling issue. To achieve efficient recycling of electric vehicles batteries, there is a pressing need to identify potential barriers and develop effective policies and measures to overcome them. To this end, the further investigation of the barriers to EVBR is an interesting and valuable research topic. Specifically, the research questions that this study aims to address are given as follows: i) What are the key batteries that affect EVBR? ii) What are the complex relationships and hierarchies that exist between these barriers? And iii) What measures should stakeholders adopt to improve battery recycling in response to these barriers?

This paper is dedicated to investigating the barriers to EVBR to provide insights for policy and decision making. The purpose of this work is thus to determine the key barriers to EVBR, to identify their interrelationships and hierarchical relationships using an interpretative structural modeling (ISM) and to provide managerial insights. To answer research question one, this paper identifies potential twenty barriers to EVBR through literature and expert opinion. To answer

research question two, this paper identifies the relationship of the barriers through the ISM method, which has been extensively adopted for the analysis of barriers. For example, the barrier analysis of green lean implementations (Cherrafi et al., 2017), barrier analysis in the energy sector (Ansari et al., 2013), barrier analysis in the supply chain (Agrawal et al., 2019), barriers to the adoption of industry 4.0 technologies in the manufacturing industry (Senna et al., 2022), and barriers to digital adoption in manufacturing (Senna et al., 2023). Finally, this paper applies the MICMAC (matriced impacts corises-multiplication appliance classement) methodology to analyze the impacts and dependencies between the barriers and to provide management and practical insights. Besides, this paper proposes measures to overcome the barriers based on the results of the study to answer research question three.

A summary of the key contributions of this study is provided below. Firstly, this study examines the barriers to the battery recycling process and identifies potential barriers to EVBR through an extensive literature review and expert consultation. Secondly, this paper identifies the hierarchy between barriers through the ISM approach, classifies the identified barriers by the MICMAC method and provides relevant stakeholders such as governments, businesses and academia with important insights on how to overcome these potential barriers. Thirdly, this paper provides a theoretical framework to analyze the barriers to EVBR for the government, enterprises, consumers, environmental organizations and other stakeholders, which helps researchers to further understand the various factors affecting the recycling of waste batteries in a comprehensive manner, and facilitates the implementation and promotion of battery recycling. Although this paper is orientated towards China, the research questions and methodology are also applicable to other countries or regions dedicated to improving the recycling of electric vehicle batteries, and can also help them to identify potential barriers so that they can formulate effective policies and measures to achieve the transition to a circular economy.

The rest of the organizational structure of this study is set out below. A review of related research is presented in Section 2. Section 3 identifies barriers to EVBR, identifies the hierarchy between barriers by the ISM method and determines the classification of barriers via the MICMAC methodology. Section 4 provides a discussion of key findings, theoretical implications, managerial and practical insights. Section 5 draws conclusions, research limitations and some interesting and valuable future research directions.

2. Literature review

This section will review the work related to this paper from two aspects. The first one is the research related to EVBR and the second one is the application of ISM methodology.

2.1. Electric vehicle battery recycling related studies

EVBR is crucial in helping to develop and promote a circular economy, and the focus for the reduction of the environmental impact of electric vehicle batteries lies in the exploration of the use of recyclable battery materials and the increase of the battery recycling rate. Increasing the recycling rate of batteries has been the subject of a considerable amount of literature. For example, Tang et al. (2018) applied a game theory approach to explore the impact of reward and punishment mechanisms on EVBR, and concluded that increasing environmental awareness can promote EVBR. Lin et al. (2023) presented four regulatory options for EVBR, and used a game-theoretic model to explore the merits and demerits of different scenarios from economic, social and environmental perspectives. Li et al. (2022) investigated four joint recycling strategies for waste batteries by applying game theory based on the manufacturer's perspective, and provided the optimal strategy selection conditions under different scenarios. Zhao et al. (2022) studied three various EVBR pricing strategies in the context of having subsidies and the results confirmed that subsidies can promote

¹ <https://data.consilium.europa.eu/doc/document/PE-2-2023-INIT/en/pdf>.

EVBR. Furthermore, there is also literature dealing with designing networks for EVBR. For example, Wang et al. (2020) discussed EVBR network design from a manufacturer's perspective, considering three strategies for battery recycling, remanufacturing, and disposal, and found that the number of waste batteries, logistics costs, and carbon taxes are key factors affecting battery recycling. Liu et al. (2021) investigated the effect of remaining battery capacity on recycling, constructed two mathematical planning models, and argued that uncertainty in remaining battery capacity has a considerable effect on the supply chain. Hu et al. (2022) developed a EVBR network model that is able to deal with both the facility locations and vehicle travelling paths problem, and validated the model with real cases. Li et al. (2023) analyzed the decision problem of EVBR systems from a cross-network cooperation perspective and developed a mixed-integer planning model, and the study's results have shown that the proposed mathematical planning method is beneficial for the reduction of the cost of recovery.

The economic, technological and environmental advantages of EVBR have been the subject of several studies. For instance, Qiao et al. (2019) investigated the wide range of economic and environmental advantages of battery recycling, arguing that as battery recycling continues to scale up, the economic and environmental advantages will be particularly strong. Pražanová et al. (2022) reviewed the potential economic and environmental effects of battery recycling and found that there is a dearth of literature analyzing current EVBR from an economic perspective. Lima et al. (2022) studied the key factors impacting the economics of EVBR, arguing that the economic benefits of EVBR are compromised by the lack of volume recycling. Yu et al. (2022) discussed the affect of policy upon battery recycling and the economic and environmental effects of battery recycling, and summarized some of the challenges facing battery recycling and made recommendations, but did not systematically analyze and identify the barriers to battery recycling. Jiang et al. (2021) argued that the economic benefits are better realized by the stepwise utilization of batteries than by simply recycling the metallic materials of the batteries. Tripathy et al. (2023) discussed the key drivers of electric vehicles lithium battery recycling and assessed them in terms of their economic, social and environmental dimensions. The literature highlighted the need and importance of recycling lithium batteries in social, economic and environmental terms; however, it did not investigate the key factors influencing the recycling of lithium batteries.

Recently, literature has been published that examines the factors influencing the recycling of electric vehicle batteries from various perspectives. Dong and Ge (2022) investigated the key factors influencing battery recycling from a consumer perspective. Huang et al. (2022) surveyed the effects of policy on the willingness to purchase electric vehicles, and the study found that battery recycling policies are conducive to increasing sales of electric vehicles. Zeng et al. (2015) found that regulation, recycling models and recycling technologies are the main factors affecting battery recycling. Chen et al. (2019) discussed three important factors affecting battery recycling, namely changes in raw material prices, uneven distribution of battery production and transport conditions, and concluded that there is a need for greater collaboration between government, academia and industry to continuously improve EVBR. Lander et al. (2021) developed a techno-economic framework for recycling batteries to make EVBR economically viable and concluded that the economic benefits of recycling batteries rely on transport distances, labour costs and the technological approach used to recycle. Beaudet et al. (2020) discussed the financial and technical challenges of battery recycling before concluding with policy recommendations, but did not systematically and comprehensively identify the main barriers to battery recycling. Tang et al. (2023) empirically analyzed the factors influencing residents' willingness to participate in battery recycling, and the study concluded that recycling price has a noteworthy effect on the recycling rate. Tripathy et al. (2022) discussed the factors promoting battery recycling from a technical, environmental

and organizational perspective, and the results showed that an advanced recycling business model can significantly improve the battery recycling rate.

These studies have laid a solid theoretical foundation for the promotion of EVBR and further in-depth research on battery recycling. For example, literature on the environmental, economic, and social merits of EVBR has emphasized the need of batteries recycling. Recycling management practices for electric vehicle batteries are shifting from a single model to sustainable systems management. This requires additional efforts by battery material developers, technologists, consumers, manufacturers, policymakers and others to improve battery recycling. With so many stakeholders involved, identifying the key barriers to battery recycling is critical to policy development and business practices. Furthermore, this paper is close to Azadnia et al. (2021), but does not have the same research topic as Azadnia et al. (2021). Azadnia et al. (2021) focused on the key barriers to the implementation of EVBR reverse logistics, whereas this paper focuses on the analysis of the barriers to EVBR. More importantly, this paper identifies broader barriers to EVBR through expert opinion and literature. In contrast to the aforementioned literature, this paper focuses on analyzing the barriers to recycling electric vehicle batteries, which may pave the way for the development of more refined policy recommendations and practices.

2.2. Application of ISM methodology

The ISM method is widely used in barrier analysis because of its hierarchical modelling technique characteristics (Mathivathanan et al., 2021; Vasanthakumar et al., 2016). For example, Nandal et al. (2019) applied the ISM to determine the key barriers to the implementation of solar energy. Chen et al. (2022) discussed the barriers to the implementation of building integrated photovoltaics and identify the hierarchy between these barriers through the ISM methodology. Balci and Surucu-Balci (2021) and Singh et al. (2023) investigated the barriers to the application of blockchain and identified the structural relationships between these key barriers using ISM and MICMAC methods. Attiany et al. (2023) explored the main barriers to the adoption of Industry 4.0 and analyzed the 10 barriers screened through the ISM and MICMAC methodologies, and finally identified 8 key barriers. Menon and Ravi (2021) investigated the obstacles to sustainable development within the electrical industry and identified 11 barriers based on expert opinion and literature, then applied ISM and MICMAC analysis to determine the hierarchy of barriers and analyzed these barriers in detail.

Recently, literature on barriers to waste recycling has been published. For instance, e-waste management barriers (Kumar and Dixit, 2018; Singhal et al., 2019), and reverse logistics barriers in construction waste management (Wu et al., 2022). Chauhan et al. (2018) applied the ISM methodology and the decision-making trail and evaluation laboratory (DEMATEL) methodology to determine the key barriers to waste recycling and found that the private sector has made a significant contribution to waste recycling. Oluleye et al. (2022) performed a structured review of the barriers to circular management of construction waste, categorized these barriers and then applied the ISM methodology to identify the interrelationships between the barriers. Jaisue et al. (2023) investigated the barriers to the development of waste-to-energy projects in Thailand, categorized the screened barriers into six dimensions: social, economic, technological, environmental, policy and project management, and finally identified the key barriers as coming from the low volume of waste and poor waste management through the ISM and MICMAC methods. Wang et al. (2023) constructed an integrated decision framework model based on ISM, DEMATEL and maximum mean de-entropy algorithm for municipal solid waste management barriers.

Much of the existing literature has demonstrated the effectiveness of using ISM and MICMAC methods to identify the hierarchy and interrelationships between barriers. However, despite the fact that the structured analysis methods of ISM and MICMAC are widely used in a

number of fields, there has been less research to date on the investigation of the interrelationships and hierarchies between the barriers to EVBR. Therefore, in this paper, ISM and MICMAC methods are applied to identify the hierarchical relationships that screen out barriers to EVBR.

2.3. Research gaps

The following research gaps have been identified herein through a review of the above literature.

First, most existing EVBR research were concerned with: i) the economic, social, and environmental impacts of EVBR; ii) the economic and environmental benefits; and iii) the network design for EVBR. These literatures, which have made important contributions, are of particular importance for a further study of the EVBR. However, the analysis of the barriers to the EVBR from a variety of relevant stakeholders is an important research topic that has been neglected in the literature to date. Although there is existing literature that analyses the factors affecting EVBR from different perspectives, there is a lack of literature that comprehensively and systematically discusses the barriers to battery recycling from a circular economy perspective. To this end, this paper discusses the barriers to EVBR to contribute to battery recycling in theory and practice.

Second, because EVBR is influenced by multiple stakeholders, the need to identify the key barriers to EVBR perceived by these participants is not an easy task. Although [Beaudet et al. \(2020\)](#) discussed the drivers for lithium battery recycling in terms of technology, organization and environment, and [Bhuyan et al. \(2022\)](#) explored seventeen barriers and enablers to lithium battery recycling in five dimensions: economic, social, environmental, technological, and policy and regulatory, these factors do not fully represent the barriers to EVBR. Therefore, there is a need to further explore the barriers to EVBR and to analyze the impact of the relationship between the barriers so that reasonable measures can be developed to address the key barriers. Literature on this is limited, for this reason, this paper analyses the interrelationships of EVBR barriers through the ISM and MICMAC methods to fill this research gap.

3. Methodology and results

The aim of this section is to identify potential barriers to EVBR, and analyze the possible hierarchy between these barriers through the ISM and MICMAC methods.

3.1. Identifying barriers to EVBR

Power battery recycling involves knowledge from many fields, including battery technology, environmental protection, laws and regulations, and economic benefits. Therefore, it is necessary to select experts from different fields to participate in the assessment. This is because firstly, experts from different fields have different professional knowledge and perspectives, which can help to fully understand all aspects of power battery recycling, including technical feasibility, environmental impacts, compliance with laws and regulations, and economic benefits, etc. Secondly, by bringing together experts from different fields to conduct the assessment, they can synthesise the opinions and suggestions of all parties and more comprehensively assess the factors of power battery recycling. Finally, experts from different fields have profound professional backgrounds and experience in their respective fields, and can provide professional suggestions on issues related to power battery recycling to ensure the professionalism and accuracy of the assessment. To make the selected barriers to battery recycling more comprehensive and systematic, this paper invites three academic experts, two experts from battery recycling companies, one expert from the power battery manufacturing industry, one expert from a governmental department, and one electric vehicle owner to form an assessment team for barriers to power battery recycling.

The reasons for choosing experts from different fields to form the assessment team on barriers to power battery recycling are as follows: 1) academic experts can provide theoretical support and have in-depth knowledge of power battery recycling technologies and environmental impacts; 2) experts from battery recycling companies have extensive experience in actual operations and can provide practical guidance for the assessment by providing information on actual operational situations, problems and challenges; 3) Power battery manufacturing industry experts understand the production process and materials of power batteries, and can provide professional opinions on the structure and characteristics of power batteries in the assessment; 4) experts from government departments understand relevant policies, regulations and standards, and can guide the assessment team to conduct the assessment within the framework of laws and regulations to ensure the compliance of the assessment work; and 5) electric vehicle owners, as end-users, can provide practical needs and feedback on issues related to power battery recycling, which will help the assessment team to be closer to users' needs and the actual situation.

Barriers to EVBR that were considered to be very important were identified through the literature and comments from the group discussions. The detailed descriptions of the barriers are given below.

3.1.1. Lack of regulatory pressure from government and society (B1)

Although existing policies and regulations have been effective in promoting battery recycling, there are still shortcomings in regulation and enforcement ([Yu et al., 2022](#)). Lack of regulatory pressure from government and society may lead to inadequate battery recycling ([Ciez and Whitacre, 2019](#)). The rise of electric vehicles has brought about a large demand for the use and renewal of batteries, while the recycling and disposal of batteries are related to resource utilization and environmental issues. Without regulatory pressure from the government and society, relevant enterprises may not have sufficient motivation and responsibility to promote battery recycling. These enterprises may not consider themselves obliged to invest in battery recycling technologies, infrastructure and recycling networks to improve battery recycling. It is necessary to strengthen the regulation of EVBR to achieve sustainable development. This involves the concerted efforts of the government, enterprises and the community to ensure that EVBR receives adequate attention and response.

3.1.2. Lack of pressure from the market and demand (B2)

Given the relative newness of the electric vehicle market, the battery recycling market is still in a developmental stage ([Feng et al., 2024](#); [Xu et al., 2022](#)). Although the market share of electric vehicles is growing rapidly, it is still relatively small, especially compared to the market for traditional fuel vehicles. As a result, the need to recycle electric vehicle batteries is also relatively low. Moreover, the challenge of identifying adequate market applications for the materials obtained through the recovery and reuse process poses obstacles to recycling efforts. Consequently, the absence of market pressure and demand has emerged as a significant impediment to battery recycling.

3.1.3. Lack of environmental awareness and education (B3)

Raising awareness about sustainable development and environmental protection can propel the EVBR market towards sustainable growth. Although the public's concern about the finite nature of resources and environmental issues has spawned a demand for circular economy and sustainable development, there is still a relatively large number of the public who lack environmental awareness ([King and Boxall, 2019](#); [Zhou et al., 2007](#)). On the one hand, a majority of the public still lacks a comprehensive understanding of the significance and implications of EVBR, hindering their ability to make meaningful contributions to the cause. On the other hand, there is a notable deficiency in educational initiatives, leading to public confusion regarding the proper methods for recycling and disposing of batteries.

3.1.4. Safety issues during storage and disassembly of batteries (B4)

Electric vehicle batteries are usually high-voltage batteries, in which electrical energy is stored in abundance (Meng et al., 2022). Safe management of batteries during storage and disassembly is very important. If a battery is damaged or operated incorrectly, it can result in short-circuiting, uncontrolled chemical reactions, and other hazards that increase the risk of fire and explosions. Furthermore, batteries contain toxic chemicals such as lithium, nickel, and cobalt, which can be harmful to the environment and human health if not handled properly. Therefore, it is crucial to prevent these substances from leaking and causing pollution to safeguard the environment and public health. As battery recycling involves safety issues, battery recycling requires strict safety measures and handling methods, increasing the complexity and cost of the recycling process.

3.1.5. Lack of efficient collection channels for waste batteries (B5)

One of the main problems in battery recycling for electric vehicles is the lack of effective collection channels for waste batteries (Islam et al., 2022). As the production of new energy vehicles is still relatively low, and at the same time the market for recycling used battery resources is not yet perfect, this has led to insufficient recycling channels for used batteries.

3.1.6. Lack of mature battery recycling technology (B6)

Electric vehicle batteries face certain technical difficulties in the recycling process due to their complex chemical structure and material composition (Sun et al., 2015; Yun et al., 2018). Due to the diverse range of electric vehicle batteries, it is essential to tailor recycling technologies to suit the specific characteristics of each type. Despite ongoing technological advancements, many enterprises and research institutes are actively investigating novel recycling methods, including chemical, physical, and thermodynamic processes, as well as the exploration of new materials. However, a significant obstacle remains in the form of the lack of mature and cost-effective recycling technologies, hindering progress in this field as battery recycling methods are still in the early stages of development.

3.1.7. Lack of mature battery recycling standards (B7)

The improvement of the standard system of EVBR is of great importance to the realization of circular economy (Zeng et al., 2015). Enhancing the standard system can play a crucial role in streamlining the recycling process and methods, boosting recycling efficiency, and minimizing resource wastage and environmental pollution. This needs the formulation of a unified recycling standard, including the type of recycling, recycling conditions, recycling process, etc. Meanwhile, assessment indicators and methods for power battery recycling should be established, including capacity loss of batteries, secondary utilization rate, material recovery rate, etc., in order to assess the effectiveness and sustainability of recycling (Yu et al., 2013). Although some countries and regions have begun to formulate relevant recycling standards and regulations to promote the development of EVBR, which helps to establish more stringent and unified recycling standards, the current immature battery recycling standards have also brought obstacles to battery recycling.

3.1.8. Lack of transparent price mechanism for waste battery recycling (B8)

The lack of a transparent price trading mechanism further limits EVBR (Feng et al., 2024). This is primarily due to the fact that the EVBR market is still in its early stages of development, with an imbalance in the demand and supply relationship. As a result, the price formation mechanism lacks standardization and transparency. Furthermore, the remaining capacity of the electric vehicle battery is crucial for battery valuation; however, it is extremely difficult to accurately assess the degree of electric vehicle battery degradation and there is a lack of compliant companies that assess battery performance. More

importantly, there is a notable absence of a transparent pricing mechanism in the waste electric vehicle battery recycling market. Illicit operators exploit this gap by engaging in competitive bidding, offering inflated prices to gain market share. Consequently, this practice drives a surge of waste electric vehicle batteries towards informal recycling enterprises (Xu et al., 2022). These enterprises often reduce the cost of treating batteries at the expense of polluting the environment, which further aggravates ecological damage.

3.1.9. Lack of mature battery recycling business model (B9)

According to the different recycling main body, there are four main modes of EVBR, namely: battery producer-based mode, vehicle manufacturer-based mode, the third-party recycling mode and the industrial alliance recycling mode. Nevertheless, the technical challenges associated with EVBR and the absence of economies of scale and consistent demand in the recycling market present obstacles for the recycling industry in developing a sustainable business model. More importantly, EVBR involves battery manufacturers, battery transporters, consumers, vehicle producers, downstream ladder utilization companies, recyclers and battery dismantlers, and there is no relatively mature business model yet, everything is still being explored (Reinhardt et al., 2019).

3.1.10. Lack of continuous innovation capability (B10)

Lack of sustained innovation is also an important limiting factor for EVBR. Recycling batteries involves the dismantling, treatment and reuse of batteries, which needs to be supported by advanced technologies and equipment (Wu et al., 2023). However, existing recycling technologies are still in the developmental stage and face certain challenges, including high recycling costs, low recycling efficiency, and complex recycling processes. Business managers need to have sufficient management and innovation capabilities in order to further invest more money and management into technology research and development, improved recycling processes, development of new recycling materials and innovative business models. For example, some companies are exploring innovative models like battery trade-in and leasing to drive the sustainable advancement of EVBR. These efforts have helped to promote innovation and improvement in EVBR technologies, and enhance recycling efficiency and resource utilization.

3.1.11. Lack of more appropriate incentive policies (B11)

Recently, some countries or regions have implemented policies to incentivize battery recycling, such as offering tax incentives and providing subsidies to recycling businesses. However, further improvement and refinement of incentive policies are needed to address the issue of EVBR (Sun et al., 2015). Effective incentive policies play a pivotal role in promoting EVBR. For example, mandatory recycling regulations that requires vehicle owners to recycle their waste batteries when they replace them, to ensure that the batteries are disposed of correctly.

3.1.12. Lack of synergy and cooperation among stakeholders (B12)

EVBR involves multiple stages and multiple stakeholders, including battery manufacturers, automobile manufacturers, recycling companies, and waste battery processors. As the recycling process may involve the distribution of benefits in different segments, it leads to difficulties in reaching an agreement among all parties, affecting synergy and cooperation (Salim et al., 2019). EVBR involves issues such as resource reuse and environmental protection, and requires unified standards and policy support. However, there are currently differences in standards and policies across regions and a lack of unified guidance and norms, making it difficult for stakeholders to synergize and cooperate under a common framework. Moreover, EVBR involves a complex supply chain and information flow, but at present, information sharing is relatively poor, and there is a lack of timely and accurate information exchange between parties. This information asymmetry makes it difficult for all parties to

make effective decisions, limiting the development of synergy and cooperation.

3.1.13. Lack of harmonized technical standards for the battery production industry (B13)

EVBR is also challenged by the lack of harmonized technical standards. Due to the fast-growing electric vehicle market, different manufacturers use different types, sizes and chemistries of batteries, which lead to inconsistent technical standards in the recycling process. The lack of harmonized recycling standards may lead to inefficiencies in recycling, increased costs and environmental pollution. In the absence of uniform standards, it is also difficult for recyclers to judge the performance and lifespan of different brands of battery products, and it also creates an unfair situation for competition between companies.

3.1.14. Lack of cluster benefits (B14)

Effective waste recycling management requires economies of scale and clustering benefits (Zhang et al., 2019). By the same token, EVBR suffers from a lack of cluster benefits. On the one hand, the technology and equipment for EVBR are not mature enough, resulting in high recycling costs; on the other hand, owing to the relatively small size of the electric vehicles market, the number of batteries recycled at present is small, making it difficult to form a large-scale recycling industry chain. Efficient EVBR relies on economies of scale, and industrial clusters can facilitate the realization of these economies. Therefore, until economies of scale in EVBR are achieved, the absence of cluster benefits will continue to be a barrier to EVBR.

3.1.15. Insufficient number of formal battery recyclers (B15)

The technical difficulties of battery recycling and the need for specialized equipment and technical support have resulted in a relatively small number of recyclers (Sun et al., 2015). Furthermore, the number of qualified recyclers is further low due to reasons such as batteries are dangerous goods, the technical difficulty of recycling and the relatively low market demand.

3.1.16. Inconvenient dismantling of batteries (B16)

The inconvenience of removing electric vehicle batteries also poses a challenge for their recycling (Tripathy et al., 2022). Electric vehicle batteries typically consist of a large amount of battery modules, which must be disassembled to recycle retired batteries (Harper et al., 2019). Nevertheless, due to the intricate structure of batteries, disassembly is a challenging task that necessitates specialized equipment and expertise, which adds to the complexity and cost of the operation.

3.1.17. Lack of effective battery recycling management experience (B17)

Experience in battery recycling management is very useful for EVBR. However, there is relatively little experience in the management of battery recycling (Azadnia et al., 2021), but it is beginning to attract attention. Effective experience in managing battery recycling is very important to protect the environment and to recycle resources. Because having rich experience in battery recycling management can help establish a perfect recycling network and recycling system, it can maximize the resource utilization of electric vehicle batteries and promote sustainable development.

3.1.18. Lack of support from top management (B18)

A key barriers to EVBR is the lack of support from top management in companies and government (Tripathy et al., 2022). Top management can provide financial support and resources, as battery recycling requires the establishment of recycling facilities, the purchase of recycling equipment, and technological research and development, all of which require significant investment. In addition, top management can also promote industry collaboration and break down information barriers, thereby promoting cooperation and information sharing among all parties and accelerating the innovation and promotion of recycling

technologies.

3.1.19. Costs and benefits (B19)

EVBR involves the process of recovering and treating used batteries, which includes collection, sorting and remanufacturing. Besides, recycling batteries requires the establishment of a comprehensive recycling system, including collection, storage, sorting and transport. All these links require substantial financial support. As the current quantity of battery recycling is small, it is difficult to create economies of scale, and therefore the issue of the cost and benefits of battery recycling has become a major barrier that restricts the development of EVBR towards a circular economy (Zhou et al., 2007).

3.1.20. Lack of widespread publicity on battery recycling (B20)

Many public currently have limited understanding of the concept of EVBR and related policies, and there is a lack of widespread publicity and education. This may be due to the fact that the market share of electric vehicles is still small compared to that of fuel vehicles, and hence there is relatively little publicity on EVBR. In addition, the relatively small and dispersed target population may result in less effective publicity. However, extensive publicity should be carried out to raise awareness and raise the importance of battery recycling.

3.2. Study methodological framework

To achieve the stated research goals, this study uses a hybrid methodology based on ISM and MICMAC. Potential barriers to EVBR were first identified through a systematic literature survey and experts opinion, and then the ISM was applied to determine the structured self-interaction matrix (SSIM), and a hierarchical map between the barriers to battery recycling was constructed (Yadav et al., 2020). Finally, MICMAC is used to categorize these barriers for further recommendations, and the framework structure of the methodology herein is given in Fig. 1.

Step 1. This paper identifies the main barriers to implementing EVBR, based on a review of the literature and expert opinion, as outlined in Section 3.1.

Step 2. Experts identified the relationship between the barriers through multiple rounds of discussions and determined the SSIM. In the SSIM, this paper uses capital letters V, A, X, and O to express the relationship between barrier i and barrier j . The symbols are expressed with the following meanings: 1) V denotes that barrier j is affected by barrier i ; 2) A denotes that barrier i is affected by barrier j ; 3) X indicates that barrier i and barrier j interact with each other; and 4) O indicates that there is no effect between barrier i and barrier j . Step 3. Determine the reachability matrix on the basis of step 2 by representing the symbols in the SSIM with the numbers 0 and 1. The rules for assigning numerical values corresponding to each letter are as follows: 1) In SSIM, if cell (i, j) is represented by the letter V, then the cell (i, j) is assigned the value 1 and cell (j, i) is assigned the value 0; 2) In SSIM, if cell (i, j) is represented by the letter A, then the cell (i, j) is assigned the value 0 and cell (j, i) is assigned the value 1; 3) In SSIM, if cell (i, j) is represented by the letter X, then the cell (i, j) and cell (j, i) is assigned the value 1; and 4) In SSIM, if cell (i, j) is represented by the letter O, then the cell (i, j) and cell (j, i) is assigned the value 0.

Step 4. Level partitions of barriers to EVBR. The reachability sets and antecedent sets can be used to obtain the level partitions of EVBR barriers. Then find the intersection sets of the reachability sets of barrier and antecedent sets of barrier. In ISM, the barrier with the same reachability sets and the intersection sets is considered to be a level 1. Barriers in level 1 are then eliminated and the iteration continues to obtain the second level of barrier classification and so on until all the barrier classifications are found.

Step 5. Determine the hierarchical directed graph between barriers.

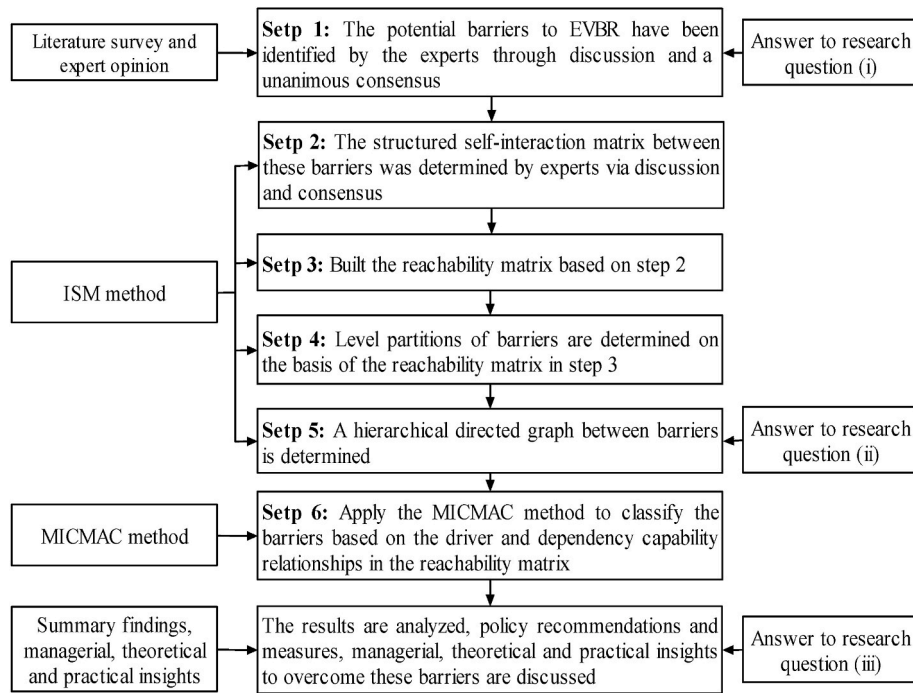


Fig. 1. Study methodological framework adopted in this paper.

Step 6. Apply the MICMAC method to categorize the EVBR barriers based on the driver and dependency capability relationships in the reachability matrix. A detailed description of the classification criteria is shown in Section 3.4.

3.3. Calculation process of the ISM method

This section describes the calculation process of the ISM method and identifies the hierarchical relationships between EVBR barriers and draws a directed graph of the barriers.

3.3.1. Structured self-interaction matrix

The eight experts evaluated the relationships between the barriers and applied the symbols V, A, X, and O to construct the adjacency matrix, i.e. SSIM, according to the introduction in step 2, and the results are given in Table 1. The assessment team meets as a group to identify specific goals for consensus to ensure that everyone is working in the

same direction; the expert team then discusses and debates in a conference-style manner, sharing ideas, making suggestions, and communicating different opinions; and ultimately, the expert team is required to vote on the assessment to determine the outcome of the assessment based on the principle of minority rule.

3.3.2. Reachability matrix

The symbols in Table 1 are used to build the initial input adjacency matrix A according to the assignment rule in Step 3, as shown in Table 2. Based on the initial adjacency matrix A in Table 2, the initial reachable matrix IR is obtained by adding it to the unit matrix I , i.e. $IR = A + I$, and then the Boolean algebra rules are used to multiply the matrix IR until two matrices of neighbouring idempotents are equal, and the matrix with the lowest idempotent among the equal matrices is the reachability matrix. The final reachability FR matrix is derived by calculating the initial reachable matrix, i.e. $FR = IR^n = IR^{n+1}$, as shown in Table 3. Besides, driving power (DRP) and dependence power (DEP) were

Table 1

Structured self-interaction matrix for EVBR barriers.

	B20	B19	B18	B17	B16	B15	B14	B13	B12	B11	B10	B9	B8	B7	B6	B5	B4	B3	B2
B1	O	V	A	O	O	O	O	O	O	A	V	V	O	V	O	O	O	X	O
B2	O	V	A	O	O	O	V	O	V	O	O	V	O	O	V	V	O	A	
B3	X	O	O	O	O	O	O	O	O	O	O	V	O	O	O	O	O		
B4	O	V	O	O	X	O	O	A	O	O	O	O	O	A	A	O			
B5	O	X	O	O	O	A	O	O	O	A	O	X	V	O	O				
B6	O	V	A	O	V	V	O	A	O	A	A	V	O	X					
B7	O	V	A	O	O	O	O	A	O	A	A	V	O						
B8	A	O	O	O	O	O	O	O	O	O	O	V							
B9	O	V	O	O	O	O	O	O	X	O	A								
B10	O	V	A	A	O	O	O	O	O	O									
B11	O	V	V	V	O	V	V	V	V										
B12	O	V	A	A	O	A	X	O											
B13	O	O	O	O	V	O	O												
B14	O	V	O	A	O	O													
B15	A	O	O	O	O														
B16	O	V	O	O															
B17	O	V	X																
B18	O	V																	
B19	O																		

Table 2
Initial adjacency matrix for EVBR barriers.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
B1	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	1	0
B2	0	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0	0	0	1	0
B3	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
B4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
B5	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0
B6	0	0	0	1	0	0	1	0	1	0	0	0	0	0	1	1	0	0	1	0
B7	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0
B8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
B9	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
B10	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	1	0
B11	1	0	0	0	1	1	1	0	0	0	0	1	1	1	1	0	1	1	1	0
B12	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0
B13	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0
B14	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
B15	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
B16	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
B17	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	1	0
B18	1	1	0	0	1	1	0	0	0	1	0	1	0	0	0	0	1	0	1	0
B19	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B20	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0

Table 3
Final reachability matrix for EVBR barriers.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	DRP
B1	1	1*	1	1*	1*	1*	1	1*	1	1	0	1*	0	1*	1*	1*	0	0	1	1*	16
B2	0	1	0	1*	1	1	1*	1*	1	0	0	1	0	1*	1*	1*	0	0	1	0	12
B3	1	1	1	1*	1*	1*	1*	1*	1	1*	0	1*	0	1*	1*	1*	0	0	1*	1	16
B4	0	0	0	1	1*	0	0	1*	1*	0	0	1*	0	1*	0	1	0	0	1	0	8
B5	0	0	0	0	1	0	0	1	1	0	0	1*	0	1*	0	0	0	0	1	0	6
B6	0	0	0	1	1*	1	1	1*	1	0	0	1*	0	1*	1	1	0	0	1	0	11
B7	0	0	0	1	1*	1	1	1*	1	0	0	1*	0	1*	1*	1*	0	0	1	0	11
B8	0	0	0	0	1*	0	0	1	1	0	0	1*	0	1*	0	0	0	0	1*	0	6
B9	0	0	0	0	1	0	0	1*	1	0	0	1	0	1*	0	0	0	0	1	0	6
B10	0	0	0	1*	1*	1	1	1*	1	1	0	1*	0	1*	1*	1*	0	0	1	0	12
B11	1	1*	1*	1*	1	1	1	1*	1*	1*	1	1	1	1	1	1*	1	1	1	1*	20
B12	0	0	0	0	1*	0	0	1*	1	0	0	1	0	1	0	0	0	0	1	0	6
B13	0	0	0	1	1*	1	1	1*	1*	0	0	1*	1	1*	1*	1	0	0	1*	0	12
B14	0	0	0	0	1*	0	0	1*	1*	0	0	1	0	1	0	0	0	0	1	0	6
B15	0	0	0	0	1	0	0	1*	1*	0	0	1	0	1*	1	0	0	0	1*	0	7
B16	0	0	0	1	1*	0	0	1*	1*	0	0	1*	0	1*	0	1	0	0	1	0	8
B17	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	0	1	0	1	1*	1*	1	1	1	1*	18
B18	1	1	1*	1*	1	1	1*	1*	1*	1	0	1	0	1*	1*	1*	1	1	1	1*	18
B19	0	0	0	0	1	0	0	1*	1*	0	0	1*	0	1*	0	0	0	0	1	0	6
B20	1*	1*	1	1*	1*	1*	1*	1	1*	1*	0	1*	0	1*	1	1*	0	0	1*	1	16
DEP	6	7	6	13	20	11	11	20	20	7	1	20	2	20	12	13	3	3	20	6	

Note: * represents the transitive links.

computed for each barrier in Table 3. The sum of rows for each barrier is DRP, while the sum of columns is DEP.

3.3.3. Level partitions of barriers

According to step 4, the final level partitions of EVBR barriers obtained are shown in Table 4.

3.3.4. Hierarchical directed graph

After obtaining a hierarchical level of the EVBR barriers, a directed graph can be used to represent the structure of these barriers, as shown in Fig. 2. The hierarchy of EVBR barriers consists of seven levels, and there is an interrelationship between these barriers. The top level contains seven barriers, which are lack of efficient collection channels for waste batteries (B5), lack of transparent price mechanism for waste battery recycling (B8), lack of mature battery recycling business model (B9), lack of synergy and cooperation among stakeholders (B12), lack of cluster benefits (B14), and costs and benefits (B19). These barriers are directly or indirectly affected by other barriers. In the ISM hierarchy diagram, the levels downwards represent the causes of the previous level. In this paper, the lowest level barrier is lack of more appropriate

incentive policies (B11).

3.4. Classification of barriers by using MICMAC method

The EVBR barriers were categorized according to the DEP and DRP values for each barrier in Table 2, as shown in Fig. 3. Twenty barriers were classified into four categories; however, none of the barriers were autonomous barriers. The second quadrant is the dependent barriers, indicating that the barriers have a high dependency force and a low drive. The third quadrant is the linkage barriers, indicating barriers have a high dependency force and a high drive. The fourth quadrant is the driver barriers, indicating barriers have a low dependency force and a high drive. The categorization results in Fig. 3 are important for practice as stakeholders can be better guided to develop sound measures based on the drivers and dependencies of these barriers.

4. Discussion

This section discusses the description of results, comparison with other methods, theoretical implications, managerial and practical

Table 4
Hierarchical classification of EVBR barriers.

Levels	Barriers to EVBR
First level	Lack of efficient collection channels for waste batteries (B5) Lack of transparent price mechanism for waste battery recycling (B8) Lack of mature battery recycling business model (B9) Lack of synergy and cooperation among stakeholders (B12) Lack of cluster benefits (B14) Costs and benefits (B19)
Second level	Safety issues during storage and disassembly of batteries (B4) Insufficient number of formal battery recyclers (B15) Inconvenient dismantling of batteries (B16)
Third level	Lack of mature battery recycling technology (B6) Lack of mature battery recycling standards (B7)
Fourth level	Lack of pressure from the market and demand (B2) Lack of continuous innovation capability (B10) Lack of harmonized technical standards for the battery production industry (B13)
Fifth level	Lack of regulatory pressure from government and society (B1) Lack of environmental awareness and education (B3) Lack of widespread publicity on battery recycling (B20)
Sixth level	Lack of effective battery recycling management experience (B17) Lack of support from top management (B18)
Seventh level	Lack of more appropriate incentive policies (B11)

insights, and measures to overcome the barriers.

4.1. Description of results

As shown in Fig. 2 and Table 4, barrier B11 (lack of more appropriate incentive policies) is at the bottom of the EVBR barriers, which is a strong confirmation that policies are of significant importance in promoting battery recycling. Thus, it is very important to develop an effective EVBR policy to protect the environment, promote economic development and enhance social responsibility. Barrier B11 has an impact on barriers B17 (lack of effective battery recycling management experience) and B18 (lack of support from top management), for

example, incentive policies can help top management to further realize the determination of the state and society to recycle batteries, and then push top management to invest more resources in the construction of battery recycling technology, recycling standards and recycling system. Barrier B18 has a direct impact on barrier B1 (lack of regulatory pressure from government and society), because if the top managers of the government and companies are strongly supportive of the battery recycling business, then the government is likely to be supportive of the regulation of the battery recycling business and companies will be interested in further regulating the battery recycling business. Furthermore, barrier B3 (lack of environmental awareness and education) affects barrier B2 (lack of pressure from the market and demand), and the environmental awareness of the public also has a major impact on EVBR, as the environmentally aware public tends to recycle batteries through a formal channels, which increases the battery recycling rate.

Barriers B6 (lack of mature battery recycling technology) and B7 (lack of mature battery recycling standards) have a high dependency and driving force and significantly affect other barriers, while other barriers also significantly affect barriers B6 and B7. This is because the difficulty of dismantling batteries can be significantly reduced and the safety of dismantling improved by having mature battery recycling technology and recycling standards. Batteries are a hazardous material that can explode or burn if they are not dismantled properly, and companies are usually required to make a more economic investment to reduce the possibility of a hazard. It is therefore necessary to establish a set of mature battery recycling technologies and standards.

As shown in Fig. 3, there are no barriers in the first quadrant with weak dependencies and weak drivers, which further confirms that the barriers proposed in this paper all have an impact on the system and all play an important role. Within the first level of barriers in Fig. 2, decision makers need to pay particular attention to barriers B5 (lack of efficient collection channels for waste batteries), B8 (lack of transparent price mechanism for waste battery recycling), B9 (lack of mature battery recycling business model), B12 (lack of synergy and cooperation among stakeholders), B14 (lack of cluster benefits) and B19 (costs and benefits).

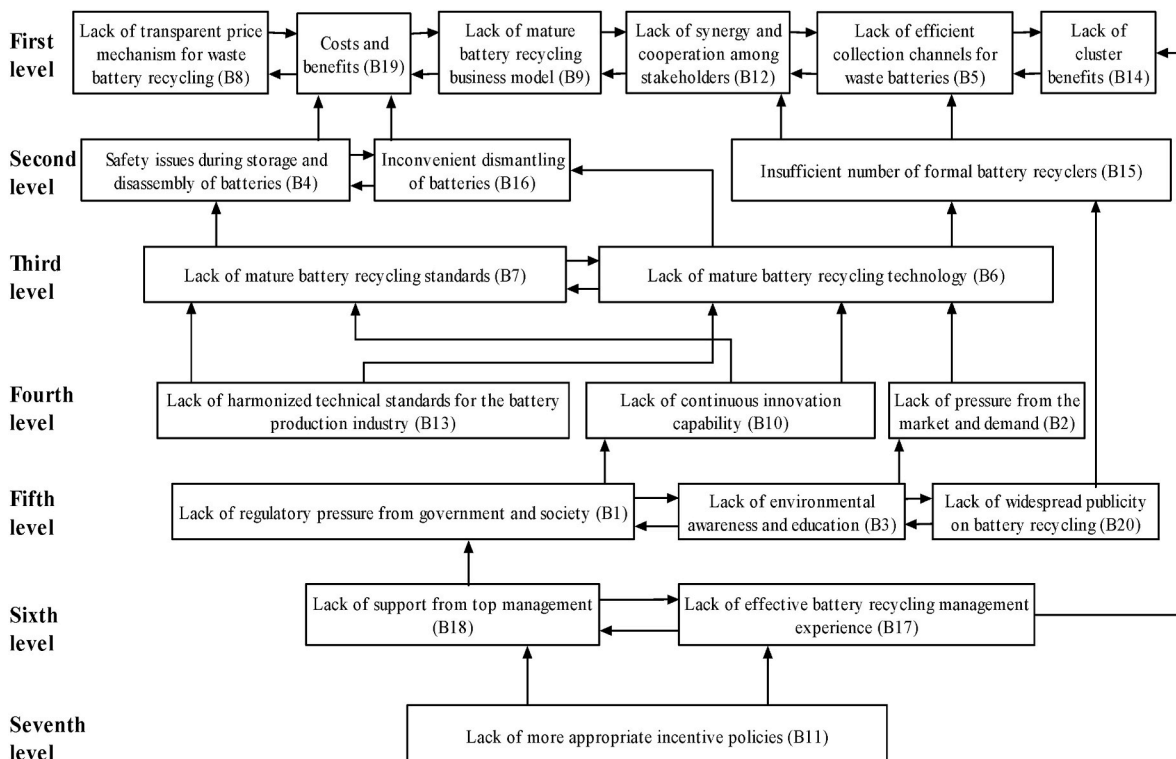


Fig. 2. Hierarchical directed graph of EVBR barriers.

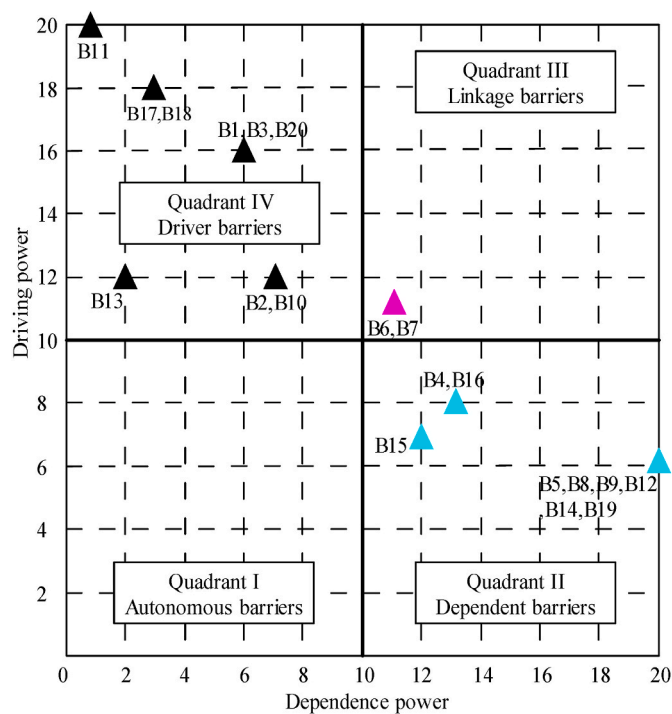


Fig. 3. MICMAC analysis for EVBR barriers.

Furthermore, barriers in the fourth quadrant of Fig. 3, such as B1, B2, B3, B10, B11, B13, B17, B18 and B20, are considered to be critical barriers to the achievement of sustainable development in EVBR, as they have a strong driving force that can effectively influence other barriers and therefore require special attention from various stakeholders.

This paper provides a comprehensive analytical framework model for identifying potential barriers to EVBR, and although the methodology presented in this paper has been applied to other fields, there is little literature that comprehensively explores the barriers to EVBR from multiple stakeholder subjects. For example, Sasikumar and Haq (2010) examined the barriers to battery recycling in the reverse supply chain. They identified ten potential barriers to battery recycling in reverse logistics from an original equipment manufacturer perspective, of which the lack of political will barrier is similar to the lack of more appropriate incentive policies (B11) barrier mentioned in this paper, and they also identified lack of political will is a key barrier affecting battery recycling, which is consistent with the findings of this paper. And other barriers also share similarities with the barriers mentioned in this paper, such as financial constraints and costs and benefits (B19); lack of effective communication and lack of widespread publicity on battery recycling (B20); lack of knowledge and lack of environmental awareness and education (B3).

4.2. Comparison with other methods

Biswas and Gupta (2019) applied the DEMATEL methodology to identify the relationship between the barriers to the implementation of blockchain technology. Raj et al. (2008) applied the ISM methodology to identify barriers to the implementation of flexible manufacturing systems and identified the interrelationships between the barriers. Kamble et al. (2018) and Dixit and Kumar (2024) employed ISM and MICMAC methodologies to explore the potential barriers to the implementation of Industry 4.0 and their interrelationships. Kazancoglu et al. (2024) explored barriers to renewable energy technologies and identified causal relationships between barriers using ISM and MICMAC techniques. Most of this literature has been studied using the ISM approach because of the important features that the ISM approach has: 1) the ISM approach is

interpretive due to the use of group opinions to determine the correlation between different barriers; 2) the ISM approach is relational as well as structural, allowing for a hierarchical structure to be obtained from the complexity of the relationships; 3) the ISM is a modelling approach that allows for the graphical visual presentation of the relationships between the various elements, which makes it easy to understand and communicate; and 4) the ISM approach takes into account the various elements of the system and analyses the complexity of the relationships between the various elements, which helps in the identification of the key elements. Furthermore, the MICMAC technique is used to identify factors of high influence within the system and to conduct comprehensive assessments and analyses. It is able to identify high-impact factors within the system, help identify key factors and carry out effective optimization and adjustment. Hence, the ISM and MICMAC techniques used in this paper to identify potential barriers to EVBR can provide multidimensional and comprehensive analyses that can help guide practical operations and decision-making.

4.3. Theoretical implications

Circular economy is an economic model focused on resource recycling that achieves sustainable economic development by reducing resource consumption and waste generation; and EVBR is the collection, reuse or reprocessing of used batteries to achieve resource recycling. However, there are barriers to EVBR and this work is the first to study the barriers to EVBR and use ISM and MICMAC methods to analyze relationships between barriers, thus this study contributes to EVBR regarding barrier analysis and adds to the literature on barrier analysis. This paper further clarifies the barriers to EVBR and paves the way for the realization of large-scale battery recycling, thus making this paper an important contribution to the literature promoting EVBR towards the development of a circular economy.

Many scholars have applied the theory of ISM and MICMAC methods for barrier analysis, and this literature confirms the effectiveness and scientific validity of ISM and MICMAC methods for barrier analysis. The results of this paper show that overcoming barriers B1, B2, B3, B10, B11, B13, B17, B18 and B20 can have a significant effect on improving the EVBR, and this study confirms the scientific validity of the ISM and MICMAC methodologies in terms of portraying hierarchical and influential relationships between barriers. Furthermore, before this paper, Tripathy et al. (2022) was one of the few contributions that discussed the factors influencing EVBR at the technological, environmental and organizational levels; and Tripathy et al. (2023) discussed the key drivers of lithium battery recycling for electric vehicles regarding environmental, economic and social and dimensions. However their study focuses more on the factors that drive EVBR, and we explore the barriers to EVBR that have been discussed more broadly. As a result, this paper provides a further exploration of the barriers to the implementation of EVBR from a theoretical point of view.

Azadnia et al. (2021) identified eight barriers to the implementation of reverse logistics for electric vehicles lithium batteries in from a manufacturer's perspective, which are important for EVBR, however, due to the large number of stakeholders involved in EVBR, some potential barriers were not identified. In this paper, twenty barriers to EVBR have been identified through extensive expert discussions and literature reviews. The results show that barrier B11 is a key factor affecting EVBR, whereas Azadnia et al. (2021) identified market and social barriers, which directly affects policies and regulations, as a key factor affecting reverse logistics of lithium batteries, whereas the study in this paper identifies the lack of more appropriate incentive policies as a key barrier affecting EVBR. This is because the policy on EVBR is closely related to the market. The development of related industries and the creation of market demand can be promoted by the formulation of an EVBR policy by the government. Policies can provide economic incentives, such as subsidies and tax breaks, to attract companies to participate in the EVBR business. The government can also establish a

complete EVBR industry chain by promoting the cooperation and synergistic development of electric vehicle manufacturers, battery producers, recycling enterprises and reprocessing enterprises. This will promote technological innovation, resource sharing and industrial upgrading. Therefore, the EVBR policy can guide and promote the development of the market and realize the sustainable development of the electric vehicle industry.

4.4. Measures to overcome the barriers

Given the complexity and significance of EVBR, it is imperative to develop more effective policies and measures. Overcoming these barriers necessitates collaborative efforts from government, industry, and academia. Therefore, this paper proposes a set of measures from three distinct perspectives – government, industry, and academia – to overcome these barriers.

At the government level, the first is to formulate clear policies and regulations to standardize the process and criteria for recycling used batteries. On this basis, provide financial support and economic incentives to further encourage electric vehicle manufacturers and recycling companies to actively participate in battery recycling. In addition, setting up a dedicated fund or subsidy scheme to support the research and development of recycling technologies and equipment upgrading is an incentive measure. Government departments should guide and establish a comprehensive recycling system to promote the cooperation and collaboration between battery recycling enterprises and related industrial chains. More importantly, government departments should also strengthen supervision and enforcement to ensure that battery recyclers comply with regulations and perform their social responsibilities. It should not be overlooked that training and education provided by government departments and enhanced publicity and awareness can also promote the development of the waste battery recycling industry.

At the industry level, battery recyclers and manufacturers have increased their investment in setting up specialized EVBR management teams and providing training and guidance to improve management experience and skills. Enterprises should increase investment in R&D of EVBR technology to improve the efficiency and safety of EVBR through improved recycling methods and equipment, process optimization and technological innovation; on the other hand, enterprises should strengthen their awareness of corporate environmental responsibility and take EVBR as part of their corporate social responsibility to ensure a closed-loop battery recycling chain. At the same time, they should not only strengthen the training of professionals and improve the R&D and application level of battery recycling technology, but also enhance the environmental protection and safety protection during the battery recycling process, and formulate strict battery recycling standards and control measures to ensure that the environmental pollution and safety hazards during the recycling process are effectively controlled. In addition, enterprises can also consider providing consumers with incentives for recycling batteries, such as recycling points and coupons, to mobilize consumers to participate in battery recycling. More importantly, enterprises should establish convenient battery recycling channels, such as through e-commerce platforms, electric vehicle manufacturers and other channels, to facilitate consumers to send back or send out used batteries.

At the academic level, academics should, on the one hand, devote themselves to researching technologies and methods to reduce the cost of recycling, such as improving the recycling process, increasing the efficiency of recycling, and lowering the cost of recycling equipment; on the other hand, improving the reuse rate of batteries after recycling is also one of the main focuses of academics' attention. Meanwhile, researchers should continue to explore how to extend the battery life by improving the battery design, and how to use the recycled materials in the manufacture of new batteries to achieve a higher recycling rate. In addition, academia should join forces with industry in a concerted effort

to find safer and more environmentally friendly high-temperature processing technologies to reduce potential contamination. Another important research is that academics should explore the promotion of IoT, big data and other technologies in battery recycling to achieve intelligent management and monitoring. The results of academic research are important for overcoming barriers to EVBR and are expected to provide more feasible and sustainable solutions for the EVBR industry in the future.

4.5. Managerial and practical insights

Barrier B11 (lack of more appropriate incentive policies) is crucial for EVBR to move towards circular economy development, as it will have a long term profound impact on the other barriers. To overcome this barrier, the Chinese government has introduced policies and regulations. For example, 1) the Chinese government encourages the recycling and utilization of electric vehicle batteries by proposing a series of supportive policies, such as financial support, tax incentives and subsidy policies, aiming to promote the development of EVBR; 2) China has implemented a battery recycling responsibility system, which requires electric vehicle manufacturers to use recyclable batteries that comply with the national standards and requirements for electric vehicles put on the market, and at the same time assume the battery recycling and disposal responsibilities; and 3) China encourages the construction of a battery recycling network to achieve full coverage of the battery recycling system through the establishment of recycling stations, recycling networks and recycling channels, etc., so as to improve the efficiency and feasibility of battery recycling. The enactment of these policies has largely facilitated EVBR, however, as the market develops, more effective policies need to be developed to further realize economies of scale in battery recycling.

In practice, attention must be paid to barriers B17 and B18, as lack of effective battery recycling management experience and lack of support from top management may have a significant impact on EVBR in terms of funding, policy, technology, markets and other aspects, limiting its scale-up and efficiency. For example, top management is often a key factor in determining funding and resource allocation. Without top management support, EVBR may face insufficient funding, leading to limitations in the construction and operation of recycling systems. Lack of top management support may not only lead to a lack of development and enforcement of relevant policies and regulations, thus reducing support and regulation of EVBR, but also to a lack of professional technical and managerial guidance, making the scale and efficiency of EVBR limited. Furthermore, top management is usually closely associated with marketing and cooperation opportunities. Lack of top management support may lead to lack of marketing and cooperation opportunities, limiting the popularity and promotion of EVBR in the market. Hence, the introduction of top management support and professional management experience should be focused on in the promotion and implementation of EVBR.

5. Conclusions

This paper investigates the barriers to EVBR from a stakeholder perspective, identifies twenty major barriers affecting battery recycling, and classifies these barriers into seven levels of structural modelling using the ISM methodology, thus providing insights into the interactions between the various factors involved in the recycling of electric vehicles batteries, and revealing the root causes and key influences that lead to the recycling barriers. In addition, by applying the MICMAC analysis method, the twenty identified barriers to EVBR are classified into three categories, namely, dependency barriers, linkage barriers and driving barriers. More importantly, this paper provides measures for governments, enterprises and academics to overcome EVBR barriers, implement responsible EVBR management, and contribute to the sustainable development of the electric vehicles industry while promoting resource

recycling and environmental protection. Despite some progress in EVBR management, there is still a significant gap compared to the requirements of a circular economy. In addition, overcoming EVBR barriers requires more efforts from all parties as they are interconnected.

While this paper has uncovered key findings on barriers to EVBR, there are still some limitations that need to be addressed. Firstly, although the ISM approach effectively illustrates the connections between EVBR barriers, the absence of quantitative impact relationships may restrict the depth of analysis in this paper. Therefore, exploring alternative methods to quantify these relationships in future studies would be particularly valuable. Secondly, as recycling technologies, channels, and standards continue to advance, the barriers to EVBR may evolve over time. This suggests that the barriers to EVBR could vary across different time periods, underscoring the need to update this work for future research. Thirdly, the study data relied on subjective judgments from experts in diverse fields. Considering the weighting factors assigned to these experts in future studies could enhance the validation of results. Moreover, conducting empirical studies to delve into the primary barriers to EVBR may offer a more engaging avenue for research.

CRediT authorship contribution statement

Jianghong Feng: Writing – original draft, Software, Resources, Project administration, Methodology, Formal analysis, Data curation.
Ping Guo: Resources, Investigation, Formal analysis, Data curation.
Guangyi Xu: Visualization, Validation, Software, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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ChatGPT-enabled two-stage auctions for electric vehicle battery recycling

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ABSTRACT

The primary objective of this study is to create an advanced management system that seamlessly integrates ChatGPT, an intelligent chatbot, with a cutting-edge two-stage auctions model. This integration aims to optimize the recycling process of electric vehicle batteries, ensuring utmost efficiency. To gauge the effect of incorporating ChatGPT on participants' values, we introduce technology coefficient parameters, providing a deeper understanding of its impact. In the initial phase of the auction, a sophisticated platform or an impartial third-party appraisal firm is employed. Their task is to collect vital attribute information from potential sellers regarding the waste batteries. Subsequently, this information is carefully matched with interested buyers. To determine the appropriate number of buyers both before and after the auction, we introduce two innovative matching mechanisms. We propose the implementation of a pioneering one-sided affine VCG (Vickrey-Clarke-Groves) auction, which portrays the affine externality of buyers to other buyers, along with a weighted generalized second-price auction. Additionally, we introduce a ground-breaking mechanism known as weighted multi-unit trade reduction. This inventive process allows successful bidders from the first stage to actively participate in the subsequent auction. Within this paper, we develop auction allocation rules based on the interplay between winning sellers' supply and winning buyers' demand. The outcomes of our numerical studies demonstrate the efficacy of the two-stage auction method in addressing buyers' concerns regarding battery performance. Furthermore, we have found that the utilization of ChatGPT technology proves advantageous for both participants and the platform; if buyers have a positive affine externality on other buyers, then the platform's revenue will be reduced, while social welfare will increase. In the realm of incentive compatibility, individual rationality, and budget balancing, our proposed mechanism stands unwaveringly strong, having undergone rigorous scrutiny and demonstrating commendable performance in numerous numerical experiments. Lastly, we offer practical management insights for stakeholders in the battery recycling market. These invaluable insights are derived from our hands-on experience, providing a fresh perspective for industry managers.

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1. Introduction

Global emissions from the transport sector reached 770 million tonnes in 2021.¹ The trend towards electrification in the transport sector is essential to further reduce carbon emissions (Xu et al., 2023). New energy vehicles have a crucial role to play in the reduction of pollution from transport and the solution to the climate crisis (Sun et al., 2023). With the increasing pressure on the environment and the growing political support, electric vehicles have been attracting more and more attention in the transport sector (Zhang et al., 2021). Driven by market and policy drivers, the global market for new energy vehicles has experienced explosive growth over the past decade (Wang and Liao, 2023). By the end of 2021, the global number of electric vehicles is about 16.5 million, and by 2030, the total number of electric vehicles is expected to reach 350 million under the zero-emission scenario (IEA, 2022). It is well known that the battery is the core component of an electric vehicle. Electric vehicle batteries contain lithium, cobalt, manganese, nickel and other metal elements. Recycling the metal elements in electric vehicle batteries is an effective way of reducing environmental impact, as well as promoting a circular economy. By 2030, it is expected that more than 6 million battery packs will be recycled every year around the world (IDTechEx, 2019). There is therefore no ignoring the fact that the increasing number of end-of-life electric vehicles presents new challenges for their recycling.

Although electric vehicle battery recycling (EVBR) has great ecological, social and economic benefits, the current EVBR market faces severe challenges. For example, there are few enterprises in the world that recycle batteries for power electric vehicles, and their capacity to dispose of waste batteries is limited (Ambrose and O'Dea, 2021). The limited number of battery recycling enterprises and processing capacity limit the sustainable development of EVBR. On the other hand, approximately 5 % of the world's lithium batteries are used sustainably by recycling (Baum et al., 2022), and low recycling rates have a negative impact on the achievement of EVBR economies of scale. Many countries around the world have adopted relevant laws and regulations to promote battery recycling, such as extended producer responsibility policies (Turner and Nugent, 2016), the new regulations on batteries and waste batteries issued by the European Union (Melin et al., 2021), and interim measures for power battery recycling and utilization promulgated by China (Yu et al., 2021). Nevertheless, these effective regulations and policies are playing an important role in the promotion of battery recycling, but there are still some problems in the process of battery recycling that need to be managed by further regulations. Furthermore, asymmetric information and limited trading channels are constraints to the development of EVBR. The recycling of power batteries is now mainly carried out by recyclers with specific qualifications for lithium batteries. Despite the huge economic benefits of battery recycling, the number of recyclers is small. Some companies without recycling qualifications may participate in battery recycling and have a disruptive effect on the EVBR market. A major challenge is thus to develop an effective market trading mechanism to facilitate the participation of qualified recyclers in the EVBR market and thereby increase battery recycling rates.

Auction as an effective resource allocation and pricing method has been extensively applied in many fields (Basar and Cetin, 2017; Cheng et al., 2023; Ding et al., 2023; Li et al., 2023b; Remli and Rekik, 2013; Xiao et al., 2021; Zhang and Kong, 2022). Xu et al. (2022) were among the first to attempt to develop a mechanism design method based on double auction to achieve efficient EVBR, but did not further discuss in the literature how to capture the performance of retired batteries and the impact of advanced technology on auction participants. Indeed, both of these two elements are important to the auction-based EVBR market. First, the importance of understanding the performance of waste batteries cannot be overstated for recyclers. Assessing battery performance based solely on the given information from the owner has proven to be a daunting task, directly impacting the recycler's bid in the auction. Therefore, it becomes imperative to explore effective strategies for information gathering, aiming to alleviate the risks faced by recyclers during the auction. Furthermore, it is necessary to acknowledge that even though the auction platform will publish detailed rules, varying levels of participant experience and diverse knowledge backgrounds may foster divergent interpretations among them. This discrepancy not only hampers participants' ability to fully grasp the auction mechanism and bidding rules, but also poses a potential threat to the long-term sustainability of the platform. Hence, it is of utmost significance to employ existing technologies and methodologies that facilitate better comprehension of the platform among participants.

Since its release, ChatGPT has been the subject of much discussion in academia and industry (Fosso Wamba et al., 2023). Several researchers have suggested that ChatGPT is an efficient and scalable natural language processing tool that could be used for a wide range of tasks (Ivanov and Soliman, 2023). Some scholars are also of the opinion that although ChatGPT has a lot of knowledge, none of them is proficient (Kocoń et al., 2023). While advances in artificial intelligence are having a radical impact on how we produce, live, think and interact, they have also raised public concerns about the risks. Some academics are also concerned about the controversies that ChatGPT brings to society, such as the risk of helping students cheat (Tlili et al., 2023), or the risk of spreading extreme rhetoric or false information (Wang et al., 2023). Artificial intelligence is a promising and emerging technology (Munoko et al., 2020), but it is also immature and unpredictably disruptive. There is no doubt that ChatGPT will make a significant difference to the lives of people in many ways in the years to come. This paper illustrates a practical example of the advantages ChatGPT brings to participants in an auction, as shown in Fig. 1. Fig. 1 clearly demonstrates ChatGPT's ability to address some of the participants' concerns and questions about the auction and to provide explanations. Thus, incorporating ChatGPT into an auction system can improve the performance of the platform.

The primary objective of this paper is to develop a sophisticated auction platform system that seamlessly integrates cutting-edge technology to achieve optimal efficiency in the EVBR process. This investigation takes into account the challenges associated with acquiring information about decommissioned batteries and the potential influence of advanced technology on the auction dynamics.

¹ <https://www.iea.org/reports/transport>.

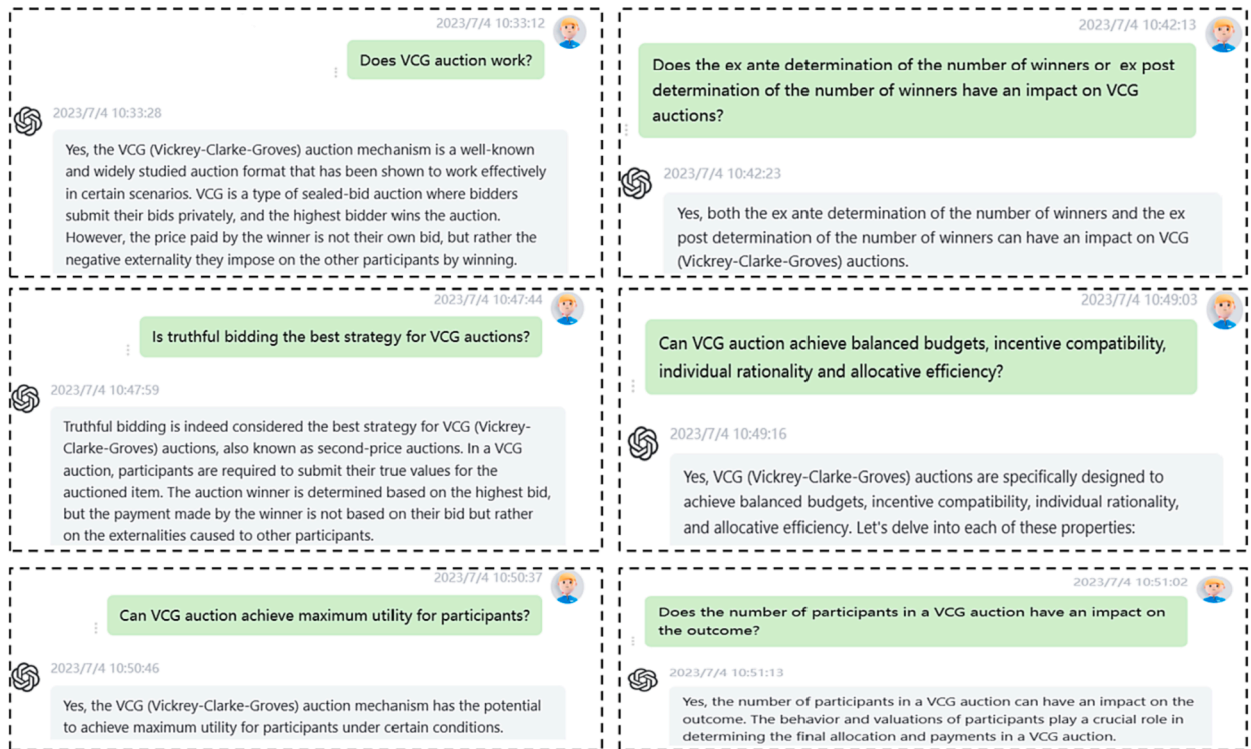


Fig. 1. Examples of ChatGPT's powerful strengths in answering conversations with VCG auction.

As recyclers place immense value on the performance of end-of-life batteries, it directly impacts the recyclable value of these batteries and subsequently affects the bids received from recyclers. Assessing the value of discarded batteries solely based on attribute information provided by battery owners on the auction platform proves to be an arduous task for recyclers. To address this concern, certain companies, such as the renowned auto auction chain Manheim, have established a battery evaluation system to alleviate the anxiety faced by recyclers (Xu et al., 2022). Additionally, implementing advanced technologies in EVBR auctions possesses the potential to further reduce costs and maximize social value. However, due to several uncertain factors, participants in EVBR auctions may harbor ambiguity in their bidding strategies. Therefore, the integration of artificial intelligence technology into the auction system is crucial, as it will significantly promote the development of EVBR auctions. This paper focuses on integrating ChatGPT into the EVBR management system, specifically targeting the reduction of information acquisition costs for participants. Consequently, the research questions addressed in this study are as follows: (1) How can an auction-based EVBR system be designed to facilitate simplified access to retired battery information for recyclers? (2) Which artificial intelligence technologies can be employed to ensure participants' comprehension of the developed system and proposed methodologies, thereby further reducing their information processing costs? (3) What impact do various parameters, such as the level of advanced technology and the number of participants, have on the auction process?

To address the aforementioned inquiries, the primary objective of this endeavor is to create an ingenious administration system that seamlessly integrates ChatGPT and a two-stage auctions model, aiming to accomplish efficient and effective recycling of wasted batteries. This scholarly manuscript expands the utilization of ChatGPT technology to encompass EVBR management, while proposing a comprehensive framework for a ChatGPT-integrated two-stage auction EVBR management system. Such a cutting-edge managerial system will greatly facilitate transactions among recyclers, third-party battery performance assessment providers, and owners of end-of-life batteries. Moreover, this system will be capable of automatically gathering diverse data types and furnishing thorough analytical results following each auction event. Furthermore, this paper presents a novel market trading mechanism for EVBR utilizing the concept of two-stage auctions. The initial stage focuses on information matching, wherein an one-side affine Vickrey-Clarke-Groves (OA-VCG) mechanism and a weighted generalized second-price auction (W-GSPA) mechanism are ingeniously designed to allocate information regarding retired battery performance to recyclers. The impact of pre- and post-allocation of the number of winners on the model is critically examined. Subsequently, in the second stage auction, a well-crafted double auction model is devised to regulate the distribution and pricing of end-of-life batteries, while adopting an innovative approach referred to as weighted multi-unit trade reduction (W-MTR). This method successfully ensures the effective allocation and pricing of said end-of-life batteries. Furthermore, this paper considers the introduction of advanced technology as a means of reducing participants' anxiety about the auction platform, and the introduction of technology is helpful in terms of cost reduction. Therefore, the proposed model and mechanism takes into account the parameter of technology impact, which is discussed and analyzed in detail herein.

The main contributions of this groundbreaking paper can be summarized into the following three aspects, shedding light on

unexplored domains and opening up new avenues of research: i) This paper pioneers the introduction of the two-stage auction method in the context of EVBR. As the existing literature has rarely delved into this particular auction method, the authors' insightful analysis fills a critical gap, enriching the understanding of auction theory and bolstering the mechanism design for EVBR trading. This pioneering work lays the foundation for further advancements in the field, propelling the industry forward. ii) This study ushers in a fresh perspective by introducing the compelling concepts of technological coefficients and affine externalities to comprehend the intricate dynamics of the auction mechanism. By examining the influence of technological coefficients and externalities, the research uncovers novel insights into how the advent of new technologies can bring about mutual benefits for both platforms and participants. This innovative approach, yet to be explored in the existing literature, fortifies the understanding of the EVBR auction platform system and its crucial stakeholders. iii) This paper gracefully tackles recyclers' anxiety regarding waste battery performance evaluation. Recognizing the significance of integrating third-party evaluation enterprises into the auction mechanism, the paper ingeniously proposes the OA-VCG and W-GSPA mechanism. Not only does this revolutionary solution alleviate the concerns surrounding waste battery performance evaluation, but it also harmoniously bridges the information gap between recycling companies and battery performance assessment enterprises, effectively transforming the EVBR chain. This remarkable contribution not only provides a fresh assessment methodology for recycling companies but also establishes a much-needed link within the EVBR ecosystem.

The rest of this paper is organized as follows. Section 2 will systematically review the literature via ChatGPT, two-stage auctions approach and EVBR. An overview of the two-stage auction method intelligence system incorporated into ChatGPT is given in Section 3. Section 4 gives a problem description, the mechanism and properties of the OA-VCG and W-GSPA, and the mechanism and properties of the W-MTR. Numerical experiments to validate the method proposed herein are provided in Section 5. Section 6 discusses the comparative study of the introduction of technical parameters, advantages of proposed EVBR smart system and managerial implications. Finally, conclusions and several future research directions are given in Section 7.

2. Literature review

This section provides a brief overview of work on three topics relevant to this paper: (i) ChatGPT; (ii) the two-stage auction approach; and (iii) EVBR.

2.1. ChatGPT

Since the launch of the ChatGPT chatbot in late 2022, it's been clear that this type of artificial intelligence technology will have a major impact on the way people live and work (van Dis et al., 2023). ChatGPT has been the focus of much attention from academia and industry due to its outstanding capabilities (Zhou et al., 2023). Despite the discussion about the possible negative consequences of the use of ChatGPT technology, the technology has undoubtedly had great positive impacts in practice (Dwivedi et al., 2023). Biswas (2023) concluded that ChatGPT could have great potential applications in promoting understanding of climate change and improving climate prediction, helping researchers conduct climate research in a variety of ways. Prieto et al. (2023) have tried using ChatGPT to generate project schedule in construction projects, and the experimental results are consistent with the practical results, which indicates the great potential of ChatGPT in engineering projects. Ali et al. (2023) discussed the feasibility of using ChatGPT to write clinical case information, and the results showed that the clinical information written using ChatGPT was readable, but there were concerns about the potential risks. Surameery and Shakor (2023) discussed the application of ChatGPT in programming, analyzed the basic features of ChatGPT and use these features to help debugging, bug interpretation, and bug prediction in research, but also emphasized the limitations of ChatGPT and the importance of using other tools to help with programming. Dowling and Lucey (2023) investigated the use of ChatGPT to write research reports on the financial sector and evaluated each article they generated. The results confirmed that ChatGPT is very suitable for experienced users. Lim et al. (2023) are positive about ChatGPT's transformative impact on education and believe that mastering and using ChatGPT resources will be beneficial to the development of education.

The above literature shows that since the release of ChatGPT, a large number of scholars have discussed the opportunities and potential risks brought by its application to industries such as education (Kasneji et al., 2023), medical (Gilson et al., 2023), and engineering projects (Prieto et al., 2023). Further research into ChatGPT applications and a further discussion of the literature will be the subject of reports in the near future. Early adoption of new technologies is often a mixed blessing: it ensures that the new technologies will benefit the industry, but at the same time it must be aware of the potential threats. Due to its excellent performance, ChatGPT is widely used in natural language processing fields such as dialogue systems, text generation and classification. As a result, ChatGPT may apply to the EVBR management system to help participants better understand and interpret the proposed auction rules. This paper attempts to apply ChatGPT to the EVBR management system as a decision support tool to reduce risk loss due to potential participant misunderstanding. To our best knowledge, this is the first literature report on the application of ChatGPT to EVBR.

2.2. Two-stage auction approach

Two-stage auctions, which are widely used in many areas, are the second stream. For instance, crowd-sourcing platform resource allocation (Mak and Lam, 2022), cloud resource allocation (Hosseinalipour and Dai, 2019), and transportation service procurement (Qian et al., 2020), etc., Katzman (1999) studied a two-stage second-price auction with an independent private value and analyzed different equilibrium outcomes when the information is symmetric and when the information is asymmetric. Ye (2007) have shown that it is reasonable to consider cost constraints in two-stage auctions. Cai et al. (2013) analyzed the impact of two-stage auctions and English auctions on the allocation of urban land in China and showed that two-stage auctions are weaker than English auctions in terms

of price and competition. [Chen et al. \(2018\)](#) designed a two-stage auction model for the transfer of tasks from the users of the macro cells to the base stations of the small cells. To solve the trust and default problems in energy auctions, [Jiang et al. \(2021\)](#) developed a two-stage auctions model based on blockchain technology to enhance the flexibility of energy transactions. [Zhu et al. \(2021\)](#) developed a two-stage auction approach to the allocation of spectrum resources, designing a directional auction-based mechanism to maximize utility in the first stage, and a unit utility-based auction algorithm to achieve stable matching between users in the second stage.

Unlike the above literature, this paper investigates a two-stage auction-based waste batteries recycling, where in the first stage two matching mechanisms are designed to ensure that the waste battery information is matched to the appropriate recycler, and the winning buyer in the first stage bids directly with the seller via the platform to achieve an optimal allocation of waste batteries. Notably, preceding two-stage auction studies failed to account for the impact of technology on the auction process. This paper addresses this gap by introducing a technology coefficient to illustrate the influence of incorporating new technology into the auction. Furthermore, this paper sets itself apart by analyzing EVBR through the construction of a winner determination model and bidding strategy for each stage, thereby making the research problem more applicable to real-world scenarios. Crucially, no existing literature offers a comparable attempt to tackle the EVBR problem utilizing a two-stage auction.

2.3. Electric vehicle battery recycling

Recently, the literature on the recycling of end-of-life batteries has seen a growing trend of research ([Li et al., 2022](#); [Sun et al., 2022](#)). [Gu et al. \(2017\)](#) studied the problem of the optimal EVBR production strategy taking into account government subsidies, constructed a game analysis model, and showed through numerical experiments that the improvement of battery recovery can help to increase the optimal output of the manufacturer. [Gu et al. \(2018\)](#) investigated the relationship between recycling rate, sorting rate and profitability by constructing an optimal model between manufacturers and remanufacturers in the battery recycling supply chain. [Wang et al. \(2020\)](#) designed the recycling network of end-of-life electric vehicle batteries from the enterprise level, built a recycling model of end-of-life batteries considering carbon emissions, and verified that transportation cost, recycling rate of end-of-life batteries and carbon tax are the three key factors affecting the design of battery recycling network through scenario analysis. [Li et al. \(2020\)](#)

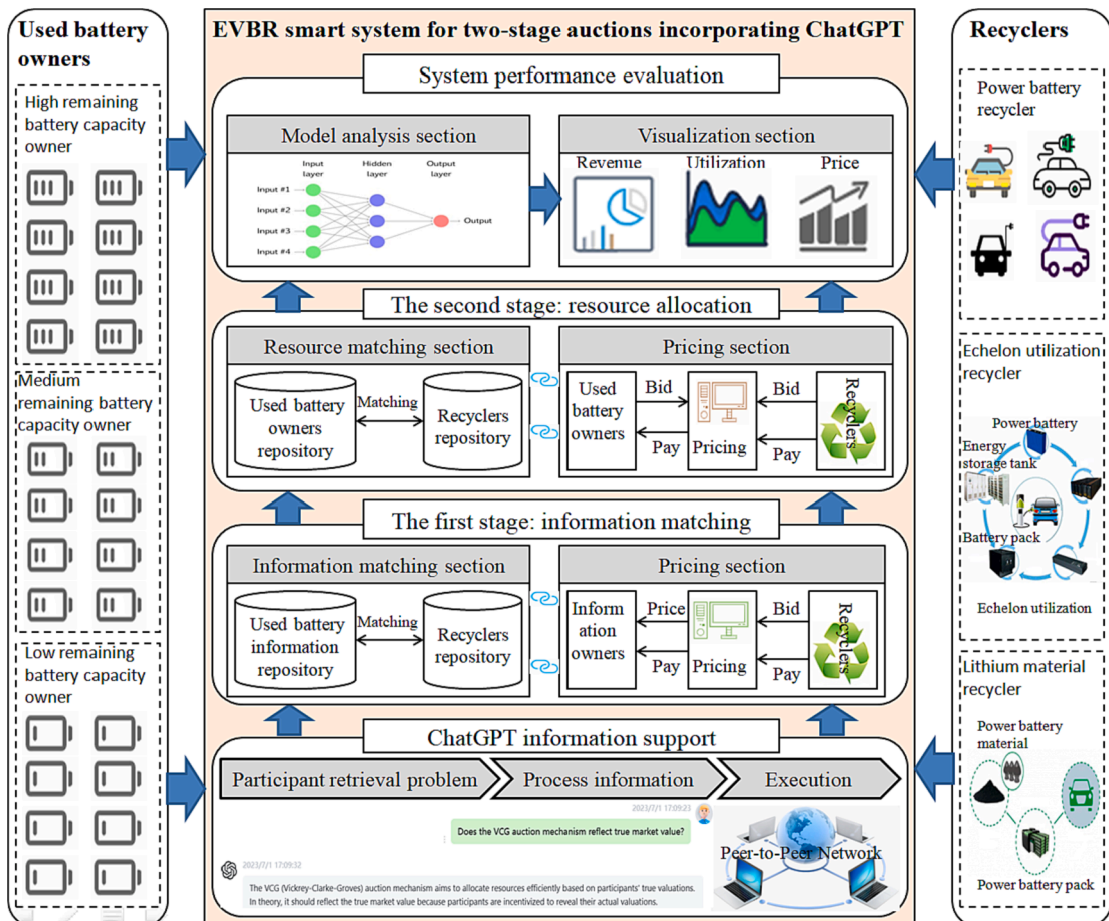


Fig. 2. Framework for EVBR smart system that integrates ChatGPT and a two-stage auction.

explored the impact of a deposit refund scheme on battery recycling, which could be promoted to some extent by increased subsidies. Government subsidies may have an important impact on the battery recycling market, and Zhao et al. (2022) considered a game theoretic approach to battery recycling pricing strategies in the context of subsidy policies, the results of which further confirm that increased recycling subsidies can promote battery recycling. Li et al. (2023a) studied used battery recycling networks from a cross-regional cooperation perspective, developed a mathematical optimization model, and showed that appropriate government penalties are beneficial for developing battery recycling networks, but that such interventions also have an impact on inter-firm cooperation. Rosenberg et al. (2023) developed a dynamic network optimization model for the retired battery recycling supply chain and validated the model with a real-life case study. Lin et al. (2023) designed four scenarios for the recycling of electric vehicle batteries and constructed a battery recycling model based on game analysis, which provided strong support to the government in formulating policy recommendations on battery recycling.

The recycling of end-of-life batteries is expected to provide a viable solution to the rapidly growing concern about raw materials for batteries. Tang et al. (2019) constructed a game analysis model to further investigate the social, economic and environmental effects of battery recycling under government incentives and penalties. Since the residual capacity of waste batteries has a significant impact on recycling, Liu et al. (2021) developed two basic models based on supplier recycling and manufacturer recycling, taking into account the impact of residual battery capacity on collection and remanufacturing in the recycling mode. Zhang et al. (2022) developed an evolutionary game model of the recycling market for end-of-life batteries, involving the manufacturing industry, the government and consumers, and their findings provide an important theoretical reference for the government's formulation of battery recycling policies. Mu et al. (2023) developed a multi-objective optimization model from the perspective of battery recycling logistics network to further optimize the battery recycling network. However, there is little literature investigating EVBR from an auction-based perspective. Xu et al. (2022) provided a way for academics and related practitioners to study EVBR by auction by developing a winner determination model and designing an efficient trading mechanism for the EVBR problem to increase recovery rates.

Existing literature has focused on EVBR design optimization, including optimization models and Stackelberg game techniques, and few studies EVBR using auction-based recycling approaches. Our study is close to Xu et al. (2022) in that both examine EVBR via an auction-based method; however, as battery attribute information is critical to their recycling value, Xu et al. (2022) do not consider how to obtain information on battery attributes, whereas this paper considers a way for recyclers to obtain attributes related to batteries through information matching, and once the battery information has been successfully matched, the second stage of the auction is carried out. To the best of our knowledge, there are no literature reports on both battery information matching and resource allocation for battery recycling. This paper makes a theoretical contribution to EVBR using an auction approach to fill this research gap.

3. EVBR smart system for two-stage auctions incorporating ChatGPT

Waste battery owners and recyclers trade their batteries via the smart system that integrates ChatGPT and a two-stage auction, as shown in Fig. 2. The overall architecture of the system consists of four components: ChatGPT assisted decision making, information matching, resource allocation and system performance evaluation.

The ultimate objective of the ChatGPT information support module is to establish an exceptional environment for intelligent information support. This insightful paper explores the incorporation of ChatGPT into the system, aiming to assist participants in addressing any uncertainties they may encounter throughout the auction process. As ChatGPT boasts formidable application scenarios, it can revolutionize the entire landscape. For instance, participants can effortlessly input their queries into the platform, and receive highly effective answers. This not only significantly reduces the expenses associated with locating participants but also entices a greater number of potential candidates. As ChatGPT technology continues to gain traction, the impact of this module will extend beyond conventional boundaries, permeating the realms of intelligent customer service, gaming, virtual entities, and other diverse fields. Moreover, it will furnish invaluable auxiliary support to the intelligent EVBR system.

The information matching module, which consists of two sections, is used to match recyclers and waste battery information, and set a reasonable transaction price for information matching. The information matching section virtualizes the waste battery information owner and recycler as agents and stores them in the waste battery information owner and recycler libraries respectively. Information matching rules are developed to efficiently match waste battery information to the appropriate recycler. Besides, price sections are used for pricing between recyclers and waste battery information owners. The OA-VCG and W-GSPA auctions are designed into this module to set flexible prices for waste battery information matching. The platform may pre-determine the number of winners (e.g. the platform may select any number of recyclers as winners) to determine the revenue, or it may determine the number of winners based on a maximum revenue target.

The resource allocation module is used to match supply and demand for recyclers and used battery owners, and to set appropriate transaction prices for matching resources. This module also contains two sections. The resource matching section virtualises the battery owner and the recycler as agents and stores them in the battery owner's repository and the recycler's repository respectively. Resource matching rules are being developed to match supply and demand for battery recycling. Besides, pricing between recyclers and end-of-life battery owners is also done in the price section. W-MTR auction is embedded in this module to make flexible prices for waste battery resource matching. Based on the bids from recyclers and waste battery owners, the platform determines the final transaction price according to the W-MTR mechanism. The platform notifies the participants and pays the corresponding amount.

The system performance evaluation consists of a model analysis section and a visualization section. The model analysis section describes the two-stage auctions method, while the visualization section is a visual graphical presentation of the sale price, participant utility and platform revenue.

4. Two-stage auctions

This section aims to introduce the construction process of the model, including the problem description, the first-stage model and the second-stage model.

4.1. Problem description

In this paper, we consider a two-stage auction EVBR management system integrating ChatGPT, which allocates waste battery information and waste battery resources to recyclers, as shown in Fig. 3. In the first stage of the auction, the platform previously collected information on various attributes of the waste batteries, including the remaining capacity of the batteries, brand, specifications, etc. The platform will then match this information with the recyclers through the auction process of the OA-VCG and the W-GSPA. It is assumed that each recycler is risk neutral and that each recycler needs only one unit of information on waste batteries. Indeed, used batteries can be seen as an infinitely supplied product, so demand from recyclers always equals supply. Besides, the number of winning recyclers can be ex ante or ex post determined by the platform. In the second stage auction, the winning recyclers from the first stage and the waste battery owners (referred to herein as sellers) bid directly via the W-MTR mechanism. Note that this paper assumes that participants' bids in the first and second stage auctions are independent. Details of the two-stage EVBR auctions are given below.

In the first stage of the auction, we use the OA-VCG and W-GSPA auctions to match information on end-of-life batteries. Since the supply of retired battery information is equal to the demand of the recycler, assume that the supply of retired battery information is x and the reservation price of recycler l is s_l , which is the maximum price that recycler l is willing to pay for a unit of information. A binary variable $Z_l = 1$ indicates that recycler l is allocated one unit of retired battery information, otherwise, $Z_l = 0$. Recycler l 's bids is $\hat{s}_l$. Here $\hat{s}_l$ may or may not be equal to s_l , indeed, in the rest of the auction rules, we will ensure that recycler l 's bids is equal to the reservation price, i.e. that recycler bids truthfully. Each recycler l only knows its own reservation price s_l and it is not possible for a recycler l to determine in advance the number of recyclers who will participate in the auction. However, it is certain that all recyclers are aware of the auction rules and the estimated reserve price set by the platform. The number of recyclers participating in the auction is known before the rules are announced, as all recycler information is automatically collected and monitored by the platform. Let the number of recyclers participating in the first stage auction be x in this paper. Please note that the number of recyclers w can be ex ante or ex post determined, and we will describe their auction rules in subsection 4.2.2 and 4.2.4.

In the second stage of the auction, the double auction will be used to allocate waste battery resources and flexible price trading mechanisms will be developed. Assume there are m recyclers (referred to herein as buyers) and n waste battery owners (referred to herein as sellers), and we use the term "agent" to denote both the buyer and the seller. The demand for each buyer i is d_i , and the supply

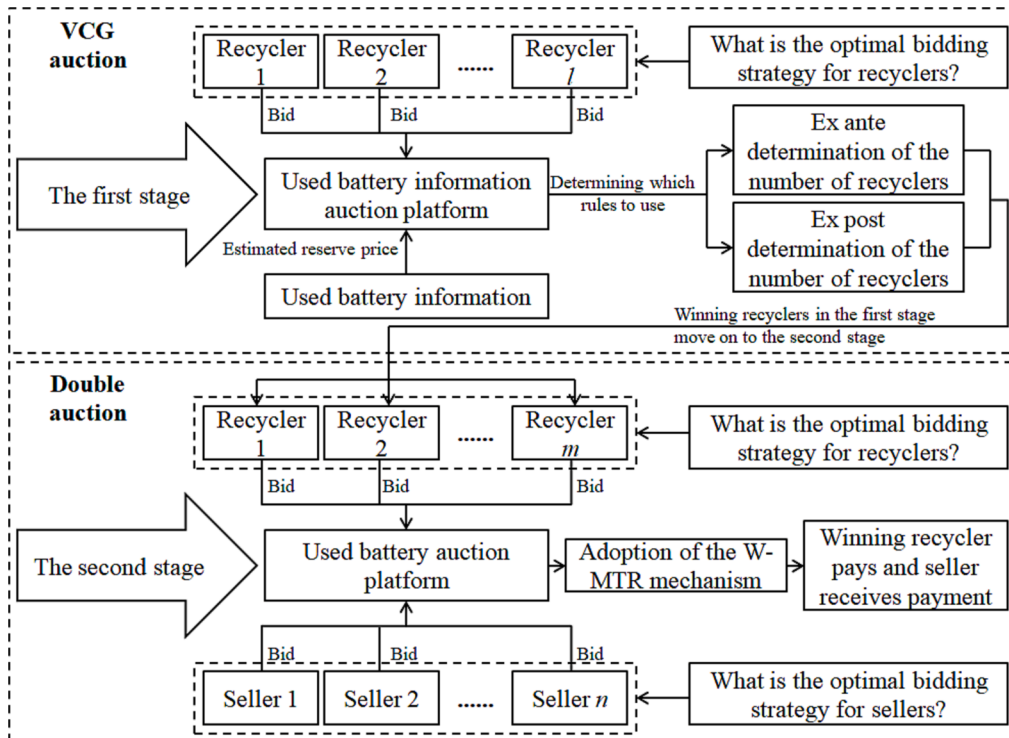


Fig. 3. Electric vehicle battery recycling based on the two-stage auctions method.

for each seller j is S_j . This paper assumes that participants are self-interested and that each participant tries to maximize their own utility. It should be noted that each participant has their own reservation price for used batteries, and this reservation price is private information. Let f_i and $\hat{f}_i$ denote the reservation price and bid price of buyer i , respectively. Let g_j and $\hat{g}_j$ denote the reservation price and bid price of seller j , respectively. In this paper, buyer's utility is the difference between the reservation price and the price paid, while seller's utility is the difference between the reservation price and the paid received.

This paper introduces the parameter λ and β to represent the effect of technology introduction on recycler (buyer) and waste battery owner (seller). The introduction of new technology to the platform has a positive effect on buyers and sellers bids, i.e. $\lambda \geq 1$, and $0 < \beta \leq 1$. This is because the new technology introduced through the platform makes it much easier for buyers and sellers to search for and acquire information, thus reducing additional costs for both sellers and buyers. We use Table 1 to give examples of the impact of new technologies on sellers and buyers. The total expected cost to buyers of a product includes the reservation price of the product and ancillary costs, and when new technology is introduced, buyers may save on some of these ancillary costs (e.g. the cost of obtaining product information). Provided that the total expected cost remains the same, buyers can raise their reserve price to win the auction, and so introducing the new technology can increase the reserve price paid by buyers, i.e. $\lambda \geq 1$. Similarly, the introduction of the new technology can reduce sellers' additional costs in terms of information acquisition. Provided that the total expected revenue remains unchanged, sellers can reduce their reservation price in order to qualify for the transaction, i.e. $0 < \beta \leq 1$.

The platform's key challenge is to design the auction trading mechanism according to the two-stage model to maximize each stage's revenue. As is well known, the auction mechanism has two key elements: the allocation of resources and the payment of prices. Each participant submits a bid based on their practical experience and expertise, aiming to maximize their utility. Once the platform receives the participants' bids, they are allocated and paid according to the auction rules.

4.2. The first stage auction

The objective of this subsection is to describe the model, mechanism and properties of the proposed OA-VCG and W-GSPA auction.

4.2.1. Model

It is assumed that waste battery information can be considered as a product with an infinite supply. The sealed bid price for recycler l is s_l . Thus the benchmark model without the introduction of ChatGPT is as follows:

$$\mathbf{P1} : \max \sum_{l=1}^x s_l Z_l \quad (1)$$

$$\text{s.t. } \sum_{l=1}^x Z_l \leq x, \quad (2)$$

$$Z_l \in \{0, 1\}. \quad (3)$$

Model **P1** above does not take into account the affine externalities that buyers impose on other buyers after the introduction of ChatGPT. Because the ChatGPT-based technology introduced by the platform increases the recyclers' utility in terms of information search and access, etc. Thus, the parameter λ_l is used in this paper to represent the degree of impact of the technology on recycler l . Besides, let γ_l table the boosting variable for buyer l . This variable can be interpreted as how buyer l gains or loses to other buyers due to his participation in the auction after the introduction of ChatGPT. The mathematical model for the maximum social welfare in the first stage is then given as follows:

$$\mathbf{P2} : \max \sum_{l=1}^x \lambda s_l Z_l + \gamma_l \quad (4)$$

$$\text{s.t. } \sum_{l=1}^x Z_l \leq x, \quad (5)$$

$$Z_l \in \{0, 1\}, \quad (6)$$

$$\lambda \geq 1. \quad (7)$$

Table 1

An example illustrating the impact of technology on buyers and sellers.

Whether to introduce new technology	Buyer			Seller		
	Reservation price	Additional costs	Expected total cost	Reservation price	Additional costs	Expected revenue
No	20	5	25	10	3	7
Yes	24	1	25	8	1	7

The maximum social welfare of a set of efficient allocations is denoted by the objective function (4); constraint (5) denotes that the number of winning recyclers does not exceed the maximum supply, indeed, the maximum supply x can be given ex ante or determined ex post, and let w denote the final number of winning recyclers and satisfies $w \leq x$; and constraint (6) denotes the binary variable.

4.2.2. OA-VCG mechanism

To induce recyclers to bid truthfully, this study proposes a novel auction to solve the problem that the platform is to ex ante or ex post determine the number of winning recyclers.

Definition 1. A novel trading mechanism called OA-VCG can be used to ensure trade validity, if the optimal allocation quantity w is ex ante determined by the platform.

Let $\pi(L)$ be the optimal value of $\sum_{l=1}^x \lambda s_l Z_l + \gamma_l$, and let $\pi(L \setminus l)$ be the optimal value of function $\sum_{l=1}^x \lambda s_l Z_l + \gamma_l$ if recyclers l does not participate in this auction. Indeed, since buyer l has affine externality to other buyers, if recycler l becomes the winner, he will determine his payment to the platform according to the following equation:

$$p_l^{OW-VCG} = s_l - \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)| = s_l - \left| s_l - s_{w+1} + \frac{\gamma_l}{\lambda} \right| \quad (8)$$

From Eq. (8), it can be seen that when buyer l has a positive imitation externality ($\gamma_l > 0$) on other buyers, the price it pays is significantly lower than the second-price auction; when buyer l does not have any effect on other buyers, i.e., ($\gamma_l = 0$), the price it pays is equal to the second-price auction; and when buyer l has a negative imitation externality ($\gamma_l < 0$) on other buyers, the price it pays is higher than the second-price auction. The utility of recycler l is

$$u_l^{OW-VCG} = s_l - s_l + \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)| = \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)| = \left| s_l - s_{w+1} + \frac{\gamma_l}{\lambda} \right| \quad (9)$$

The total payment (TP) received by the platform is then given by the following equation:

$$TP = \sum_{l=1}^w p_l^{OW-VCG} \quad (10)$$

The procedure of the OA-VCG mechanism is given as follows:

- The platform publishes the auction rules and the number of winning recyclers w .
- Recycler l submits a sealed bid s_l to the platform.
- Calculate the amount to be paid by the winning recycler from Eq. (8), and determine the TR by Eq. (10).
- The TR received by the platform is compared to the reservation revenue (RR) of the platform and if $TP > RR$, the transaction is successful; otherwise, the transaction fails.

4.2.3. Properties of OA-VCG

Theorem 1. If the number of winning recyclers w is determined ex ante by the platform, then it is reasonable to use the OA-VCG second-price auction and the best strategy for the recycler is to bid truthfully.

Proof. If all recycler bids truthfully, then the utility of recycler l is $u_l^{OW-VCG} = s_l - p_l^{OW-VCG} = \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)|$, where $\pi(L) = \lambda s_l + \gamma_l + \sum_{j \in X \setminus l} (\lambda s_j + \gamma_j)$. If recycler l does not bid truthfully, and the recycler $L \setminus l$ bids truthfully, then the recycler l makes a VCG-like payment, $\hat{p}_l^{OW-VCG} = \hat{s}_l - \frac{1}{\lambda} |\pi(L \setminus l) - \hat{\pi}(L)|$, where $\hat{\pi}(L) = \lambda \hat{s}_l + \gamma_l + \sum_{j \in X \setminus l} (\lambda s_j + \gamma_j)$. The utility of recycler l is $\hat{u}_l^{OW-VCG} = s_l - \hat{p}_l^{OW-VCG} = s_l - \hat{s}_l + \frac{1}{\lambda} |\pi(L \setminus l) - \hat{\pi}(L)|$, then

$$u_l^{OW-VCG} - \hat{u}_l^{OW-VCG} = \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)| - s_l + \hat{s}_l - \frac{1}{\lambda} |\pi(L \setminus l) - \hat{\pi}(L)| \geq 0 \quad (11)$$

Clearly, Eq. (11) is greater than or equal to zero because buyer l 's reservation value s_l is fixed regardless of whether he bids truthfully or not. Then we will discuss this in two cases. Case 1: If $\hat{s}_l > s_l$, and recycler l becomes the winner, i.e. recycler l 's sealed bid is greater than the reserved value, then his utility does not increase. Case 2: The purpose of recycler l not choosing the true bid is to obtain a greater utility (i.e. it should be greater than the utility of bidding truthfully), so if $\hat{s}_l < s_l$, then

$$\begin{aligned} \hat{u}_l^{OW-VCG} &> u_l^{OW-VCG}, \\ s_l - \hat{s}_l + \frac{1}{\lambda} |\pi(L \setminus l) - \hat{\pi}(L)| &> \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)| \end{aligned} \quad (12)$$

Obviously, Eq. (12) leads to a result that is inconsistent with the hypothesis, and then the recycler l does not increase his utility. Furthermore, recyclers who bid below the reserve price risk not being able to become winners, while bidding above the reserve price increases the probability of being a winner, but does not increase its utility. Thus, the incentive compatibility (IC) of the OA-VCG mechanism has been demonstrated, and truthful bidding is the optimal strategy for recyclers.

Theorem 2. The proposed OA-VCG mechanism is individually rational (IR), budget balanced (BB), and allocation efficiency (AE).

Proof. According to the proposed OA-VCG rule, it follows that each winning recycler pays an amount equal to $p_l^{OW-VCG} = s_l - \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)|$ and has the utility of $s_l - p_l^{OW-VCG} = \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)|$. Clearly, recyclers who do not win in the auction have zero utility, while winning recyclers have utility greater than zero, i.e., each winning recycler has non-negative utility due to truthful bidding. Thus, the proposed OA-VCG mechanism is IR. The total amount paid by the winning recyclers is $TP = \sum_{l=1}^w p_l^{OW-VCG}$ and if $TP > RR$, then the transaction succeeds, otherwise, the transaction fails. In either scenario, the platform always has positive utility, and hence the OA-VCG mechanism is BB. Because recyclers bid truthfully, then the use of the OA-VCG mechanism achieves maximum social welfare, thus ensuring that the OA-VCG mechanism is AE.

Proposition 1. If buyer l has a positive externality, $\gamma_l > 0$, on other participating auctions after the introduction of ChatGPT, then total social welfare will increase; conversely, if buyer l 's negative externality γ_l on the other participating auctions exceeds $(\lambda - 1)s_l$ after the introduction of ChatGPT, then social welfare will decrease.

Proof. The difference between model P2 and model P1 is $\sum_{l \in w} (\lambda s_l + \gamma_l) - \sum_{l \in w} s_l = \sum_{l \in w} (\lambda - 1)s_l + \gamma_l$ when $\gamma_l > 0$ holds. It is obvious that $\sum_{l \in w} (\lambda - 1)s_l + \gamma_l > 0$. However, total social welfare is reduced if and only if the value added by the introduction of ChatGPT is less than the value of the loss to other buyers caused by buyer l .

Theorem 3. If each buyer has a positive affine externality, i.e., $\gamma_l > 0$, on all other buyers, then the platform's revenue will decrease.

Proof. If $\gamma_l > 0$ holds, then the platform's return is $\sum_{l=1}^w p_l^{OW-VCG}$, and the platform revenue obtained from the traditional second-price auction (model P1) is ws_{w+1} . Since $\gamma_l > 0$, $p_l^{OW-VCG} = s_l - \frac{1}{\lambda} |\pi(L \setminus l) - \pi(L)| = s_l - \frac{1}{\lambda} [\pi(L) - \pi(L \setminus l)]$, then

$$\begin{aligned} \sum_{l=1}^w p_l^{OW-VCG} - ws_{w+1} &= \left(s_1 - \frac{1}{\lambda} [\pi(L) - \pi(L \setminus 1)] \right) + \left(s_2 - \frac{1}{\lambda} [\pi(L) - \pi(L \setminus 2)] \right) + \cdots + \left(s_w - \frac{1}{\lambda} [\pi(L) - \pi(L \setminus w)] \right) - ws_{w+1} \\ &= s_1 + s_2 + \cdots + s_w - \frac{1}{\lambda} (\lambda s_1 + \gamma_1 + \lambda s_2 + \gamma_2 + \cdots + \lambda s_w + \gamma_w - w \lambda s_{w+1}) - ws_{w+1} = -\frac{1}{\lambda} \sum_{l \in w} \gamma_l \end{aligned} \quad (13)$$

Obviously, when $\gamma_l > 0$, $\sum_{l=1}^w p_l^{OW-VCG} - ws_{w+1} = -\frac{1}{\lambda} \sum_{l \in w} \gamma_l < 0$. This suggests that with the introduction of ChatGPT, if buyers have a positive affine externality on other buyers, then the platform's benefits will be smaller, while total social welfare will increase.

Three simple examples are given to illustrate the scenarios where γ_l is greater than 0, less than 0 and an arbitrary number, respectively. Example 1 is where γ_l is greater than 0, example 2 is where γ_l is less than 0 and example 3 is where γ_l is an arbitrary number.

Example 1. Let $\lambda = 1.2$, $w = 3$, $s_1 = 9$, $\gamma_1 = 3$, $s_2 = 8$, $\gamma_2 = 4$, $s_3 = 7$, $\gamma_3 = 2$, $s_4 = 6$, $\gamma_4 = 1$, $s_5 = 4$, $\gamma_5 = 1$. Bringing the above data into model P2 yields $\pi(L) = 39.8$, and the buyer 1, 2, 3 become winners, $p_1^{OW-VCG} = 9 - \frac{1}{1.2} (39.8 - 33.2) = 3.5$, $p_2^{OW-VCG} = 8 - \frac{1}{1.2} (39.8 - 33.4) = 2.67$, $p_3^{OW-VCG} = 7 - \frac{1}{1.2} (39.8 - 36.6) = 4.33$, and the total return of the platform is $TP = \sum_{l=1}^3 p_l^{OW-VCG} = 10.5$.

Example 2. Let $\lambda = 1.2$, $w = 3$, $s_1 = 9$, $\gamma_1 = -3$, $s_2 = 8$, $\gamma_2 = -1$, $s_3 = 7$, $\gamma_3 = -2$, $s_4 = 6$, $\gamma_4 = -1$, $s_5 = 4$, $\gamma_5 = -2$. Bringing the above data into model P2 yields $\pi(L) = 19.8$, and the buyer 1, 2, 3 become winners, $p_1^{OW-VCG} = 9 - \frac{1}{1.2} |19.8 - 19.2| = 8.5$, $p_2^{OW-VCG} = 8 - \frac{1}{1.2} |19.8 - 18.4| = 6.83$, $p_3^{OW-VCG} = 7 - \frac{1}{1.2} |19.8 - 20.6| = 6.33$, and the total return of the platform is $TP = \sum_{l=1}^3 p_l^{OW-VCG} = 21.66$.

Example 3. Let $\lambda = 1.2$, $w = 3$, $s_1 = 9$, $\gamma_1 = 2$, $s_2 = 8$, $\gamma_2 = -2$, $s_3 = 7$, $\gamma_3 = 0$, $s_4 = 6$, $\gamma_4 = 1$, $s_5 = 4$, $\gamma_5 = -3$. Bringing the above data into model P2 yields $\pi(L) = 26.8$, and the buyer 1, 2, 3 become winners, $p_1^{OW-VCG} = 9 - \frac{1}{1.2} |26.8 - 21.2| = 4.33$, $p_2^{OW-VCG} = 8 - \frac{1}{1.2} |26.8 - 26.4| = 7.67$, $p_3^{OW-VCG} = 7 - \frac{1}{1.2} |26.8 - 25.6| = 6$, and the total return of the platform is $TP = \sum_{l=1}^3 p_l^{OW-VCG} = 18$.

Corollary 1. If $\gamma_l > 0$ holds, then the larger the positive affine externality γ_l of buyer l to other buyers, the smaller the price he pays, and if $\gamma_l = 0$ holds, then the price he pays is the second price.

Proof. Since $\gamma_l > 0$ holds, then Eq. (8) can be written as $p_l^{OW-VCG} = s_l - |s_l - s_{w+1} + \frac{\gamma_l}{\lambda}| = s_{w+1} - \frac{\gamma_l}{\lambda}$. If $\gamma_l > \gamma_l > 0$ hold, then $p_l^{OW-VCG} - p_l^{OW-VCG} = \frac{\gamma_l - \gamma_l}{\lambda} > 0$. Thus we can obtain $p_l^{OW-VCG} > p_l^{OW-VCG}$. If $\gamma_l = 0$ holds, then $p_l^{OW-VCG} = s_{w+1}$.

Corollary 2. If $\gamma_l < 0$ holds, then the stronger the negative externality of buyer l to other buyers, the higher the price it pays.

Proof. Under the condition that $\gamma_l < 0$ and $s_{w+1} - s_l \leq \frac{\gamma_l}{\lambda} < 0$ hold, then Eq. (8) can be written in the form of $p_l^{OW-VCG} =$

Table 2

An illustrative example that bidding truthfully by the recycler under the OA-VCG mechanism is not an optimal strategy for ex post determining the allocation quantity.

Recyclers l	Bidding price $\hat{v}_l$	w	Revenue	Bidding price $\hat{v}_l$	w	Revenue
1	24	1	21	21	1	17
2	21	2	34	17	2	28
3	17	3	42	14	3	36
4	14	4	48	12	4	40
5	12	5	45	10	5	45
6	9	6	36	9	6	36
7	6	7	35	6	7	35
8	5	—	—	5	—	—

$s_l - |s_l - s_{w+1} + \frac{\gamma_l}{\lambda}| = s_{w+1} - \frac{\gamma_l}{\lambda}$. If $\gamma_l < \gamma_l < 0$ hold, then $p_l^{OW-VCG} - p_l^{OW-VCG} = s_{w+1} - \frac{\gamma_l}{\lambda} - (s_{w+1} - \frac{\gamma_l}{\lambda}) = \frac{\gamma_l - \gamma_l}{\lambda} < 0$, thus we can obtain $p_l^{OW-VCG} < p_l^{OW-VCG}$.

4.2.4. W-GSPA mechanism

Observation 1: If the number of winning recyclers w is determined by model **P2** after receiving their bid prices, then bidding truthfully in the second-price auction is not the optimal strategy for recyclers.

We use a practical example to illustrate the **Observation 1**. As shown in Table 2, assuming that there are 8 recyclers buying waste battery information and the bids are 24, 21, 17, 14, 12, 9, 6, and 5 in descending order, then the optimal number of allocations for the platform is 4 and the maximum value is 48. If the highest bid recycler with the value of 24 submits a bid of 10, then the optimal number of allocations for the platform is 5 and the maximum value is 45. The number of winning recyclers has increased, but the maximum revenue has decreased. Why would the highest recycler with value 24 submit at a lower price? This is because the recycler with value 24 only has to pay 9 instead of the previous 12. It is clear that the recycler has an incentive to misrepresent his bid and, therefore, a truthful bid by the recycler under the second price auction mechanism is not an optimal strategy for the ex-post determination of the quantity to be allocated.

If the optimal allocation quantity w is determined ex post, then the use of the OA-VCG mechanism described above does not ensure that the recyclers will bid truthfully. To ensure that recyclers bid truthfully, we will describe the following transaction mechanism.

Definition 2. A novel trading mechanism called W-GSPA can be used to ensure trade validity, if the optimal allocation quantity w is ex post determined by the platform.

As it is assumed in this paper that information on waste batteries is a variable supply product, the platform also has its reserved price for information on waste batteries which is allocated to a different number of recyclers. It is assumed that the platforms' reserved price per unit of waste battery information increases as the number of bidding recyclers increases. This assumption is in line with a realistic scenario, as the more recyclers that participate in the bidding process, the more competitive the market will become, which means that the platforms' expected reserved price per unit of waste battery information will also increase. We use an example to illustrate the proposed generalized second-price auction, as shown in Table 3.

Assume that eight recyclers participate in the bidding and their bidding prices are listed in order from highest to lowest, and the platform uploads their reservation price h_l in order from lowest to highest, based on the number of units recycled. Then the optimal allocation quantity w satisfies $\{w \geq 1 : \hat{v}_w > h_w\}$, and the winning recycler w will pay $\max\{\hat{v}_{(w+1)}, h_w\}$ to the platform. Since $\hat{v}_4 = 15 > h_4 = 11$ in Table 3, the optimal allocation quantity w is 4. Furthermore, since $\max\{\hat{v}_{(w+1)} = 12, h_w = 11\} = 12$, then each winning recycler will pay 12 to the platform and the total revenue of the platform is 48. The procedure of the proposed W-GSPA mechanism is given as follows:

- The platform announces the rules of the W-GSPA mechanism.
- Recycler l submits a sealed bid $\hat{v}_l$ in accordance with the auction rules to the platform, and the platform's reservation price h_l is determined by the number of bids received from recyclers.
- Sort the recyclers' bids $\hat{v}_l$ in descending order $\hat{v}_1 \geq \hat{v}_2 \geq \dots \geq \hat{v}_l$, while the platform's reserved prices h_l are sorted in ascending order $\hat{h}_1 \leq \hat{h}_2 \leq \dots \leq \hat{h}_l$. Determine the optimal allocation quantity w according to the following expression:

$$\{w | w \geq 1 : \hat{v}_w > h_w\} \quad (14)$$

- Determine the price paid by each winning recycler according to the following expression:

$$p_w^{W-GSPA} = \max\{\hat{v}_{(w+1)}, h_w\} \quad (15)$$

- Calculate total platform revenue $TR = w * p_w^{W-GSPA}$.

4.2.5. Properties of W-GSPA

Theorem 4. If the optimal allocation quantity w is determined ex post, then it is optimal to apply the W-GSPA mechanism, and bidding

Table 3

An illustrative example of proposed generalized second-price auction.

Recyclers l	Recyclers' bidding price $\hat{v}_l$	Platform' reservation price h_l	Whether to win	w	Revenue
1	22	3	Yes	4	$4 * 12 = 48$
2	19	6	Yes		
3	17	8	Yes		
4	15	11	Yes		
5	12	13	No	5	$5 * 9 = 45$
6	10	15	No		
7	7	16	No		
8	4	19	No		

truthfully in the W-GSPA mechanism is the optimal strategy for the recycler.

Proof. Assuming that recycler l does not bid truthfully and other recyclers bid truthfully, there are several scenarios based on the relationship between the recycler's bid price $\hat{v}_l$, the reserved price v_l and the platform's reserved price h_l as follows:

- 1) If $v_l > \hat{v}_l > h_w$ or $\hat{v}_l > v_l > h_w$, then recycler l is able to be the winner, but his utility $v_l - \max\{\hat{v}_{(w+1)}, h_w\}$ does not increase. Thus, recycler l will not misrepresent his bid price $\hat{v}_l$.
- 2) If $v_l > h_w > \hat{v}_l$, $h_w > v_l > \hat{v}_l$ or $h_w > \hat{v}_l > v_l$, then recycler l cannot be the winner and his utility is zero. Thus, recycler l is likely to be the loser of the bid (e.g. $v_l > h_w > \hat{v}_l$) because of his misrepresentation of the bid price $\hat{v}_l$.
- 3) If $\hat{v}_l > h_w > v_l$, then recycler l has a negative utility despite being the winner by increasing his bid price $\hat{v}_l$. As a result, as a rational recycler l would not choose to be the winner in this way.

Misrepresenting his bid price $\hat{v}_l$ does not increase his utility, but may instead decrease the utility. As a result, truthful bidding is the optimal strategy for the recycler.

Theorem 5. The W-GSPA mechanism is IR, BB, and AE.

Proof. In the W-GSPA mechanism, the utility of the winning recycler l is $v_l - p_l^{OW-VCG} = v_l - \max\{\hat{v}_{(l+1)}, h_l\}$, and each recycler bids truthfully, then $v_l = \hat{v}_l > h_l$, and $\hat{v}_l > \hat{v}_{(l+1)}$. This means that all recyclers participating in the auction have non-negative utility as long as they bid truthfully. Thus, the W-GSPA mechanism is IR. Apparently, as long as the W-GSPA mechanism is traded successfully, then the platform always gains and therefore the W-GSPA mechanism is able to achieve BB. Using the W-GSPA mechanism can achieve maximum benefit based on recyclers bidding truthfully, and therefore the proposed W-GSPA mechanism is AE.

4.3. The second stage auction

Once waste batteries information has been matched to recyclers, resource allocation and pricing between recyclers and waste battery owners must be achieved. The purpose of this subsection is therefore to describe the model, mechanism and properties of the proposed W-MTR auction.

4.3.1. Model

Consider a waste battery recycling marketplace consisting of an auction platform, m buyers and n sellers. Recall that the demand of each buyer i ($i = 1, 2, \dots, m$) is d_i , the supply of each seller j ($j = 1, 2, \dots, n$) is S_j , and $d_i \in N^*$, $S_j \in N^*$ is satisfied. Note that d_i and S_j are splittable transactions, i.e. the number of batteries for buyers and sellers is splittable. In this paper, symbols f_i^* and g_j^* are used to denote the reservation prices for buyer i and seller j , respectively, when no technical coefficient parameter is introduced. Besides, the quantity sold by seller j to buyer i is y_{ij} . If all participants bid truthfully, then maximizing social welfare $W(m, n)$ is determined by the model **P3**.

$$\mathbf{P3} : W(m, n) = \max \sum_i^m \sum_j^n (\hat{f}_i - \hat{g}_j) y_{ij}, \quad (16)$$

$$s.t. \sum_{j=1}^n y_{ij} \leq d_i, \forall i, \quad (17)$$

$$\sum_{i=1}^m y_{ij} \leq S_j, \forall j, \quad (18)$$

$$\hat{f}_i = \lambda f_i^*, \quad (19)$$

$$\hat{g}_j = \beta g_j^*, \quad (20)$$

$$\lambda \geq 1, \quad (21)$$

$$0 < \beta \leq 1, \quad (22)$$

$$y_{ij} \geq 0, \forall i, j. \quad (23)$$

Eq. (17) represents that buyer i will not buy more waste batteries than his demands; Eq. (18) represents that seller j will not sell more waste batteries than her supplies. Constraints (19) and (20) denote the reservation prices for buyer i and seller j , respectively, after the introduction of the technical coefficient parameter. Model **P3** only reflects bid and ask prices and does not show trade prices, but this does not mean that trade prices do not affect participants' utility. The W-MTR mechanism will be introduced in the next section to address these issues as model **P3** alone cannot determine trading prices and ensure that participants bid truthfully.

4.3.2. W-MTR mechanism

This section introduces the W-MTR mechanism to induce sellers and buyers to bid truthfully. The buyer's sealed bids $\hat{f}_i$ and the seller's sealed bids $\hat{g}_j$ are first ranked in descending and descending order, respectively, and the expressions are given below:

$$\begin{aligned} \hat{f}_1 &\geq \hat{f}_2 \geq \dots \geq \hat{f}_m \\ \hat{g}_1 &\leq \hat{g}_2 \leq \dots \leq \hat{g}_n \end{aligned} \quad (24)$$

Assuming that there are T ($0 < T < m$) buyers and K ($0 < K < n$) sellers who win the auction, the optimal total number of trades determined by model P3 is $B^* = \min\{\sum_{i=1}^T d_i, \sum_{j=1}^K S_j\}$. While the total number of trades for the proposed W-MTR mechanism is $B' = \min\{\sum_{i=1}^{T-1} d_i, \sum_{j=1}^{K-1} S_j\}$. In practice, if there is more than one optimal solution, they can be solved by using perturbation techniques so that the model has a unique best solution.

Observation 2: There are three scenarios here, equilibrium between supply and demand ($\sum_{i=1}^T d_i = \sum_{j=1}^K S_j$), undersupply ($\sum_{i=1}^{T-1} d_i < \sum_{j=1}^{K-1} S_j < \sum_{i=1}^T d_i, \hat{g}_{K+1} > \hat{f}_T \geq \hat{g}_K$) and oversupply ($\sum_{j=1}^{K-1} S_j < \sum_{i=1}^T d_i < \sum_{j=1}^K S_j, \hat{f}_T \geq \hat{g}_K > \hat{f}_{T+1}$).

Indeed, on the factual basis of $\hat{f}_T \geq \hat{g}_K$ and $\hat{f}_{T+1} < \hat{g}_K$, it is easy to obtain the results of **Observation 2**. The W-MTR mechanism proposed herein is able to address these three scenarios. In the proposed W-MTR mechanism, consider the following two inequalities:

$$\sum_{j=1}^{K-1} S_j \leq \sum_{i=1}^{T-1} d_i \quad (25)$$

$$\sum_{j=1}^{K-1} S_j \geq \sum_{i=1}^{T-1} d_i \quad (26)$$

For inequalities (25) and (26), two different rules are defined in this paper to determine their allocation quantities respectively.

Definition 3. If inequality (25) holds, then it means that the sum of buyers' demand is greater than or equal to the sum of sellers' supply, and the following allocation mechanism 1 is used to determine the buyers' final allocation quantity.

Allocation mechanism 1

- Winning seller j ($j \leq K-1$) sell their supply quantity S_j at a unit price $\hat{g}_K$, while winning buyer i ($i \leq T-1$) purchase waste batteries at a unit price $\hat{f}_T$.
- The platform will rank buyers according to their demands and use perturbation techniques to break the tie if there is an identical demand. Let δ_i represent the sorting of buyer i . The platform will then rank the winning buyers ($i \leq T-1$) in ascending order $\delta_1' < \delta_2' < \dots < \delta_{(T-1)}'$ based on their demands.
- In this paper the symbol $\lfloor X \rfloor$ is used to denote the largest integer that does not exceed X . Then the basic number of battery transactions for buyer i is $\bar{c}_i = \lfloor d_i \sum_{j=1}^{K-1} S_j / \sum_{i=1}^{(T-1)'} d_i \rfloor$, and satisfying $\bar{c}_i \leq d_i$. The remaining unallocated supply is represented by the symbol RUS , $RUS = \sum_{j=1}^{K-1} S_j - \sum_{i=1}^{T-1} \bar{c}_i$. The RUS is reallocated according to the ranking of buyer i . The expression for the optimal number of waste batteries allocated to buyer i , c_i , is then given as follows:

$$c_i = \left\{ \min \left\{ d_i, \bar{c}_i + \left[RUS - \sum_{a=(i+1)'}^{(T-1)'} (c_a - \bar{c}_a) \right] \right\} \min \{ d_{(T-1)'}, \bar{c}_{(T-1)'} + RUS \}, i = (T-1)', 1 \leq i \leq (T-2)' \right\} \quad (27)$$

Definition 4. If inequality (26) holds, then it means that the sum of sellers' supply is greater than or equal to the sum of buyers' demand, and the following allocation mechanism 2 is used to determine the sellers' final allocation quantity.

Allocation mechanism 2

- Winning buyer i ($i \leq T-1$) purchase their demand quantity d_i at a unit price $\hat{f}_T$, while winning seller j ($j \leq K-1$) sell waste batteries at a unit price $\hat{g}_K$.
- The platform will rank sellers according to their supplies and use perturbation techniques to break the tie if there is an identical supply. Let δ_j represent the sorting of seller j . The platform will then rank the winning sellers ($j \leq K-1$) in ascending order $\delta_1' < \delta_2' < \dots < \delta_{(K-1)}'$ based on their supply.
- Then the basic number of battery transactions for seller j is $\bar{c}_j = \lfloor S_j \sum_{i=1}^{T-1} d_i / \sum_{j=1}^{K-1} S_j \rfloor$, and satisfying $\bar{c}_j \leq S_j$. The remaining unallocated demand is represented by the symbol RUD , $RUD = \sum_{i=1}^{T-1} d_i - \sum_{j=1}^{K-1} \bar{c}_j$. The RUD is reallocated according to the ranking of seller j . The expression for the optimal number of waste batteries allocated to seller j , c_j , is then given as follows:

$$c_j = \left\{ \min \left\{ S_j, \bar{c}_j + \left[RUD - \sum_{b=(j+1)}^{(K-1)'} (c_b - \bar{c}_b) \right] \right\} \min \{ S_{(K-1)'}, \bar{c}_{(K-1)'} + RUD \} \right\}, j = (K-1)', 1 \leq j \leq (K-2)' \quad (28)$$

The procedure of the proposed W-MTR mechanism is given as follows:

- The platform announces the rules of the W-MTR mechanism.
- Buyers submit their bid prices and demand and sellers submit sealed bid prices and supply.
- Sort the buyers' bids $\hat{f}_i$ in descending order $\hat{f}_1 > \hat{f}_2 > \dots > \hat{f}_m$, and sort the sellers' bids $\hat{g}_j$ in ascending order $\hat{g}_1 < \hat{g}_2 < \dots < \hat{g}_n$.
- Determine $B^* = \min \{ \sum_{i=1}^T d_i, \sum_{j=1}^K S_j \}$ where $\hat{f}_T \geq \hat{g}_K$ and $\hat{f}_{T+1} < \hat{g}_{K+1}$, and exclude buyers with subscript $i \geq T$ and sellers with subscript $j \geq K$.
- Determine the quantity of waste batteries to be allocated. Check if inequality (25) or (26) holds. Use allocation mechanism 1 if inequality (25) is satisfied and allocation mechanism 2 if inequality (26) is satisfied.

4.3.3. Properties of W-MTR

Theorem 6. *The W-MTR mechanism is incentive compatibility, and truthful bidding is the dominant strategy for sellers and buyers.*

Proof. We begin by discussing the utilities of buyers and sellers when inequality (25) holds. Indeed, subject to the fact that inequality (25) holds, the seller j who gets the deal can sell all of his waste batteries. Assuming that seller j does not bid truthfully and that the other buyers and sellers bid truthfully. This paper will discuss the following scenarios: i) If $g_K > g_j > \hat{g}_j$ or $g_K > \hat{g}_j > g_j$, then the seller j 's utility is the same as the utility of a real bid $\varphi_j = (g_K - g_j)S_j$; ii) If $\hat{g}_j > g_K > g_j$ or $\hat{g}_j > g_j \geq g_K$, it is clear that seller j will not be the winner; and iii) If $g_j \geq g_K > \hat{g}_j$ or $g_j > \hat{g}_j > g_K$, seller j will have negative utility. To this end, truthful bidding is the best strategy for sellers.

Assuming that buyer i does not bid truthfully and that the other buyers and sellers bid truthfully, there are several scenarios as follows: i) If $\hat{f}_i > f_i > f_T$ or $f_i > \hat{f}_i > f_T$, then the utility of buyer i is the same as the utility of a real bid; ii) If $f_T > \hat{f}_i > f_i$ or $f_T \geq f_i > \hat{f}_i$, it is clear that buyer i will not be the winner; iii) If $\hat{f}_i > f_T \geq f_i$, then the buyer i will have negative utility; and iii) If $f_i > f_T > \hat{f}_i$, the buyer i , who should have been the winner, do not become the winner due to misrepresentation of the bid price. To this end, the best strategy for the buyer is to bid truthfully.

The process is similar to the one described above for proving that inequality (26) holds. Therefore, for both sellers and buyers, truthful bidding is the dominant strategy in the W-MTR mechanism.

Theorem 7. *The W-MTR mechanism is BB and IR.*

Proof. Since the price paid $\hat{f}_T$ by the buyer is greater than or equal to the price received $\hat{g}_K$ by the seller, i.e. $\hat{f}_T \geq \hat{g}_K$, the platform always receives a non-negative return, which means that the platform is able to achieve BB. As Theorem 6 shows, participants who bid truthfully receive non-negative utility. To this end, the proposed W-MTR mechanism is IR.

Observation 3: The W-MTR mechanism proposed herein suffers from efficiency losses.

Since the W-MTR mechanism will remove the winning buyer T and seller K , i.e. it will reduce the number of waste batteries traded, the efficiency loss of the platform thus is $(\lambda f_T^* - \beta g_K^*)(B^* - B')$. Besides, the use of the W-MTR mechanism can result in efficiency losses for both buyers and sellers, which denote τ . If $\sum_{j=1}^{K-1} S_j \leq \sum_{i=1}^{T-1} d_i$, then $\tau \leq (\lambda f_1^* - \lambda f_T^*)S_K$; If $\sum_{j=1}^{K-1} S_j \geq \sum_{i=1}^{T-1} d_i$, then $\tau \leq (\beta g_K^* - \beta g_1^*)d_T$. In the proposed W-MTR mechanism, the symbol $\epsilon(T, K)$ is used to denote the efficiency loss and the expression is given:

$$\epsilon(T, K) = (\lambda f_T^* - \beta g_K^*)(B^* - B') + \tau \quad (29)$$

In this paper, $(\lambda f_T^* - \beta g_K^*)B^*$ denotes the platform's revenue obtained via model P3. Also $\sum_{i=1}^{T-1} (\lambda f_i^* - \lambda f_T^*)d_i$ and $\sum_{j=1}^{K-1} (\beta g_K^* - \beta g_j^*)S_j$ indicates the buyer's and seller's efficiency contribution to the platform, respectively. The maximum value $\vartheta(T, K)$ is thus given by:

$$\vartheta(T, K) = (\lambda f_T^* - \beta g_K^*)B^* + \sum_{i=1}^{T-1} (\lambda f_i^* - \lambda f_T^*)d_i + \sum_{j=1}^{K-1} (\beta g_K^* - \beta g_j^*)S_j \quad (30)$$

Theorem 8. *In the W-MTR mechanism, the market inefficiency ratio $\rho(T, K) \leq \epsilon(\max\{\frac{1}{T}, \frac{1}{K}\})$, where ϵ is a constant.*

Proof. Assuming that sellers and buyers bid on the interval $[u^-, u^+]$, the difference in expectations between any buyer or seller depends only on their order numbers, i.e. there are $E[\hat{f}_i - \hat{f}_T] = E[\lambda f_i^* - \lambda f_T^*] = \lambda \frac{T-i}{m+1} (u^+ - u^-)$, $1 \leq i < T \leq m$ and $E[\hat{g}_K - \hat{g}_j] = E[\beta g_K^* - \beta g_j^*] = \beta \frac{K-j}{n+1} (u^+ - u^-)$, $1 \leq j < K \leq n$. Then $\rho(T, K)$ can be determined from Eq. (29) and Eq. (30).

$$\rho(T, K) = \frac{E[(\lambda f_T^* - \beta g_K^*)(B^* - B) + \tau]}{E[(\lambda f_T^* - \beta g_K^*)B^* + \sum_{i=1}^{T-1} (\lambda f_i^* - \lambda f_T^*)d_i + \sum_{j=1}^{K-1} (\beta g_K^* - \beta g_j^*)S_j]} \quad (31)$$

Regarding the Eq. (31), the paper will be divided into four scenarios as follows:

Case (i): If $\sum_{j=1}^K S_j \leq \sum_{i=1}^T d_i$ and $\sum_{j=1}^{K-1} S_j \leq \sum_{i=1}^{T-1} d_i$, then Eq. (31) can be written

$$\begin{aligned} \rho(T, K) &= \frac{E[(\lambda f_T^* - \beta g_K^*)(B^* - B) + \tau]}{E[(\lambda f_T^* - \beta g_K^*)B^* + \sum_{i=1}^{T-1} (\lambda f_i^* - \lambda f_T^*)d_i + \sum_{j=1}^{K-1} (\beta g_K^* - \beta g_j^*)S_j]} \\ &\leq \frac{E[(\lambda f_T^* - \beta g_K^*)S_K + (\lambda f_1^* - \lambda f_T^*)S_K]}{E[(\lambda f_T^* - \beta g_K^*)\sum_{j=1}^K S_j + \sum_{i=1}^{T-1} (\lambda f_i^* - \lambda f_T^*)d_i + \sum_{j=1}^{K-1} (\beta g_K^* - \beta g_j^*)S_j]} \\ &= \frac{E[(\lambda f_T^* - \beta g_K^*)]E[S] + \lambda \frac{T-1}{m+1} (u^+ - u^-)E[S]}{E[(\lambda f_T^* - \beta g_K^*)]E[KS] + \lambda \frac{T(T-1)}{2(m+1)} (u^+ - u^-)E[d] + \beta \frac{K(K-1)}{2(n+1)} (u^+ - u^-)E[S]} \\ &\leq \max \left\{ \frac{E[(\lambda f_T^* - \beta g_K^*)]E[S]}{E[(\lambda f_T^* - \beta g_K^*)]E[KS]}, \frac{\lambda \frac{T-1}{m+1} (u^+ - u^-)E[S]}{\lambda \frac{T(T-1)}{2(m+1)} (u^+ - u^-)E[d]} \right\} = \max \left\{ \frac{1}{K}, \frac{2E[d]}{E[S]T} \right\} \quad (32) \end{aligned}$$

Case (ii): If $\sum_{j=1}^K S_j \leq \sum_{i=1}^T d_i$ and $\sum_{j=1}^{K-1} S_j \geq \sum_{i=1}^{T-1} d_i$, then $\rho(T, K) \leq \frac{2E[d]}{E[S]K}$.

Case (iii): If $\sum_{j=1}^K S_j \geq \sum_{i=1}^T d_i$ and $\sum_{j=1}^{K-1} S_j \leq \sum_{i=1}^{T-1} d_i$, then $\rho(T, K) \leq \frac{2E[S]}{E[d]T}$.

Case (iiii): If $\sum_{j=1}^K S_j \geq \sum_{i=1}^T d_i$ and $\sum_{j=1}^{K-1} S_j \geq \sum_{i=1}^{T-1} d_i$, then $\rho(T, K) \leq \max \left\{ \frac{1}{T}, \frac{2E[d]}{E[S]K} \right\}$.

Observation 4: It is easy to see from Theorem 8 that this W-MTR mechanism is asymptotically efficient.

It is clear from the results of Theorem 8 that $\rho(T, K) \leq \varepsilon(\max \{ \frac{1}{T}, \frac{1}{K} \})$ tends to zero when T and K involved in the transaction tends to infinity. Therefore, the W-MTR mechanism proposed here is asymptotic efficient.

Theorem 9. The total trade volume B increases as the number of participating bids increases.

Proof. If inequality $\sum_{j=1}^{K-1} S_j \leq \sum_{i=1}^{T-1} d_i$ holds, then the $B' = \sum_{j=1}^{K-1} S_j$, and expected total trade volume $E[B'] = E[\sum_{j=1}^{K-1} S_j] = (K-1)E(S)$; If inequality $\sum_{j=1}^{K-1} S_j \geq \sum_{i=1}^{T-1} d_i$ holds, then the $B' = \sum_{i=1}^{T-1} d_i$, and expected total trade volume $E[B'] = E[\sum_{i=1}^{T-1} d_i] = (T-1)E(d)$. T and K denote the quantity of winning buyers and sellers determined by model P3. Obviously, the values of T and K obtained by model P3 are larger when there are more bidders in the W-MTR auction. Thus, Theorem 9 is proved.

Theorem 10. The parameter of the technical coefficient is able to increase the income of the platform.

Proof. Recall that if the platform does not introduce new technology, then the platform revenue is $(f_T^* - g_K^*)B'$; if the platform introduces new technology, then the platform revenue is $(\lambda f_T^* - \beta g_K^*)B'$. As $\lambda \geq 1$ and $0 < \beta \leq 1$, it is clear that $\lambda f_T^* \geq f_T^*$ and $\beta g_K^* \leq g_K^*$ hold. Thus, $(\lambda f_T^* - \beta g_K^*)B' \geq (f_T^* - g_K^*)B'$ holds. This theorem has practical implications, as reducing additional costs for buyers and sellers through the introduction of new technology increases the number of winning participants and the profitability of the platform.

5. Numerical experiments

This section is dedicated to numerical investigations to verify the performance of the proposed two-stage auction method, as well as to illustrate the applicability and effectiveness of the OA-VCG, W-GSPA and W-MTR mechanisms developed in this paper for the EVBR problem.

5.1. Experiments setting

In the numerical study, such a two-stage EVBR auction platform is under consideration. In the first stage of the auction, there are l recyclers who need to buy waste battery information, the platform announces the auction rules in advance and determines the choice of either the OA-VCG mechanism or the W-GSPA mechanism, then the sealed bids are collected from the recyclers and the platform determines the winner of the auction. In the second stage, assuming that the winners in the first stage are m buyers and n sellers directly auctioned via the platform, the platform will announce the rules of the W-MTR mechanism, the buyers and the sellers will submit their bids, and then the platform will determine the winning buyers and the winning sellers according to the P3 model and the auction transaction rules.

Without loss of generality, this paper assumes that the recycler l 's reservation price s_l obeys a continuous uniform distribution (CUD) in the interval $[9, 12]$ in the first stage. Assume that due to the existence of ChatGPT, each buyer l has a positive affine externality to all other buyers, i.e., γ_l is a random number on the interval $[1, 3]$. If the W-GSPA mechanism is used, then the reservation

prices of the platform obey a CUD in the interval [8, 14]. In the second stage, it is assumed that the buyer i 's reservation price f_i^* when the technology is not introduced obeys a CUD in the interval [7, 11], while the seller j 's reservation price g_j^* when the technology is not introduced obeys a CUD in the interval [9, 14]. Besides, buyer i 's demand d_i follows a discrete uniform distribution in the interval [1, 5], and seller j 's supply S_j follows a discrete uniform distribution in the interval [1, 3]. d_i and S_j can only be positive integers. It is worth mentioning that since the technical coefficients parameter λ and β is introduced in this paper, the reservation prices of buyers and sellers are given herein when the technical coefficient parameters are not introduced. Assumptions $\lambda = 1.2$, $\beta = 0.8$, the number of recyclers $L = 20$ in the first stage.

5.2. Performances of OA-VCG and W-GSPA mechanisms

If the platform determines ex ante the allocation quantity $w = 13$, then the maximum average value obtained by the model **P2** is 213.55 and the optimal average value obtained by the proposed OA-VCG mechanism is 135.41, and the satisfaction degree (SD), which denotes the ratio of platform returns to the model optimum, is 64.02 %. If the platform determines ex post the allocation quantity w , then the average optimal value obtained via the proposed W-GSPA mechanism is 159.75, and the average allocation quantity w is 13.3. Applying the ex post determined number of recyclers to the objective function of model **P1** yields a maximum average value of 174.19. Thus, the SD obtained by the W-GSPA mechanism is 91.71 %. Note that we do not consider the buyer's affine externality in the W-GSPA mechanism. Both mechanisms have their own advantages, and the platform has the choice of which one is appropriate for the situation at hand. For example, the OA-VCG mechanism can be used to determine the quantity in advance if there are fewer sellers in the second stage and more recyclers are expected to participate in the first stage.

Table 4 demonstrates the impact of changes in the number of recyclers on the OA-VCG and W-GSPA mechanisms. In the OA-VCG mechanism, if $w = 13$ remains constant, then the value of the objective function of model **P1**, the SD and the maximum social welfare achieved by the OA-VCG mechanism will increase as L increases. Because if w remains constant and the number of participants increases then this will lead to an increase in competition in the market and thus an increase in social welfare. In the W-GSPA mechanism, the maximum social benefit and w will increase as L increases, while the change in satisfaction level is not significant.

Table 5 shows the results when $L = 60$, $L = 80$, and $L = 100$ remain constant while the number of winning recyclers w increases. It can be seen that when L is held constant, SD increases as w increases in most scenarios. This is because the number of recyclers participating in the auction remains the same, i.e., under certain market size conditions, the platform is able to increase the competition in the market by increasing w , and therefore the platform is able to gain more revenue.

5.3. Performances of W-MTR mechanism

In the second stage of the auction, this paper considers a market for battery recycling in which there are more sellers than buyers, and we investigate a number of key indicators in the W-MTR mechanism: 1) the maximum value of the model **P3**; 2) the platform revenue; 3) the utility of buyers and sellers; 4) the total trade volume; and 5) allocation efficiency. Table 6 gives the results for pairs (10, 20), (20, 40), (30, 60), (40, 80) and (50, 100). As shown in Table 7, when m and n increase, the maximum value of model **P3** increases and the allocation efficiency achieved by the W-MTR mechanism increases from 94.08 % to 99.13 %. Additionally, the numerical results confirm Theorem 9 by showing that the total volume of transactions increases with the number of participants.

On a practical level, there are scenarios where the number of buyers or the number of sellers involved in the bidding process changes. A sensitivity analysis to changes in the number of buyers or sellers is performed to explore the impact of changes in the number of participants on the W-MTR mechanism, as shown in Table 7. Scenario 1 represents the result when m increases while n remains the same. Scenario 2 represents the result when m is held the same while n increases. When the number of parties involved in the auction remains the same and the amount of the other parties increases, the social welfare and the total trade volume will increase. When m increases and n remains constant, the utility of buyers does not increase exactly with m ; instead, the utility of sellers increases with m . For example, when m remains constant, the utility of seller is $E\left[\sum_{j=1}^{K-1} \varphi_j\right] = E\left[\sum_{j=1}^{K-1} (g_K - g_j) \times \min\{c_j, S_j\}\right]$. Obviously, the utility of sellers is related to $g_K - g_j$ and the volume of transactions, when as the number of sellers keeps increasing, the value of $g_K - g_j$ becomes smaller and smaller despite the increase in the volume of transactions, so the utility of sellers decreases. Besides, platform

Table 4
Impact of changes in the number of recyclers on the OA-VCG and W-GSPA mechanisms.

Mechanisms	L	w	$\pi(L)$	Platform revenue	SD
OA-VCG	20	13	213.55	123.28	57.73 %
	40		257.10	136.39	53.05 %
	60		298.40	142.27	47.68 %
	80		346.44	142.39	41.10 %
	100		387.64	144.30	37.22 %
W-GSPA	20	13.30	174.19	159.75	91.71 %
	40	26.22	344.85	313.98	91.05 %
	60	38.60	505.72	460.66	91.09 %
	80	54.30	715.41	652.35	91.19 %
	100	68.50	908.96	821.89	90.42 %

Table 5The effect of increasing w on SD in the OA-VCG mechanism.

w		5	15	25	35	45	55
$L = 60$	$\pi(L)$	193.61	331.79	464.66	591.96	711.73	824.70
	Platform revenue	51.41	143.02	230.24	300.28	358.62	408.00
	SD	26.55 %	43.11 %	49.55 %	50.73 %	50.39 %	49.47 %
$L = 80$	$\pi(L)$	228.85	367.72	502.01	631.91	757.71	879.07
	Platform revenue	50.18	144.83	233.05	311.55	383.38	452.83
	SD	21.93 %	39.39 %	46.42 %	49.30 %	50.60 %	51.51 %
$L = 100$	$\pi(L)$	275.41	415.25	551.08	683.78	813.03	938.46
	Platform revenue	50.59	147.08	238.22	321.82	401.57	470.97
	SD	18.37 %	35.42 %	43.23 %	47.06 %	49.39 %	50.19 %

Table 6

Calculated results for different numbers of participants.

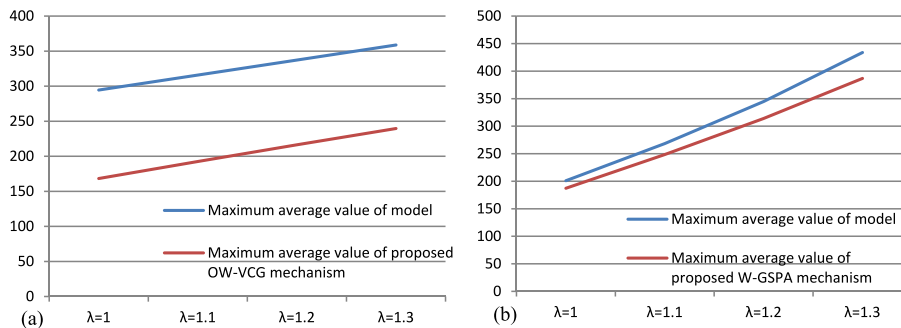
(m, n)	Maximum average value of P3	Platform revenue	Buyers' utility	Sellers' utility	Total trade volume	Allocation efficiency
(10,20)	64.87	9.34	30.36	21.33	24.41	94.08 %
(20,40)	145.29	10.76	81.68	48.39	38.63	96.93 %
(30,60)	217.53	12.16	129.95	72.92	66.17	98.85 %
(40,80)	291.42	13.42	178.41	96.48	87.96	98.93 %
(50,100)	355.33	14.71	217.72	119.81	111.57	99.13 %

Table 7

The result of a change in the number of buyers or sellers.

Scenario	(m, n)	Maximum average value of P3	Platform revenue	Buyers' utility	Sellers' utility	Total trade volume	Allocation efficiency
Scenario 1	(10,60)	92.69	14.35	54.75	18.76	27.13	94.79 %
	(20,60)	160.58	12.27	97.61	46.82	48.88	97.58 %
	(30,60)	216.82	11.46	129.95	72.92	66.17	98.85 %
	(40,60)	254.19	10.62	137.55	103.84	80.82	99.14 %
	(50,60)	292.76	11.56	136.19	143.29	93.61	99.41 %
Scenario 2	(20,20)	95.84	11.23	47.76	31.31	27.88	94.22 %
	(20,40)	145.29	10.76	81.68	48.39	38.63	96.93 %
	(20,60)	160.58	12.27	97.61	46.82	48.88	97.58 %
	(20,80)	169.59	13.21	112.25	41.34	51.46	98.35 %
	(20,100)	185.09	15.55	128.71	39.26	56.86	99.15 %

revenue does not vary monotonically, as platform revenue $(f_T - g_K) \times \min\{\sum_{i=1}^{T-1} d_i, \sum_{j=1}^{K-1} S_j\}$ is related to $f_T - g_K$ and $\min\{\sum_{i=1}^{T-1} d_i, \sum_{j=1}^{K-1} S_j\}$. When n remains constant, and the buyer increases, the value of $f_T - g_K$ changes more significantly than the value of $\min\{\sum_{i=1}^{T-1} d_i, \sum_{j=1}^{K-1} S_j\}$, so the platform revenue decreases, while with further increase of the buyer, the value of $f_T - g_K$ stabilizes, while the value of $\min\{\sum_{i=1}^{T-1} d_i, \sum_{j=1}^{K-1} S_j\}$ is increasing, so the platform revenue increases.

**Fig. 4.** The effect of λ changes on: a) the OA-VCG mechanism; and b) the W-GSPA mechanism.

5.4. Impact of technical coefficient parameter on mechanisms

This paper is validated by setting up several sets of numerical experiments to further analyze the effect of the technical coefficient parameters λ and β on the results, as follows: 1) the effect of increasing λ from 1 interval of 0.1 to 1.3 on the OA-VCG and W-GSPA mechanisms; 2) The effect of changes in parameters λ and β , respectively, on the W-MTR mechanism; and 3) the effect on the W-MTR mechanism when λ increases by 1.3 from 1 interval 0.1 while β decreases from 1 interval 0.1 to 0.7. Furthermore, the number of buyers is 40 ($w = 20$) in the OA-VCG and W-GSPA mechanism, and the number of buyers and sellers is $(m, n) = (40, 60)$ in the W-MTR mechanism. Fig. 4 shows the effect of changes in λ on social welfare and the model maximum for the OA-VCG and W-GSPA mechanisms. Apparently, in the OA-VCG and W-GSPA mechanisms, the technical coefficients may benefit the buyers, and the maximum social welfare achieved by the proposed mechanisms increases with the increase in the technical coefficients. In the OA-VCG mechanism, the maximum value of model P3 is $\sum_{i=1}^w \lambda s_i Z_i + \gamma_i$. Clearly, when w is fixed, the maximum value increases as λ increases.

The effect on the W-MTR mechanism when $\lambda = 1.2$ is held constant and β is decreased from 1 to 0.7, is shown in Fig. 5(a); and the effect on the W-MTR mechanism when $\beta = 0.8$ is held constant and λ is increased from 1 to 1.3, is shown in Fig. 5(b). The introduction of the new technology has contributed to the optimal value of model P3, platform revenue, participant utility and trading volume, showing a linear trend for the main indicators in the W-MTR mechanism.

The effect of simultaneous changes in λ and β on the W-MTR mechanism is shown in Fig. 6. We can find that as the technical coefficient parameter λ increases, a decrease in β can increase social welfare, platform revenue, participant utility and total trading volume in the W-MTR mechanism. Indeed, an increase in the technical coefficient parameter λ corresponds to an increase in the valuation range of the buyer, while a decrease in the technical coefficient parameter β corresponds to a decrease in the valuation range of the seller, thus allowing more buyers and sellers to become winners, which will significantly increase the total trade volume. Besides, the difference between the price λp_T^* paid by the buyer and the amount βg_K^* received by the seller is likely to be greater and, therefore, the average value of the platform's returns will increase.

6. Discussion

Based on the above theoretical analysis and numerical experiments, this section will discuss the comparative study of the introduction of technical parameters, the advantages of the proposed EVBR smart system and provide several interesting managerial implications.

6.1. Comparative study on whether to introduce technical parameters

The transformative impact of introducing the technical coefficient parameter in the comparative analyses is lucidly presented in Table 8. Delving into its revelations, we unravel the following pivotal conclusions: 1) A comprehensive consideration of both the technological parameters and the affine externality of buyers amidst the advent of ChatGPT unveils a notable decrease in the platform's revenue, juxtaposed with a promising surge in total social welfare. Notably, the platform's profits remain steady only when assessing the direct effect of ChatGPT's implementation on outcomes, fortifying the amplified social welfare. 2) A compelling revelation surfaces as all mechanisms resonate with the simultaneous elevation of social welfare and the platform's profits, synchronized with an augmentation in the number of buyer participants. This illuminates the dire need for both platforms to proactively thrive in attracting a larger pool of participants into the bidding process, while underscoring the transformative potential of new technologies to engender a ripple effect of positive affine externalities.

6.2. Advantages of proposed EVBR smart system

Given the remarkable findings derived from our rigorous numerical experiments and the outstanding performance exhibited by the groundbreaking method proposed in this research, we can summarize the multitude of advantages that our EVBR smart system brings to the integration of ChatGPT's two-stage auction.

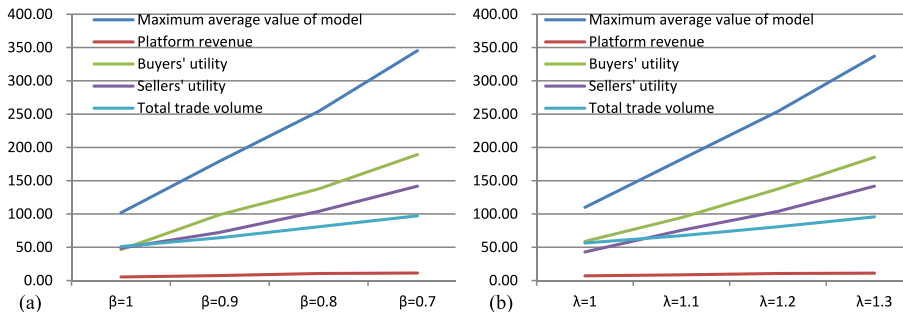


Fig. 5. Parameters (a) $\lambda = 1.2$, β change; and (b) $\beta = 0.8$, λ change on the W-MTR mechanism.

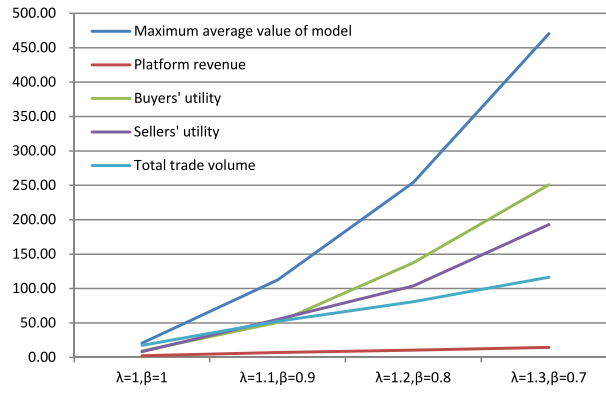


Fig. 6. Effects of different combinations of λ and β changes on the W-MTR mechanism.

Table 8

Comparative analysis including and excluding the technical coefficient.

Model	Mechanisms	L	w	$\pi(L)$	Platform revenue	SD
$\max \sum_{i=1}^X \lambda s_i Z_i + \gamma_l$	OA-VCG	20	13	213.55	123.28	57.73 %
		40		257.10	136.39	53.05 %
		60		298.40	142.27	47.68 %
		80		346.44	142.39	41.10 %
		100		387.64	144.30	37.22 %
$\max \sum_{i=1}^X \lambda s_i Z_i$	Traditional second price auction	20	13	173.20	131.41	75.87 %
		40		178.71	142.30	79.63 %
		60		181.88	146.99	80.82 %
		80		182.69	148.40	81.23 %
		100		183.70	149.78	81.54 %
$\max \sum_{i=1}^X s_i Z_i$	Traditional second price auction	20	13	144.34	131.41	91.04 %
		40		148.92	142.30	95.55 %
		60		151.56	146.99	96.98 %
		80		152.24	148.40	97.48 %
		100		153.09	149.78	97.84 %

Firstly, recyclers' concerns about the performance of end-of-life batteries are addressed by the two proposed matching mechanisms. It is difficult for recyclers to provide an accurate bid value based solely on the battery attribute information uploaded by the waste battery owner, as the value of a waste battery is closely related to the remaining capacity of the battery. A third party evaluation company or platform can collect battery information from sellers interested in selling and provide their evaluation report beforehand, and the platform will match the battery information evaluation report with a suitable buyer, removing the hurdle of having to evaluate battery performance for buyers. In fact, there are already useful practical attempts to address buyer concerns about the trade in waste batteries. For example, the auto auction chain Manheim is investing in facilities to address the battery concerns of potential bidders at car auctions.

Secondly, the proposed EVBR intelligent system is easy to use and can have a cost reduction effect for the participants. ChatGPT is an intelligent dialogue system based on natural language processing technology, which has proven to be a powerful advantage in intelligent dialogue (Lund and Wang, 2023). In this paper, ChatGPT technology is introduced into EVBR auctions to alleviate potential participant concerns. In addition, the two-stage intelligent auction system built in this paper can reduce costs for participants, for example, the lack of an online auction trading platform for previous transactions can make it more expensive (e.g. time, money, etc.) for sellers and buyers to conduct transactions. More importantly, in the proposed two-stage EVBR auction system, bidding truthfully is the best strategy for bidders, so they only need to be truthful bidding to get the maximum utility without a lot of other tedious operations, making it very easy to use.

Thirdly, the proposed mechanisms of the OA-VCG, the W-GSPA and the W-MTR are capable of setting flexible trading prices for the participants in an uncertain market environment. Some sellers may exploit information asymmetries to the detriment of buyers due to the potential recycling value of end-of-life batteries; however, the proposed mechanism can solve this problem and realize EVBR's real-time market value. Moreover, the proposed mechanisms have the potential to maximize social welfare and therefore, in terms of their superior performance, will be an incentive for more participants in EVBR.

However, despite the many conveniences and potential benefits of an integrated ChatGPT and two-stage EVBR auction system, there are some potential risks. For example, ChatGPT may provide inaccurate or misleading answers, especially when dealing with complex or controversial issues. This could lead to users being misinformed or generating misleading opinions. The potential for content bias and discrimination may exist in ChatGPT because if biased and discriminatory content is present in the ChatGPT model's training data, then it may be reflected in its answers. This may lead to unfair treatment or influence the user's opinion. To counter these

risks, efforts need to be made to improve model training in future deployments of ChatGPT technology to ensure more accurate, unbiased and secure results. More importantly, users should also maintain a modicum of scepticism and self-judgment and not rely solely on ChatGPT responses.

6.3. Managerial implications

A number of interesting management insights from a practical point of view are provided for managers in the battery recycling market.

First, from an economic point of view, the proposed EVBR market based on two-stage auctions is beneficial for platforms, recyclers and owners of waste batteries. Due to the unique advantages of the proposed mechanism in terms of IC, IR, BB, AE, etc., more waste battery owners and recyclers will be incentivized to join the EVBR market. Recyclers and owners of waste batteries can operate the system by simply submitting a truthful bid, significantly reducing transaction and information access costs. It is noteworthy that in the first stage of the matching mechanism, when the platform collects the evaluation report of waste batteries, the platform's revenue is the maximum average of proposed mechanisms. Otherwise, the platform has no revenue at this stage and the platform will benefit from the difference between the sum of the price paid by the buyer and the sum of the amount received by the seller in the second stage of the auction.

Second, since the two matching mechanisms proposed in the first stage can effectively regulate the number of winning recyclers, the number of buyers in the second stage can be changed to better match the number of sellers and ensure the sustainable development of the platform. Although under-supply and over-supply in the W-MTR mechanism can increase platform benefits, this may harm some participants in the long run and is not conducive to the sustainable development of the platform. Fortunately, the proposed OA-VCG mechanism allows for an ex-ante determination of the number of recyclers, whereas the proposed W-GSPA allows for an ex-post determination of the number of recyclers. Decision-makers can regulate the number of recyclers through the OA-VCG mechanism on the basis of historical data on the number of owners of waste batteries who participate.

Third, this paper introduces technology coefficient parameters to characterize the impact of new technologies on participants and platforms. However, a more precise value for the technology factor parameter is difficult for decision makers to give in practice. Nevertheless, numerical experiments have shown that the introduction of new technologies can have a positive impact on stakeholders, and that decision makers can make more technical efforts to improve the trading environment, the trading process, etc. in order to increase participant satisfaction and achieve an efficient and convenient battery recycling trading system.

6.4. Practical implications

There are important practical implications to the integrated ChatGPT and two-stage auction approach for the EVBR market proposed in this paper. First, the paper effectively designs two matching mechanisms, taking into account buyers' concerns about the performance of used batteries. The platform or a third-party appraisal company gives the battery performance assessment report of the waste battery owner in advance and matches this information to the suitable buyer, thus addressing the barriers to the performance assessment of waste batteries. Once the buyer has access to the appraisal report, they may place a bid at the appropriate reserved price in the second stage of the auction. Second, the introduction of ChatGPT technology can have a positive impact on the participants. For example, some participants may be unfamiliar with the auction mechanism, the auction process, etc., so ChatGPT can give sensible answers to questions about the auction mechanism. Third, although the proposed two-stage auctions method can achieve efficient EVBR recovery, the applicability of the proposed mechanism is insufficient if an integrated ChatGPT and two-stage auctions method cannot be developed to apply this mechanism. To this end, this paper develops a ChatGPT-enabled two-stage auctions EVBR management system to ensure the full process management of battery recycling. Thus, the proposed ChatGPT-enabled two-stage auctions EVBR management system can contribute to EVBR market.

7. Conclusions

Battery recycling has become an increasingly important issue in both academic and industrial circles as a result of a dramatic rise in end-of-life electric vehicle batteries. This paper proposes an EVBR management system integrating ChatGPT and a two-stage auction model to address the shortcomings of the battery recycling process to achieve efficient battery recycling, and introduces the technology factor parameter to characterize the impact of ChatGPT on participant value. In the first stage of auction, this paper considers a platform (or third-party valuation company) that collects waste batteries attributes information from sellers interested in selling them, and then matches this information to buyers. Two matching mechanisms, which called OA-VCG auction and W-GSPA, are designed to determine ex-ante and ex-post the number of buyers, respectively. The winning buyers in the first stage will enter the second stage auction, and a W-MTR mechanism is proposed. The numerical experimental results show that the two-stage auction approach proposed in this paper is not only effective in addressing the concerns of the buyers about the performance of the batteries, but also in allocating the retired battery resources in an efficient way. We also observe that the introduction of ChatGPT technology can benefit both platforms and participants. Finally, this paper presents several interesting management implications for stakeholders in the battery recycling market.

It is worth mentioning that although the numerical experiments herein show the effectiveness of the proposed method, there are still some limitations that require more effort in future research. First, the two-stage auctions considered in this paper are independent of each other, but in practice there may be scenarios where they are not independent of each other. For example, the buyer's total

reserve price for the purchase of a unit of waste batteries is the sum of the reserve prices of the two stages, i.e. $\hat{v} = \hat{v}_1 + \hat{v}_2$. As long as $\hat{v}$ remains the same, then the buyer is free to allocate the values of $\hat{v}_1$ and $\hat{v}_2$. Thus, an important future research direction is to study the bidding strategies of bidders in linked two-stage auctions. Second, this paper considers different categories of batteries as homogeneous. Indeed, different categories of batteries may have different recycling values. To this end, the types of batteries could be subdivided in future research to explore the issue of the auctioning of more than one type of battery. Third, an attempt is made to include more realistic constraints or objective functions in the proposed model, such as the satisfaction of the buyer and the seller. The platform cannot be sustainable development without the support and satisfaction of the participants, so future research on realistic constraints such as the satisfaction and support of the participants to the platform may make the model more challenging, but it will also make the research more interesting. A final interesting research direction is to explore the nexus of GPT technology providers, platform operators and platform participants via analytical and empirical methods.

CRedit authorship contribution statement

Jianghong Feng: Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Yu Ning:** Visualization, Validation, Software, Investigation, Data curation. **Zhaohua Wang:** Visualization, Software, Resources, Investigation. **Guo Li:** Validation, Supervision, Software, Resources, Data curation. **Su Xiu Xu:** Conceptualization, Formal analysis, Investigation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

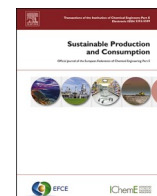
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Review Article

Moving towards a circular economy: A systematic review of barriers to electric vehicle battery recycling

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ABSTRACT

In view of the fact that the rapidly growing number of electric vehicles around the world will result in more used batteries, how to efficiently recycle used batteries has become an important issue for sustainable development practices. Recognizing that the recycling of used batteries is affected by many factors, there is an urgent need to clarify the barriers to recycling used batteries. The lack of systematic reviews has led to an incomplete understanding of the barriers to battery recycling and a failure to effectively integrate the results and perspectives of various studies. In this paper, a systematic literature review has been conducted according to the PRISMA systematic review checklist to explore the current state of scientific research on the factors influencing the recycling of used batteries in order to summarize the potential barriers to the recycling of used batteries. By analyzing 92 articles from Web of Science and Google Scholar, this study identifies the key factors affecting the recycling of used batteries, including six dimensions: technology, economy, society, environment, policies and regulations, and supply chain, and systematically analyses the barriers within each dimension. Furthermore, this paper highlights several potential future research directions to further overcome these barriers, i.e. the need for comprehensive influencing factor studies, recycling network optimization, consumer behavior, policy effectiveness assessment, recycling market mechanisms, life cycle assessment, case studies, battery life data and cross-industry collaboration. These research directions provide practical guidance for researchers to further explore the recycling of used batteries and provide insights for practice and research towards a circular economy.

1. Introduction

Electric vehicles play a crucial role in driving the transition to renewable energy in the transport sector (Feng et al., 2024c). By reducing reliance on fossil fuels, electric vehicles help to reduce carbon emissions, promote decarbonization of transport and contribute to the achievement of global climate goals (Xu et al., 2023). The promotion of electric vehicles is therefore an important step towards achieving sustainable transport and reducing carbon emissions (Zhao et al., 2024c). Many countries have introduced public policies to motivate more consumers to buy electric vehicles (Biresselioglu et al., 2018; Qadir et al., 2024; Stekelberg and Vance, 2024). However, as the number of electric vehicles increases year by year, the number of end-of-life electric vehicle batteries also shows a growing trend (Qiao et al., 2021). For example, a survey by the European Commission suggests that by 2030 there will be more than 1.1 million end-of-life batteries from electric vehicles (Statista, 2018). Jiang et al. (2021b) estimated that by 2040, China will

have 15–33 million tonnes of end-of-life electric vehicle batteries, using a forecasting methodology. Crespo et al. (2022) explored Catalonia's future end-of-life electric vehicle battery numbers and showed that the number of end-of-life electric vehicle batteries could increase by up to 72 times by 2040. Managing the recycling of large numbers of end-of-life electric vehicle batteries is therefore critical to sustainable development (Feng et al., 2024b).

It is universally acknowledged that if retired power batteries are not properly handled, they will inevitably bring serious harm to the ecological environment and human health (Mrozik et al., 2021). Depending on the status of the retired electric vehicle battery, secondary utilization can be an effective solution or, if the end-of-life battery is no longer of use, recycling the rare metals in the battery can be advantageous (Hertel et al., 2024). Both secondary utilization and recycling the rare metals have a positive impact in dealing with end-of-life electric vehicle batteries (Choi and Rhee, 2020). Nevertheless, retired power battery recycling still faces significant challenges (Hantanasirisakul and

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Sawangphruk, 2023). For example, despite the huge potential of the recycling market, the recycling industry is still in the early stages of development, and recycling facilities, recycling channels, market demand, and recycling modes have led to a low battery recycling rate (Baum et al., 2022). To this end, a series of comprehensive measures must be taken to promote the recycling and secondary utilization of retired power batteries to meet the challenges currently faced.

However, before effective measures can be developed to promote battery recycling, the various factors affecting the recycling of used electric vehicle batteries need to be identified. These factors include not only challenges at the technical level, such as the efficiency and cost of recycling technologies (Beaudet et al., 2020; Cong et al., 2021), but also changes in market demand, as well as consumer awareness and participation in recycling (Tang et al., 2023). Furthermore, the support of policies and regulations (Hoarau and Lorang, 2022), the layout and accessibility of recycling facilities (Nguyen-Tien et al., 2022), as well as the smoothness of recycling channels all have a significant impact on the overall effectiveness of battery recycling. Therefore, it is particularly necessary to study the analysis of barriers to battery recycling in electric vehicles in this context. With the popularity of electric vehicles, the battery waste problem becomes more and more prominent. However, the current battery recycling rate is still low, which is mainly hindered by various aspects such as technology, economy, policy and social acceptance. Technologically, the complexity and high cost of existing recycling methods limit their further recycling; economically, there is insufficient market demand for recycled materials; policy-wise, the lack of uniform regulations and incentives in many countries leads to insufficient willingness of enterprises to invest in recycling; and social acceptance is reflected in the lack of consumers' knowledge about battery recycling, which affects the participation in recycling behavior. Therefore, a literature review that delves into these barriers aims to identify and analyze the key factors affecting battery recycling, providing a theoretical basis and practical guidance for promoting EV battery recycling. By understanding these barriers, effective solutions can be provided to policy makers, industry participants and consumers to promote the sustainable development of the battery recycling industry.

This paper is motivated by the lack of systematic literature analyzing the current barriers to recycling of used power batteries. There is a body of literature analyzing the barriers to the recycling of used batteries from various perspectives. However, there is no comprehensive and systematic compendium of these studies. For example, Feng et al. (2024a) identified twenty barriers to the recycling of retired electric vehicle batteries through literature and expert opinion, however did not analyze the obtained barriers in a categorical manner. Tripathy et al. (2024) explored the organizational, technological and environmental dimensions of the factors influencing the recycling of retired batteries, without considering economic and social factors. Further, Tripathy et al. (2023) investigated the key drivers for the recycling of retired electric vehicle batteries from economic, social and environmental perspectives. Liu and Gong (2014) investigated through simulation methods that factors such as battery reconditioning rate, electric vehicle life, and battery reconditioning time have an impact on the recycling of used batteries. Different studies may focus on specific factors, such as technological challenges, economic feasibility, policies and regulations, and consumer behavior, but few studies organically combine these factors for a comprehensive analysis. Furthermore, research methods and data sources in the existing literature vary, resulting in compromised comparability and consistency of findings. Some studies may focus on quantitative analyses, while others may adopt qualitative research methods, lacking interdisciplinary perspectives and comprehensive considerations. A systematic review of the existing literature is thus needed to identify the key barriers to the recycling of end-of-life power batteries.

Through a systematic review of the barriers to the recycling of used electric vehicle batteries, this paper aims to provide a comprehensive

framework for policymakers, industry practitioners and researchers to understand the complexity of the recycling process of used electric vehicle batteries and thus facilitate the development and implementation of efficient solutions to promote the sustainability of battery recycling. To the best of our knowledge, the existing literature still has some shortcomings in this area, lacking systematic analyses and comprehensive guidance frameworks that can comprehensively reveal the various barriers faced in the recycling process of used electric vehicle batteries. Consequently, this paper will fill this gap and provide theoretical support and practical guidance for future research and practice.

This paper provides a framework for guidance through a literature review to identify the key factors that influence the recycling of batteries. Therefore, this review paper makes the following contributions to the literature. First, this paper identifies the key factors affecting battery recycling through an in-depth review of relevant literature. This involves not only systematically collating and analyzing existing research, but also comprehensively comparing studies from different fields to identify key barriers and challenges in the battery recycling process. To the best of our knowledge, no previous studies have systematically and comprehensively identified barriers to the recycling of used electric vehicle batteries. Secondly, this paper discusses specific measures to enhance the recycling efficiency of end-of-life electric vehicle batteries, such as strategies in technological innovation, policy incentives, market mechanisms, and public participation. Through these analyses, this paper hopes to provide a guiding framework that offers practical references and suggestions for policy makers, industry practitioners and researchers in promoting the sustainable development of battery recycling. Last but not the least, in light of the urgency of recycling end-of-life electric vehicle batteries, this paper explores future research directions to promote recycling of end-of-life electric vehicle batteries, helping the recycling industry to take more effective actions in addressing battery recycling challenges.

The rest of the paper is structured as follows. Section 2 presents the methodology of the systematic literature review. Section 3 explores in detail the results of the analyses of the screened literature. Section 4 discusses the benefits of used electric vehicle battery recycling, policy and regulatory insights, and highlights key directions for future research. Finally, conclusions are given in Section 5.

2. Literature review methodology

The literature review methodology for constructing barriers to the recycling of end-of-life electric vehicle batteries and the analysis of the characteristics of the retrieved literature will be given in this section.

2.1. Literature search

In order to find the existing literature related to the barriers to recycling of used electric vehicle as much as possible, this paper conducted a search of relevant literature based on Web of Science database

Table 1
Literature search scheme in the database Web of Science and Google Scholar.

Database	Scheme	Description
Web of Science	Search in Language	Web of Science Core Collection English
	Document types	Article and review article
	Timespan	2000-01-01 to 2024-07-01
	Search fields	Topic
	Search keywords	barriers OR influencing factors AND electric vehicle battery recycling OR EV battery recycling
Google Scholar	Language	English
	Document types	Article and review article
	Search keywords	challenges OR setbacks AND electric vehicle battery recycling OR EV battery recycling

and Google Scholar, and their search scheme are shown in Table 1. Google Scholar serves as a database to supplement the collection of literature, therefore, challenges, setbacks, electric vehicle battery recycling, and EV battery recycling are considered in this paper in terms of search terms. All searches were conducted on 1 July 2024 and the literature published to date was evaluated in later analysis.

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method was used to identify and process relevant literature (Moher et al., 2009; Page et al., 2021), as shown in Fig. 1. Firstly, 298 documents were collected from Web of Science using the search strategy in Table 1, and 181 documents were collected through Google Scholar, and then duplicates were excluded to obtain 368 documents. Then, by reviewing the titles, keywords and abstracts of the 368 documents, 265 documents that were not relevant to this paper were excluded, resulting in a preliminary list of 103 documents. After a comprehensive review of the 103 documents, the final number of documents that could be used for the literature review of this paper was 92. It is worth mentioning that during the full-text review process, as long as at least one factor related to the impact of end-of-life battery recycling is mentioned in the full text, it can be shortlisted. Finally, the 92 shortlisted papers were analyzed in a comprehensive manner to categorize the mentioned influencing factors and suggest potential future research directions for priorities to overcome the barriers to end-of-life battery recycling.

2.2. Literature characteristics

In order to analyze the publication of the factors affecting the recycling of used power batteries over the years, this paper plots the number of publications per year related to the factors affecting the recycling of used electric vehicle batteries, as shown in Fig. 2. In terms of the

disciplines involved in the literature, they include different fields such as chemistry, materials science, energy, circular economy, operations management, and transport, which are intertwined and have contributed to the research and practice of recycling used batteries in a sustainable manner, especially in response to global climate change and resource scarcity. In terms of year of publication, the amount of literature on the research topic of barriers to electric vehicle battery recycling showed a trend of growth followed by decline in the last decade. In particular, with the popularity of electric vehicles and the rise of renewable energy sources, there has been a growing interest in the recycling of end-of-life electric vehicle batteries in both academia and industry. In recent years, more and more studies have begun to focus on various aspects of end-of-life battery recycling, including advances in recycling technology, the development of policies and regulations, the establishment of market mechanisms, and the assessment of environmental impacts. During this period, the quantity of related literature has increased, and researchers have gradually realized that the recycling of end-of-life electric vehicle batteries is not only a technical issue, but also a complex system involving various aspects such as economy, society and environment. Many studies have explored the assessment of the environmental impact of battery recycling, the analysis of the environmental benefits of recycling technologies, the market mechanism, policy incentives and economic feasibility of battery recycling, and other aspects of comprehensive research. Overall, research on the factors influencing the recycling of waste electric vehicle batteries has been diversified in the context of multidisciplinary crossover, reflecting the wide attention and multidimensionality of research in this field. The year 2021 has the highest number of relevant publications, as can be seen in Fig. 2, and although publications are growing, they also seem to be stagnating in recent years. This stagnation may reflect the growing maturity of research in the field, leading to a gradual stabilization of new

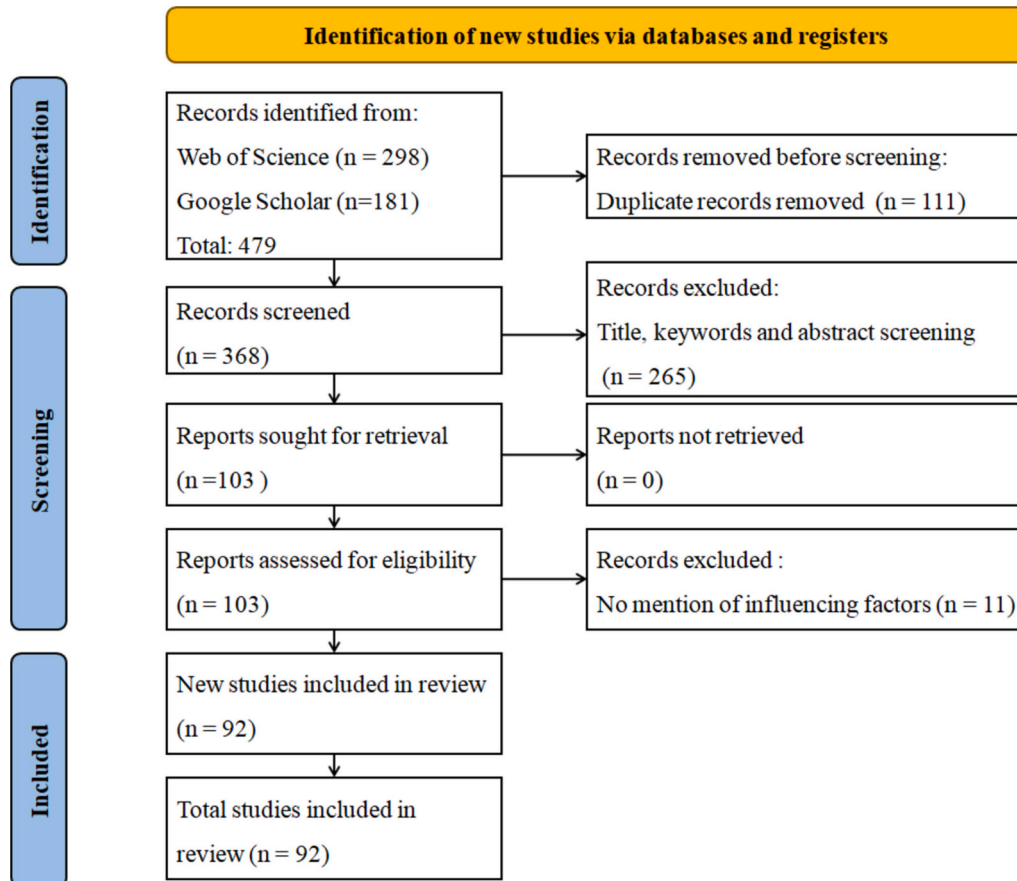


Fig. 1. PRISMA flowchart overview.

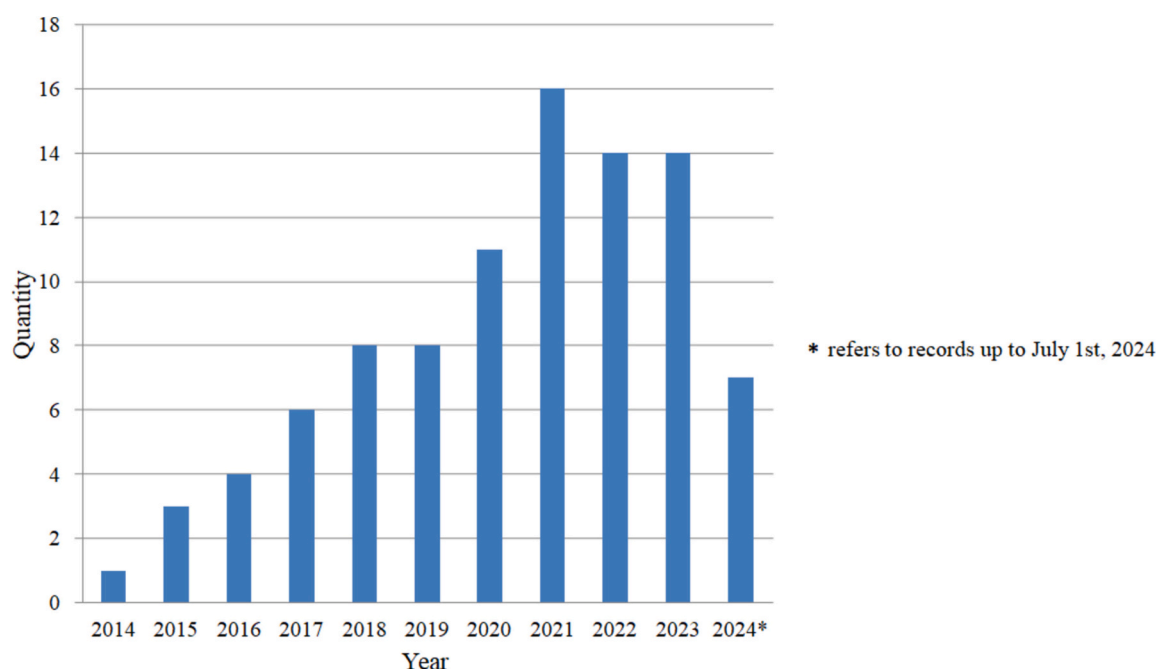


Fig. 2. Number of publications per year.

research in quantitative terms. This is surprising considering the importance of the research topic of analyzing barriers to the recycling of used electric vehicle batteries. However, it may be that there is a lack of a guiding framework on the analysis of barriers to recycling of used electric vehicle batteries or further exploration of the topic, and for this reason it further highlights the need and importance of the research in this paper.

3. Results

By reviewing and analyzing the relevant literature, this paper classifies the barriers to the recycling of decommissioned batteries into the following dimensions, as shown in Fig. 3. The next subsections provide a comprehensive analysis of the relevant literature findings following the organizational structure in Fig. 3.

3.1. Technical barriers to battery recycling

Technology is critical to the sustainability of large-scale recycling of used electric vehicle batteries. Gautam and Bolia (2024) argued that the key to achieving recycling of used electric vehicle batteries lies in addressing the technical challenges. However, current recycling technologies are less than rational and there are still many challenges to overcome (Chen et al., 2019).

3.1.1. Maturity of recycling technology

Regarding the recycling of end-of-life power batteries, the general process includes (as shown in Fig. 4), firstly, the application of specialized equipment to test and assess whether the waste power batteries can be used directly as secondary batteries; secondly, if they cannot be used directly, the valuable materials in the end-of-life power batteries are extracted through recycling technologies. It is well known that used batteries for electric vehicles do not completely deplete the remaining power and can still be used for secondary purposes if properly managed, e.g., household energy storage, electric motorbikes, communication base stations, etc. Only after they are fully depleted should they be dismantled to recover or recycle their internal materials. It is worth noting that the most commonly cited figure for the battery recycling rate is about 5 % (Baum et al., 2022). Besides, a minimum recycling rate of

50 wt% for lithium-ion batteries is required in the European Union regulation (Directive 2006/66/EC) and is proposed to reach 70 wt% by 2030 (Vanderbruggen et al., 2022). The recovery of iron, nickel, cobalt, etc. varies from one recovery process to another. For example, Huang et al. (2009) studied the pyrometallurgical recovery process of scrap nickel-cadmium batteries, and the results showed that the recovery rates of cadmium, iron, nickel and cobalt reached 99.2 %, 99.2 %, 96.1 % and 86.4 %, respectively. Huang et al. (2019) recovered metals such as cobalt, lithium and manganese from spent lithium ions by bio-electro-hydrometallurgical process with recoveries of 91.45 %, 93.64 % and 87.92 % respectively. He et al. (2017) explored a leaching process for the recycling of used batteries, and the recovery of Li, Co, Ni and Mn metals was able to reach 97 %.

Besides, this section will focus on the batteries recycling technologies. Waste electric vehicle battery recycling technologies are technologies and methods for the collection, treatment and reuse of retired or discarded electric vehicle batteries. These technologies are designed to efficiently and safely extract valuable materials (such as lithium, cobalt, nickel, etc.) from batteries and to reduce the impact on the environment. Fig. 5 lists commonly used technologies for the recycling of waste batteries (Kang et al., 2023). Classified according to the attributes of waste battery recycling technologies, they include physical recycling technologies, biological recycling technologies, chemical recycling technologies and electrochemical recycling technologies, and each recycling method has its unique characteristics and applicability. Current battery recycling technologies are still in the research and development stage and have not yet been realized for large-scale application (Leon and Miller, 2020; Neumann et al., 2022). For example, an innovative lithium battery recycling technology is growing rapidly due to the relative simplicity of the process, its low cost and its environmental friendliness (Hantanasirisakul and Sawangphruk, 2023). Existing technologies make it difficult to meet the rapidly growing demand for battery recycling due to limitations in recycling efficiency, cost and environmental impact (Zeng et al., 2015). For example, there are technical and market challenges in the stepwise utilization of retired batteries. The technical challenge is that there are batteries with multiple technical standards on the market, so the health status of the batteries must be assessed and tested according to their design standards (Yu et al., 2022b). The main technical barriers to the recycling of spent batteries are therefore the

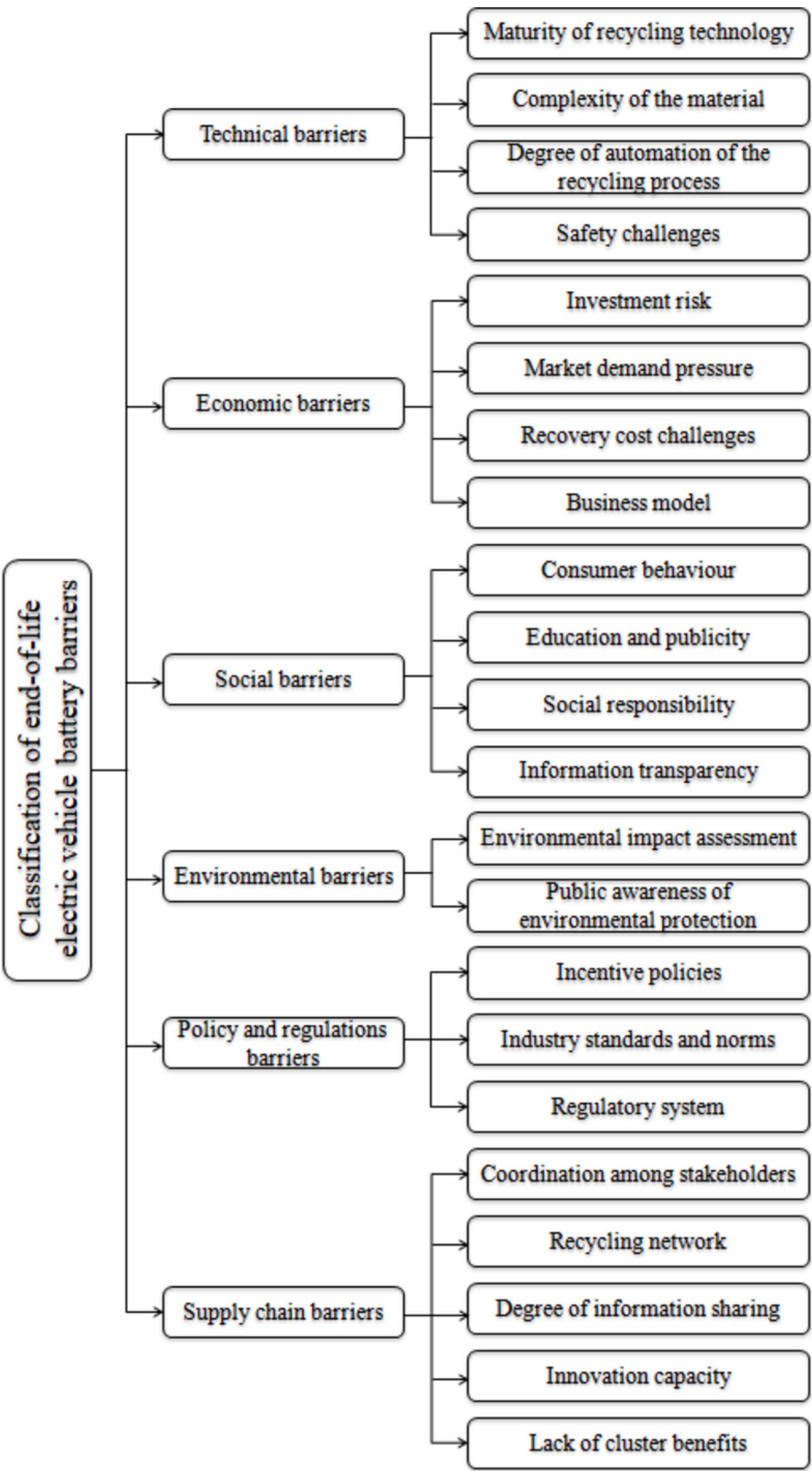


Fig. 3. Classification of obstacles in relevant publications.

safety of the batteries, the assessment of their health status and the screening and restructuring of the batteries (Hua et al., 2021). Additionally, electric vehicles use different types of batteries (e.g., lithium-

ion batteries, nickel-metal hydride batteries, etc.) (Mohammadi and Saif, 2023), and recycling technologies and processes vary greatly between different types of batteries, for example, lithium-ion batteries and

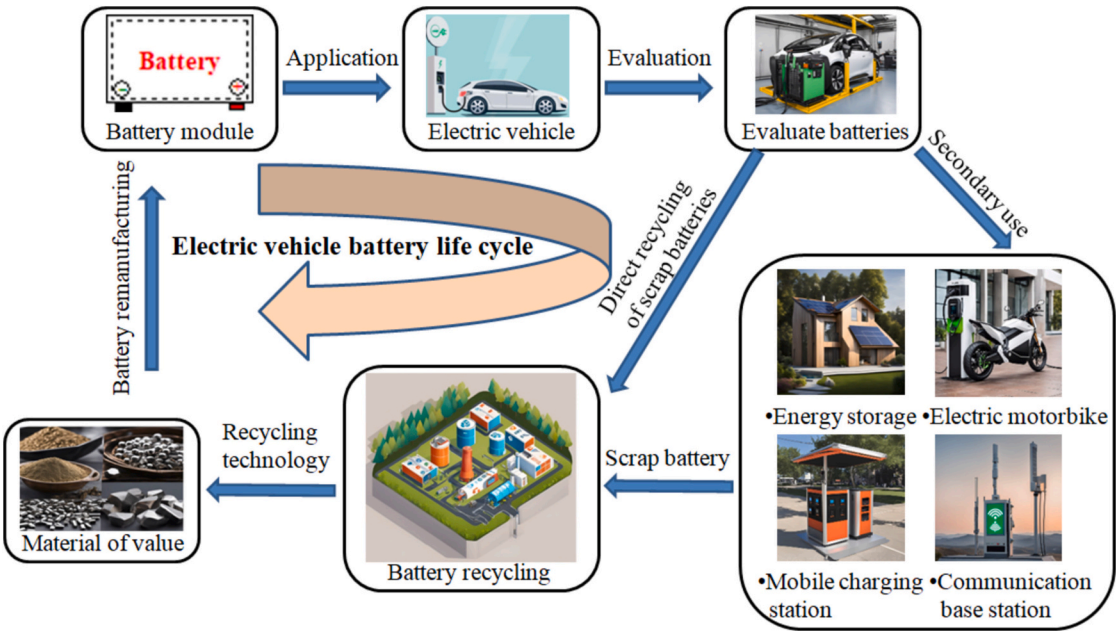


Fig. 4. Electric vehicle battery life cycle.

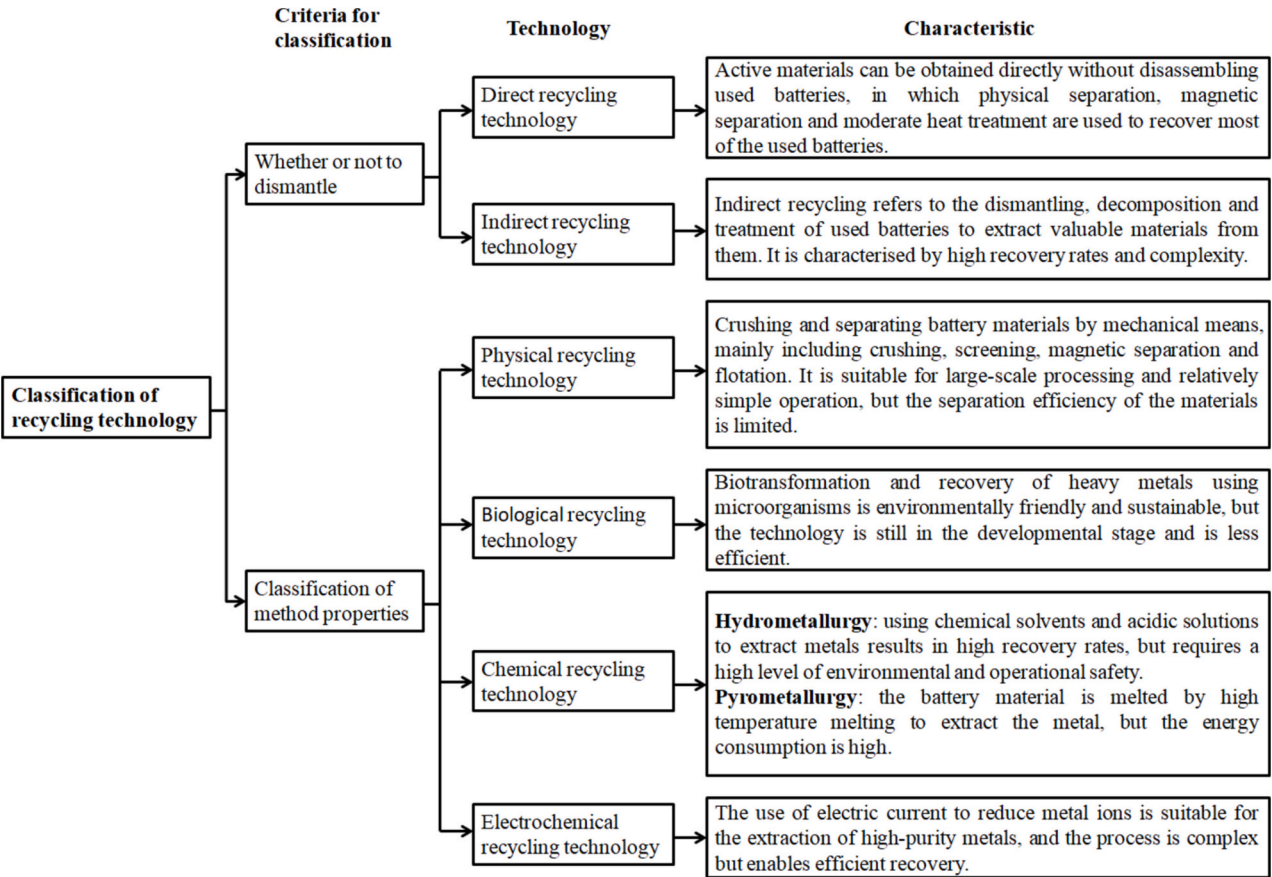


Fig. 5. Classification of waste electric vehicle battery recycling technologies.

lead-acid batteries have very different recycling processes. Lithium-ion batteries are usually recycled through chemical recycling technology, which involves complex steps such as dismantling the battery, extracting the electrolyte, and using an acidic solution to extract metals such as lithium, cobalt, and nickel, a process that not only requires specialized

equipment and technicians, but also strict control of the chemical reaction to ensure safety and environmental protection. In contrast, the recycling of lead-acid batteries is relatively simple, mainly through physical recycling techniques involving mechanical crushing and separation of lead and acid. Although the technical requirements are lower,

acidic waste solutions still need to be disposed of to avoid environmental pollution. Therefore, the type and composition of batteries directly affects the choice of recycling method and the complexity of implementation, increasing the difficulty of the overall recycling technology. Table 2 summarizes the recycling methods for different battery types (Toro et al., 2023).

3.1.2. Complexity of the material

Electric vehicle batteries are usually composed of a variety of materials, including lithium, cobalt, nickel, aluminum, manganese and copper (Andersson and Råde, 2001; Salgado et al., 2021). These metallic materials play an important role in the energy storage and release process of batteries. In the case of lithium-ion batteries, for example, their internal structure contains different active and inactive chemicals, and this diversity not only enhances the overall performance of the batteries, but also makes the recycling process of lithium batteries more complex. This complexity further hinders the construction and improvement of the lithium-ion battery recycling system (Neumann et al., 2022). A battery with an average capacity of 60 kW-hours (kWh) was found in a research study to contain approximately 185 kg of minerals, excluding the electrolyte, binder, separator and materials in the battery pack casing (Bhutada, 2022). Table 3 summarizes the metal-mineral content in different types of 60 kWh lithium-ion batteries (Bhutada, 2022).

During the recycling process, since these materials have different chemical and physical properties, a number of different technologies and methods are required to efficiently separate and extract the valuable materials. This not only increases the cost of recycling. Although there are many different types of batteries, the main components include and cathode (or positive electrode), anode (or negative electrode), electrolyte, current collector and separator (Feng et al., 2023; Miranda et al., 2023; Nasajpour-Esfahani et al., 2024). In addition, components such as thermal management systems, current limiting devices, etc. depend on the specific battery chemistry and intended application. It should be noted that the battery casing, which provides physical protection, is also an important component. Each type of battery has a unique chemistry and material composition, making it necessary for recyclers to organize the recycling process according to the characteristics of the battery during dismantling. Table 4 summarizes the material composition of different types of electric vehicles batteries, showing the differences in composition between the various types of batteries. For example, lithium metal oxides such as LiCoO_2 , LiNiO_2 , LiMn_2O_4 , $\text{LiMn}_{1/3}\text{Ni}_{1/3}\text{Co}_{1/3}\text{O}_2$, LiFePO_4 , and LiNiCoAlO_2 are commonly used in the manufacture of cathodes for lithium batteries, and polymers such as polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) have been used as binders (Rostami et al., 2022). Besides, solid-state batteries have yet to be commercialized on a large scale as a potential solution for future electric vehicles (Janek and Zeier, 2023). It is worth mentioning that effective separation of valuable materials in used batteries is a major challenge in the recycling process (Zhou et al., 2023). Silveira et al. (2017) utilized electrostatic separation to efficiently recover valuable materials from spent lithium batteries, and this method may

Table 2
The recycling methods for different battery types.

Battery types	Recycling technology	Challenges
Alkaline, Ni—Cd, Ni-MH, Lithium-ion	Mechanical separation	Pure metal cannot be recovered, further refining is required
	Pyrometallurgy	Requires high energy consumption and produces harmful emissions
	Hydrometallurgy	Complex process, large amount of reagents and wastewater treatment required
All Battery Types	Biotechnological methods	The technology is still in its early stages
All Battery Types	Direct recycling	Business model immaturity

Table 3

Mineral content in different types of 60 kWh lithium-ion batteries (Unit: kilogram).

Materials	NMC811 battery	NMC622 battery	NMC523 battery	NCA+ battery	LFP battery
Lithium	5	6	7	6	6
Cobalt	5	11	11	2	0
Nickel	39	32	28	43	0
Manganese	5	10	16	0	0
Aluminum	30	33	35	30	44
Copper	20	19	20	17	26
Steel	20	19	20	17	26
Iron	0	0	0	0	41
Graphite	45	50	53	44	66

Note: NMC811 battery indicates 80 % nickel, 10 % manganese, 10 % cobalt in the cathode composition; NMC622 battery indicates 60 % nickel, 20 % manganese, 20 % cobalt in the cathode composition; NMC523 battery indicates 50 % nickel, 20 % manganese, 30 % cobalt in the cathode composition; NCA+ battery indicates that the cathode material composition is nickel cobalt aluminum oxide; LFP battery indicates that the cathode material composition is lithium iron phosphate.

become one of the promising methods to efficiently recover materials from spent lithium batteries. However, as mentioned earlier there are many types of used scrap electric vehicle batteries and there is still a need for further development of effective separation methods to obtain the important materials in the batteries (Ordoñez et al., 2016). As a result, existing technologies are still deficient in separation efficiency and purity, which affects the quality and market competitiveness of recycled materials.

3.1.3. Degree of automation of the recycling process

Many different types of electric vehicle batteries do not have a standardized design, making disassembly and recycling more difficult (Hellmuth et al., 2021; Meng et al., 2022). The lack of harmonized standards makes the recycling process take more time and resources, increasing costs. Indeed, these batteries are not designed for easy disassembly and reuse (O'Neill, 2021). In addition, the encapsulation of batteries is often designed to be complex for safety and durability, and the dismantling process may involve the use of specialized tools and techniques, increasing the technological threshold. More importantly, the variety and uncertainty of decommissioned batteries makes battery disassembly a major challenge that hinders their recycling (Wegener et al., 2015; Zhao et al., 2024a). Disassembly is the first step in recycling battery materials, and therefore, good battery disassembly is critical for subsequent disposal (Wang et al., 2023b). For example, disassembly should be cost-effective, which is a prerequisite for battery materials to be competitive in the market (Rallo et al., 2020). Choux et al. (2024) argued that automation of the battery dismantling process is key to the development of its recycling scale, and an inevitable response to the future of large-scale decommissioning battery recycling.

Nevertheless, automated dismantling and manual dismantling of end-of-life batteries have their own advantages and disadvantages, and the choice of the appropriate dismantling method depends on factors such as the size of the enterprise, the type of recycled batteries and market demand. Although there may be technical and cost barriers to automated dismantling at present, with the advancement of technology, the cost of automated dismantling is expected to be reduced, and its flexibility and adaptability will continue to improve, and it may gradually replace manual dismantling as the mainstream method of battery recycling (Lu et al., 2023; Yu et al., 2022a). At the same time, a hybrid disassembly method combining manual and automated disassembly may also become an effective solution to balance efficiency and flexibility (Tian and Chen, 2016; Xiao et al., 2023).

3.1.4. Safety challenges

The safety challenges of recycling end-of-life batteries are mainly

Table 4
Material composition of different types of electric vehicles batteries.

Types	Cathode material	Anode material	Electrolyte	Diaphragm
Lithium ion battery	Lithium cobalt oxide (LiCoO ₂), Nickel cobalt manganese oxide (NCM), Nickel cobalt aluminum oxide (NCA)	Graphite (C)	Consists of three types of substances: lithium salt, solvent and additives (e.g. LiPF ₆ , LiBF ₄ , LiBOB)	Polyethylene (PE) or Polypropylene (PP)
Lithium iron phosphate battery	Lithium iron phosphate (LiFePO ₄)	Graphite (C)		
Nickel-metal hydride battery	Nickel-metal hydride (NiMH)	Hydrogen adsorption alloys	Potassium hydroxide (KOH) aqueous solution	Polyethylene (PE)
Solid State Batteries	Lithium ion conductor (e.g. LiCoO ₂)	Lithium metal or graphite	Solid state electrolyte (sulphide or oxide)	Solid-state electrolyte

reflected in a number of aspects (Amusa et al., 2024). First, used batteries contain a variety of hazardous substances, such as lead, cadmium, heavy metals such as lithium and cobalt, and corrosive electrolytes. If these substances are leaked during the recycling process, they may cause serious contamination of soil and water sources, which in turn affects the ecosystem and human health. Therefore, how to handle these hazardous components safely and effectively is an important challenge (Alamerew and Brissaud, 2020). Secondly, the lack of safety standards for used batteries during recycling, handling and transport poses a risk of fire and explosion, especially for lithium-ion batteries (Sopha et al., 2022). When batteries suffer physical damage, short circuit or overheating, they may cause fire or explosion, posing a danger to operators and the surrounding environment. Furthermore, improper storage conditions, such as high temperatures or humidity, can increase the risk of spontaneous combustion. Furthermore, in terms of personnel safety, operators without adequate professional training may be exposed to chemical exposure and other safety risks when handling end-of-life batteries. For example, according to the United States Environmental Protection Agency report, between 2013 and 2020, more than 240 fires caused by lithium-ion batteries occurred in 64 factories (Environmental Protection Agency, 2024). In addition, failure to wear appropriate personal protective equipment can further increase the probability of accidents. In this regard, the recycling of waste batteries faces multiple safety challenges that need to be urgently addressed through technological innovation, policy improvement and public education in order to ensure the safety and sustainability of the recycling process (Catton et al., 2019).

3.2. Economic barriers to battery recycling

The economic influences on electric vehicle battery recycling mainly include investment risks, market demand pressures, recycling costs and business models, which are interrelated and together affect the sustainable development of the recycling industry.

3.2.1. Investment risk

The investment risk challenge of battery recycling is an important issue facing the recycling industry today, affecting the profitability of companies and market development (Beaudet et al., 2020). With the popularity of electric vehicles and the increasing number of spent batteries, the market potential of battery recycling is huge, but the ensuing investment risks cannot be ignored. First, technological uncertainty is one of the main investment risks. Battery recycling technology is still under constant development, and existing recycling processes and methods may not be able to meet future changes in battery types and sizes. When choosing the technology to invest in, enterprises often face problems such as lack of technological maturity and inefficiency, which may result in the R&D investment failing to realize the expected return. In addition, the R&D cycle of new technologies is long, and enterprises need to find a balance between technology development and market demand, which undoubtedly increases the uncertainty of investment (King and Boxall, 2019). Second, fluctuations in market demand are also a risk factor that cannot be ignored. Although the demand for battery

recycling is gradually rising, future changes in market demand may be affected by a variety of factors, including sales of electric vehicles, adjustments in policies and regulations, and consumers' concern for sustainable development. If market demand fails to grow as expected, companies' returns on investment will be seriously affected. In addition, increased competition is also an important challenge. As the electric vehicle market continues to develop rapidly, more and more companies are entering the battery recycling business and competition is becoming fierce. This not only leads to the dilution of market share, but also may trigger a price war, further compressing the profit margins of enterprises. Companies need to constantly innovate and improve their competitiveness to keep up with changing markets. Finally, the risk of capital chain should not be ignored. The construction and operation of battery recycling facilities require a large amount of capital investment, and if enterprises fail to effectively manage the flow of funds, it may lead to a break in the capital chain, affecting the continuity of operations. Therefore, battery recycling investment risk challenges are multifaceted and complex, and companies need to fully assess technology, market, policy, competition and capital factors when making investment decisions to reduce risk and achieve sustainable development.

3.2.2. Market demand pressure

Market demand pressure is an important factor affecting the recycling of electric vehicle batteries. For example, Azadnia et al. (2021) explored the barriers to the implementation of lithium battery recycling for electric vehicles and showed that market and society are among the biggest barriers to battery recycling. With the popularity of electric vehicles, the number of used batteries has increased dramatically. Hossain et al. (2019) argued that the barrier of insufficient market demand for the secondary use of batteries could be overcome by continued investment in expanding the market. Rising sales of electric vehicles have directly driven demand for battery recycling services. However, the battery recycling industry has yet to establish a comprehensive recycling system to meet this challenge and satisfy market demand (Albertsen et al., 2021). Besides, consumers are increasingly concerned about the environment and many want to participate in battery recycling to support sustainable development. Market demand for recycling services is driven by this change in consumer awareness. Companies may face a decline in market share if they fail to meet consumer expectations for environmentally friendly recycling. More importantly, companies must constantly innovate and optimize their services to meet changing customer needs in an increasingly competitive marketplace. In this competitive environment, companies need to be flexible and responsive to market changes in order to remain competitive and profitable.

3.2.3. Recovery cost challenges

High recycling costs have become a key barrier to the sustainable development of the battery recycling industry (Gautam and Bolia, 2024; Kurdve et al., 2019; Sopha et al., 2022). Recycling costs are highly dependent on transport distances, dismantling costs, recycling process costs, etc. Table 5 summarizes the share of different cost types in the

battery recycling process in different countries. First, battery recycling involves complex technologies and processes. From collection and transportation to dismantling and material recovery, each step requires specialized equipment and technical support, resulting in a high investment in operations. The process of dismantling batteries requires the use of specialized tools and technicians, and these high costs have a direct impact on the profitability of companies (Rallo et al., 2020). Secondly, batteries contain precious metals such as lithium, cobalt and nickel. Although these metals can be reused after recycling, the extraction process is not simple and often requires advanced technology and equipment. This means that companies must invest heavily in research and development and equipment upgrades to ensure that the recycling process is efficient and environmentally friendly, thus adding to the cost burden. In addition, market price fluctuations also affect the economics of recycling to a certain extent (Richa et al., 2017). The market price of battery raw materials fluctuates. When metal prices fall, the economic attractiveness of recycling is weakened and companies face the risk of falling profits, which affects their incentives to recycle. It should be noted that consumer awareness and participation in battery recycling also has a direct impact on costs. Without active consumer participation, collection and transport costs for businesses will increase, reducing overall recycling efficiency and therefore the economy.

3.2.4. Business model

The lack of mature business models is one of the important factors affecting electric vehicle battery recycling (Albertsen et al., 2021; Tripathy et al., 2024), which is mainly reflected in several aspects. Firstly, the technology and process of battery recycling is relatively complex, involving the separation and treatment of a wide range of materials, but many companies do not yet have a standardized and scalable operating process in place, resulting in inefficient and costly recycling. In addition, the uncertainty of market demand puts companies at risk when investing in recycling facilities and technologies, and consumers' low awareness of and participation in battery recycling results in unstable recycling volumes. Although there have been some studies exploring battery recycling models (Wu et al., 2024), further exploration is needed as battery recycling involves many stakeholders. It is also difficult for the business model to be sustainable due to the lack of effective recycling channels (Yu et al., 2022b). On the other hand, imperfect regulatory policies limit the development of business models, and the lack of mandatory regulations and incentives makes it difficult for companies to invest in recycling, resulting in a lack of motivation and direction for recycling activity (Costa Lima et al., 2022). Furthermore, the lack of competition and the scarcity of participants in the market also limit the innovation of business models and efficiency improvement, the limited number of recycling enterprises and the lack of effective competition mechanism make the industry overall lack of vitality. Therefore, promoting the maturity of business models in the field of battery recycling is crucial to enhancing recycling efficiency, promoting resource reuse and achieving sustainable development (Wralsen et al., 2021). Table 6 lists business model challenges and future research for recycling key raw materials for

Table 5
summarizes the percentage of different cost types (Lander et al., 2021).

Cost types	Percentage of total costs	Country
Transport cost	7–13 %	China
	2 %	Belgium and the UK
Disassembly cost	Depending on the recycling method	South Korea and the US
	2 %	China
	5–7 %	South Korea
	8–11 %	US
	15–21 %	Belgium
Recycling process costs	12–17 %	UK
	75 %–90 %	–

lithium batteries (Wesselkämper and Von Delft, 2024).

3.3. Social barriers to battery recycling

The social influences on electric vehicle battery recycling include consumer behavior, education and publicity, social responsibility and information transparency.

3.3.1. Consumer behavior

The impact of consumer behavior on electric vehicles battery recycling is reflected in a number of key aspects. Firstly, consumers' knowledge and awareness of battery recycling directly affects their willingness to participate in recycling (Dong and Ge, 2022). Consumers are more likely to participate actively in recycling activities if they are aware of the importance of battery recycling, its environmental benefits and its impact on resource recycling (Tang et al., 2023). For example, consumers with a strong environmental awareness are more likely to be concerned about recycling and reusing batteries (Islam et al., 2022), while those who are indifferent to environmental issues may ignore this responsibility. Secondly, consumers' attitudes and values play a decisive role in this process. Consumers with a strong environmental philosophy are more inclined to actively participate in battery recycling. Subsidies and rewards for battery recycling can also effectively motivate consumers and promote their active participation (Cheng et al., 2021; Wei et al., 2022). At the same time, the attitudes of public around them and discussions on social media may influence consumers' decisions.

Table 6
Business model challenges and future research for recycling key raw materials for lithium batteries.

No.	Challenges	Descriptions	New model drivers	Future research
1	Scalable business model	Insufficient inputs; uncertainty about the quantity of used batteries	• Modelling of used batteries using predictive techniques • Building close co-operation with stakeholders	• Forecasting studies incorporating big data • Study of partnerships in the battery circular economy
2	Recycling process efficiency	Long pre-processing times not only increase the cost of labour and equipment usage, but can also lead to higher storage costs.	• Battery standardization • Automated pretreatment technology • Stakeholder support • Artificial intelligence technology	• Researching new ways to save costs in battery pre-processing • Research into battery recycling incorporating artificial intelligence technology • Research on design methods favorable to battery recycling
3	Waste battery recycling system	High logistics and warehousing costs due to lack of cluster effects	• Optimizing the location of recycling plants • Recycling sites and consumer participation in recycling • Co-operation with local logistics providers	• Research on optimal recycling system based on triple bottom line • Recycling network optimization study • Study on customer participation in recycling activities

Another issue of concern is that social media, by providing a platform for information dissemination and interaction, has to some extent increased consumer awareness of and participation in battery recycling, thus prompting the public to actively participate in recycling activities (Li et al., 2023b; Sujata et al., 2019). Meanwhile, success stories and advocacy campaigns on social media can motivate consumers to take action, thereby increasing the overall recycling rate (Jiang et al., 2021a). To this end, understanding the multidimensional characteristics of consumer behavior can help to develop more targeted recycling strategies, thus promoting the effective implementation of electric vehicles battery recycling and achieving resource recycling and environmental protection.

3.3.2. Education and publicity

Lack of public knowledge and insufficient dissemination of information on recycling of used batteries, many consumers do not have sufficient understanding of the importance and specific processes of battery recycling, resulting in low motivation to participate in recycling (Tian et al., 2015). The lack of systematic education and publicity means that the public may not be sufficiently aware of the environmental hazards of batteries and may therefore ignore the need to recycle them. Sun et al. (2015) studied consumer behavior in the recycling of used batteries through a questionnaire method and stressed the importance of education in promoting the recycling of used batteries. Besides, inadequate information channels can also affect the recycling of used batteries. For example, although social media and advertisements are effective promotional tools, the recycling participation rate will be affected if the information does not reach all target audiences (Feng et al., 2024a). The complexity or lack of clarity of the promotional content may also confuse consumers and discourage them from participating in waste battery recycling activities. It is worth noting that the general lack of attention to environmental issues in society makes it difficult to attract sufficient publicity for battery recycling. Thus, the lack of education and publicity not only affects public awareness and participation, but also may lead to the inefficient operation of the electric vehicles battery recycling system, which is one of the obstacles to achieving sustainable development.

3.3.3. Social responsibility

Social responsibility is seen as an obstacle to the recycling of electric vehicle batteries. This is mainly in the form of a lack of awareness of corporate and consumer participation in environmental initiatives. Currently, many automakers and battery manufacturers, in their quest to maximize profits, may neglect their social responsibility to recycle batteries and lack the motivation to proactively implement recycling plans. Enterprises should take social responsibility and actively integrate into the supply chain network of waste battery recycling (Song et al., 2017). This lack of responsibility can lead to an inadequate recycling system and difficulties for consumers to find reliable recycling channels. There is also low consumer awareness about battery recycling, with many people believing that recycling is a corporate responsibility rather than a personal one. This mentality makes the public pay less attention to recycling after electric vehicles batteries are used, resulting in a low recycling rate. The lack of clear regulations and policy support may also cause companies to under-invest in retired battery recycling (Liu and Zhu, 2024), further weakening the implementation of social responsibility. The lack of social responsibility can also lead to poor information transfer. As a result, consumers do not understand the recycling process and channels. For this reason, the lack of social responsibility not only affects the participation of enterprises and consumers, but also the effective recycling of retired batteries.

3.3.4. Information transparency

Information transparency is seen as one of the barriers affecting the recycling of electric vehicle batteries. Many consumers are confused about how to participate in recycling when they dispose of their

batteries because they are not aware of the specific steps and requirements for battery recycling. This information asymmetry makes consumers less motivated, which in turn affects the recycling rate of retired batteries (Zhang et al., 2023b). If companies do not provide sufficient transparency on battery recycling, consumers will not be able to clearly understand the specific actions and commitments made by companies in the recycling process and will lack confidence in their environmental responsibility. For example, if companies fail to disclose their recycling data or recycling plans, consumers may question the authenticity and effectiveness of their recycling. In addition, a lack of consistency and clarity in the information provided by government and industry organizations can also lead to ambiguity in the public's perception of battery recycling (Crenna et al., 2021). Providing transparent information not only builds consumer confidence, but also effectively encourages them to participate, thereby improving overall recycling efficiency. More importantly, the lack of information transparency may also lead to a decrease in the importance society attaches to battery recycling, further hindering the implementation of related policies. Therefore, improving information transparency in the electric vehicles battery recycling process is crucial to enhancing public participation (Júnior et al., 2022).

3.4. Environmental barriers to battery recycling

Environmental barriers affecting the recycling of retired batteries include environmental impact assessment and public awareness of environmental protection.

3.4.1. Environmental impact assessment

Environmental impact assessment not only provides a systematic analysis of the potential impacts of the battery recycling process on ecosystems and human health, but also identifies the environmental risks associated with the battery recycling process (Wang and Yu, 2021), such as releasing heavy metals and hazardous chemicals, which can contaminate soil and water if not properly managed. Therefore, identifying and mitigating these risks and ensuring the safety and sustainability of the recycling process can be achieved by conducting an appropriate environmental impact assessment. Besides, an environmental impact assessment can help to evaluate the environmental benefits of different recycling technologies and methods, provide a scientific basis for companies and policy makers, and encourage the implementation of more environmentally friendly recycling plans. The lack of effective environmental impact assessment may lead to enterprises neglecting environmental protection in the recycling process, increasing the ecological burden and ultimately affecting the realization of sustainable development goals. Therefore, incorporating environmental impact assessment into the decision-making process of electric vehicles battery recycling can help ensure that recycling activities are carried out under the premise of protecting the environment and promote the green transformation and development of the electric vehicles battery recycling industry (Picatoste et al., 2022).

Pyrometallurgy is currently a widely used method for metal extraction from used batteries, and despite its outstanding performance in metal recovery efficiency, its high energy consumption has attracted widespread attention (Rajaeifar et al., 2021). Pyrometallurgy typically requires melting at high temperatures, which not only requires significant energy inputs, but also relies on fossil fuels, resulting in significant carbon emissions (Harvey et al., 2022). Such peaks in energy demand make pyrometallurgy a serious challenge in terms of sustainability. In addition to energy issues, pyrometallurgy may release large amounts of harmful gases and heavy metals during the process, causing air and water pollution (Faraji et al., 2022). For example, exhaust gases such as sulphur dioxide and nitrogen oxides generated during the smelting process will pose a threat to the surrounding environment and the health of residents if they are not effectively treated. On the other hand, although hydrometallurgy is relatively low in energy consumption, the

chemical reagents and solvents used in it also pose potential environmental risks (Chagnes and Pospiech, 2013; Jung et al., 2021). The process of hydrometallurgy often requires the use of strong acids or bases, and these chemicals can pollute the environment when not handled properly. In addition, the treatment and discharge of waste liquids is also a complex issue. If waste liquids are discharged directly without compliant treatment, they will have a serious impact on water bodies, leading to a decline in water quality and affecting biodiversity. Therefore, it is necessary to further improve the environmental impact assessment of the waste battery recycling process.

3.4.2. Public awareness of environmental protection

Environmental awareness is directly related to consumers' willingness and behavior to participate. Public awareness and attitudes towards battery recycling and batteries is increasingly becoming a key driver of recycling activities as global concerns for sustainable development and environmental protection grow. A high level of environmental awareness motivates consumers to pay more attention to the use and disposal process of batteries, and thus actively participate in recycling. On the contrary, a lack of public awareness of environmental issues may lead to a lack of understanding of the importance of battery recycling, thus reducing the recycling rate (Cao et al., 2016). In addition, the public's environmental awareness also affects the expectation and monitoring of the performance of enterprises and the government in the field of battery recycling (Feng et al., 2024a). Enterprises are more likely to adopt proactive recycling measures and transparent recycling processes to enhance their brand image and sense of social responsibility when faced with consumers' environmental demands. As well as increasing public participation in battery recycling, raising environmental awareness encourages companies and governments to adopt more effective environmental policies and practices.

3.5. Policy and regulations barriers to battery recycling

Policy and regulations barriers affecting the recycling of retired batteries include incentive policies, industry standards and norms, and regulatory system.

3.5.1. Incentive policies

Incentive policies are directly related to the motivation and participation of businesses and consumers in the recycling process (Tang et al., 2019). Effective incentive policies can boost recycling rates through financial incentives, tax breaks, subsidies and convenient recycling channels, encouraging companies to invest in battery recycling technologies and facilities and lowering the cost of ownership (Costa Lima et al., 2022; Guo et al., 2022; Hao et al., 2022; Li et al., 2019; Li et al., 2020). For example, governments can implement subsidy policies for battery producers and recycling companies to promote the development of more efficient recycling technologies that reduce environmental impacts (Chen et al., 2022; Tang et al., 2024; Zhu et al., 2024). Meanwhile, incentive policies can also raise public environmental awareness by rewarding consumers for their recycling behavior and encouraging them to take the initiative to participate in battery recycling. Consumers are more willing to return used batteries to professional recycling organizations when they receive financial rewards or convenient services. In addition, the incentive policy can accelerate the development of the battery recycling industry by promoting competition among enterprises, encouraging the improvement of industry standards and creating a favorable market environment (Gu et al., 2017b). Although some incentive policies have been introduced to promote the recycling of retired batteries, the existing incentive policies may only be short-term measures that lack long-term support and guarantee to motivate enterprises to continuously invest in recycling technologies and facilities. In addition, the implementation effect of the incentive policies varies significantly across regions and markets, with the lack of appropriate infrastructure and services in some regions preventing the policies from

working as intended. Therefore, it is difficult to realize a win-win situation between economic benefits and environmental protection without a sound incentive policy (Nie et al., 2024).

3.5.2. Industry standards and norms

Battery recycling industry standards are not uniform, leading to large differences in the operating procedures and technical requirements of recycling enterprises around the world (Kumar et al., 2021). There is also a lack of specific operational guidance, making it difficult for enterprises to follow effective processes in actual recycling (Feng et al., 2024a). Clear industry standards can provide operational guidelines for recycling companies to ensure that safe battery recycling and disposal procedures are followed, reducing environmental pollution and potential safety risks. The lack of standards for the recycling of retired batteries may lead to companies taking improper measures during the recycling process, resulting in the leakage of hazardous substances or waste of resources. Establishing battery recycling standards and norms can also promote fair market competition, prevent the emergence of non-compliant enterprises, protect the interests of law-abiding enterprises and promote healthy industry development. Meanwhile, understanding and trusting industry standards increases consumers' willingness to participate in battery recycling activities and improves their green credentials. Therefore, the development and implementation of a comprehensive set of industry standards and norms for battery recycling can not only enhance the overall level of recycling work, but also promote the recycling of resources and environmental protection, and facilitate the sustainable development of the electric vehicle industry.

3.5.3. Regulatory system

A robust regulatory system can ensure that battery recyclers comply with laws and regulations and prevent non-compliance (Deshwal et al., 2022). For example, clear regulatory requirements can motivate companies to dismantle and dispose of batteries in accordance with environmental standards, thereby reducing the risk of pollution to the environment (Winslow et al., 2018). Li et al. (2021) argued that the unclear definition of the competence of government departments to regulate the disposal of used batteries greatly affects battery recycling. Bhuyan et al. (2022) argued that inadequate regulation is a key factor affecting the recycling of used batteries. The effectiveness of the regulatory system is also reflected in the uniform management of the market, which can deter unscrupulous companies from gaining advantages through illegal means, protect the legitimate rights and interests of law-abiding companies, and promote fair competition. In addition, through regular inspections and evaluations, the regulatory system can ensure that the operations of recycling companies meet industry standards, thereby improving the overall efficiency and quality of recycling. Simultaneously, a sound regulatory mechanism can strengthen public confidence in battery recycling, stimulate consumer participation awareness, create a good social atmosphere and promote battery recycling popularity. With the rapid development of the electric vehicle market, the challenges facing battery recycling are also increasing, and the regulatory system needs to keep pace with the times and adjust its policies in a timely manner to cope with new situations, such as the use of new battery materials and the advancement of recycling technologies (Beaudet et al., 2020).

3.6. Supply chain barriers to battery recycling

Supply chain barriers affecting the recycling of retired batteries include coordination among stakeholders, recycling network, degree of information sharing, innovation capacity, and cluster benefits.

3.6.1. Coordination among stakeholders

Coordination between stakeholders is essential to promote battery recycling, as battery recycling involves many stakeholders, including

vehicle manufacturers, recycling companies, government regulators, consumers and environmental organizations (Albertsen et al., 2021). For example, if there is effective communication and collaboration between vehicle manufacturers and recycling companies, then the recyclability of battery design can be ensured and the recycling rate can be increased (Guo et al., 2022). Manufacturers should also consider the ease of recycling batteries when designing products to reduce the difficulty and cost of recycling at a later stage. There is a need for government regulators to work closely with all stakeholders to develop clear policies and standards that will promote the synergistic development of the battery recycling industry. Meanwhile, only through coordination among stakeholders can the public be effectively guided to participate in battery recycling, forming a social consensus and increasing the amounts of decommissioned batteries recycled. Environmental organizations also play an important role in raising social awareness of battery recycling through publicity and education, and promoting joint efforts by all parties. It is therefore only through coordination and cooperation between stakeholders that a synergy can be created to solve the complex problems of battery recycling and achieve efficient use of resources and environmental protection.

3.6.2. Recycling network

The battery recycling network is one of the most important factors affecting the recycling of electric vehicle batteries, as an efficient and wide-coverage recycling network can significantly improve the convenience and effectiveness of battery recycling. Many studies have been devoted to the optimization of battery recycling networks (Chai et al., 2024; Zhang et al., 2023a). For example, Li et al. (2023a) discussed the retired battery recycling network optimization problem from the perspective of cross-network cooperation, and constructed a mixed-integer nonlinear planning model. Li et al. (2023c) applied a game theory approach to explore the optimal strategy problem of joint recycling of used batteries. Wang et al. (2023a) explored the inclusion of third-party companies in the battery recycling network, constructed a mathematical optimization model, and validated the model with real case data. Lin et al. (2023) studied the regulatory strategy of battery recycling, focusing on the dual-channel supply chain of battery recycling. Limited recycling infrastructure for used batteries restricts network optimization (Dunn et al., 2021; Mossali et al., 2020). In order to promote battery recycling, these studies have shown that well-established recycling networks are essential. In addition, the effective operation of a recycling network not only relies on the layout of physical facilities, but also requires the support of information technology, such as the provision of real-time recycling information and services through mobile applications or online platforms, to further facilitate consumer participation (Choi and Rhee, 2020). Therefore, there is a need to build an efficient and convenient battery recycling network (Grandjean et al., 2019; Slattery et al., 2024), which not only promotes the recycling of batteries, but also promotes the sustainable development of the entire industry, and ensures that the dual objectives of rational allocation of

resources and environmental protection are realized. Table 7 outlines the barriers to building a recycling network for used batteries and the corresponding measures to address them.

3.6.3. Degree of information sharing

Transparent and efficient information flow can facilitate collaboration and communication among various stakeholders (Feng et al., 2024a). Information sharing among vehicle manufacturers, recyclers, government agencies and consumers can ensure a smooth battery recycling process. For example, manufacturers can provide information on the type of battery and its recycling requirements, which can help recycling company to optimize the process and reduce recycling costs and time (Xiao et al., 2024b). Government agencies can guide and regulate market behavior to ensure the legality and effectiveness of recycling activities through the publication of policy and guidance information. Information sharing can also help identify market demand and technological advances, and promote the innovation and application of recycling technologies, thereby enhancing overall recycling efficiency. More importantly, there is a need to establish an information-sharing platform so that data from various parties can be pooled and recycling trends and effects analyzed for policy adjustment and resource allocation. Thus, promoting the level of information sharing will not only increase the capacity for cooperation and market transparency of all stakeholders, but also improve the overall efficiency of battery recycling.

3.6.4. Innovation capacity

The ability to innovate has a profound impact on battery recycling, especially in the context of the rapid development of the electric vehicle industry (Bonsu, 2020). Technological innovation is a key factor in improving the efficiency of battery recycling (Zhang et al., 2020). With the emergence of new materials and processes, companies can adopt more advanced recycling technologies to improve the recovery rate of valuable metals such as lithium, cobalt and nickel (Makuza et al., 2021). For example, the use of new methods such as chemical leaching or electrochemical recovery can effectively reduce the waste of resources in the traditional recycling process and enhance economic efficiency. The ability to innovate is also reflected in the optimization of the recycling process. Through the introduction of automated and intelligent equipment, the operation process can be simplified, manual intervention can be reduced, and safety and efficiency can be improved. In addition, innovation includes the transformation of business models. For example, companies can explore circular economy models that combine recycling and reuse to form a closed-loop supply chain that reduces environmental impact and maximizes the use of resources. Policy innovation is equally important. By setting incentives and standards, governments can encourage companies to invest more in battery recycling and research and development to promote the sustainable development of the battery recycling industry.

Table 7
Barriers and measures for building a recycling network for used batteries.

Barriers	Description	Measures	Reference
Inadequate infrastructure	The lack of adequate recycling points and transport facilities in many areas makes it difficult for consumers to drop off used batteries.	Establish more convenient recycling points, optimize the transport network and increase the coverage of drop-off facilities.	Debrah et al. (2024), Gautam and Bolia (2024), and Mrozik et al. (2021)
Insufficient public awareness	Consumers are not sufficiently aware of the importance and methods of recycling used batteries and lack the motivation to participate.	Conduct publicity and education campaigns to increase public awareness and participation through social media and community events.	Wang et al. (2020), Rizos and Urban (2024), and Negara et al. (2022)
Technical limitations	There are many types of batteries, and recycling technologies are not yet mature, making it difficult to handle different types of batteries.	Invest in research and development of new technologies to improve the recycling rate and treatment efficiency of used batteries and promote technological innovation.	Chigbu (2024), and Fan et al. (2020)
Economic viability	For recycling enterprises that have not yet realized economies of scale, the cost of the recycling process may be higher than the economic returns from recycling, inhibiting their willingness to participate.	The government provides financial subsidies and incentives to encourage enterprises to participate in the construction and operation of recycling networks.	Costa et al. (2021), Islam and Iyer-Raniga (2022), and Guo et al. (2024)

3.6.5. Lack of cluster benefits

Battery recycling enterprises are dispersed in different regions, resulting in insufficient sharing of information and resources, a lack of effective cooperation and synergy among enterprises, and difficulties in forming a scale effect (Feng et al., 2024a). This fragmentation increases the waste of resources in the recycling process by making recycling inefficient and unable to fully utilize existing infrastructure and technology. Due to the lack of cluster benefits, recycling enterprises face higher costs in their operations, including transport costs (Slattery et al., 2021), equipment investment and human resource management, which in turn affects their market competitiveness and leads to higher recycling prices, inhibiting the willingness of consumers and enterprises to participate. Moreover, technological innovation is limited, and fragmented enterprises find it difficult to form a synergy for R&D, resulting in lagging recycling technologies that are difficult to meet the growing demand for battery recycling and environmental standards. Ultimately, this lack of cluster benefits not only restricts the development of the battery recycling industry, but also affects the sustainability of the battery recycling industry. Therefore, it is particularly important to establish a clustered recycling system to facilitate resource integration, reduce costs and promote technological advancement, so as to enhance the overall recycling efficiency and achieve the goal of a circular economy.

4. Discussion

The benefits of end-of life battery recycling, policy implications, managerial insights, potential future research directions, and research limitations are discussed in this section.

4.1. Benefits of end-of-life battery recycling

The purpose of this section is to discuss the economic, social and environmental benefits of recycling end-of-life batteries to underline the need and importance of battery recycling.

4.1.1. Economic benefit

There is no doubt that battery recycling has huge potential economic benefits (Islam and Iyer-Raniga, 2022; Jiang et al., 2021b; Mossali et al., 2020). Steward et al. (2019) discussed the economics of battery recycling for new energy vehicles, concluding that systematic optimization of the reverse supply chain network for retired battery recycling is needed to fully realize its economic benefits. Sun et al. (2020) focused on the economics of the secondary use of recycled lithium batteries for electric vehicles, and the results of the study found that the secondary use of used lithium batteries is particularly suitable for battery energy storage systems. Yang et al. (2024) investigated the economic advantages associated with the recycling of used electric vehicle batteries, for example, the recycling of used batteries is expected to reach 4.17 million tons by 2035, which is about 55% of the demand, and metals such as nickel, cobalt and manganese recovered from used batteries can meet the demand for battery manufacturing. Tian et al. (2024) constructed a cross-regional joint recycling model on the recycling of used batteries, and the results showed that in relatively economically underdeveloped regions, investing 70–80 % of financial resources in regulation would significantly improve the economic and environmental benefits of battery recycling. Xia et al. (2024) investigated the economic and environmental benefits of used battery recycling from the perspective of recycling model, and the results showed that the collaborative recycling model among battery manufacturers, third-party recyclers and electric vehicle enterprises has better economic benefits. The economics of waste battery recycling are affected by factors such as the residual value of the battery, collection and transport costs, and prices of materials in the recycling market, and therefore more efficient and cost-effective recycling frameworks need to be developed to facilitate waste battery recycling (Ali et al., 2021; Li et al., 2024b). Bottom line,

recycling of used electric vehicle batteries not only brings direct economic benefits, but also promotes the recycling of resources and environmental protection, and promotes the sustainable development of society and economy, which is of great strategic significance. On the one hand, waste batteries can be utilized for secondary use, thus exerting economic value; on the other hand, waste batteries contain valuable metals such as lithium, cobalt and nickel (King and Boxall, 2019), which can be recycled to reduce raw material procurement costs and meet the growing demand for batteries.

4.1.2. Social benefit

Waste electric vehicle battery recycling has social benefits (Tang et al., 2019). Firstly, by recycling and safely disposing of used electric vehicle batteries, the pollution of soil and water by hazardous substances can be reduced, thereby protecting public health. Proper disposal of the harmful components in batteries avoids their potential harm to humans and animals, and improves the quality of life of community residents. Secondly, the development of the battery recycling industry can create a large number of jobs and promote the prosperity of related industries (Chigbu, 2024). New jobs are created in the community and the overall economic vitality is enhanced by the increase in recycling, processing and transport. Finally, waste battery recycling also raises the public's awareness of environmental protection and promotes the spread of green consumption concepts. Through publicity and education, the public is encouraged to actively participate in recycling batteries, increasing social awareness of protecting the environment and creating a favorable social atmosphere.

4.1.3. Environmental benefit

Recycling used power batteries is undoubtedly positive for the ecosystem (Dunn et al., 2015). Luo et al. (2024) quantified the environmental performance of used power battery recycling technologies to further identify favorable recycling pathways. Used batteries contain heavy metals and harmful chemicals, which, if improperly handled, can cause serious damage to soil and water sources and harm the ecological balance, and recycling used batteries can therefore effectively reduce the environmental pollution caused by discarded batteries (Feng et al., 2024c). Waste battery recycling promotes the recycling of resources and reduces the need for new resource mining. The main components of electric vehicle batteries, such as lithium, cobalt and nickel, are scarce resources, and the mining process can cause serious damage to the environment. By recycling these materials, not only is resource consumption reduced, but the burden of mining on the environment is also reduced, promoting the sustainable management of resources. In addition, the process of recycling and reprocessing used batteries typically results in significant reductions in energy consumption compared to the mining and production of raw materials, thereby reducing greenhouse gas emissions. This has positive implications for combating global climate change and achieving emission reduction targets.

4.2. Policy implications

This paper provides a systematic review of the relevant literature on the factors influencing the recycling of used electric vehicle batteries, with the aim of identifying and analyzing the key factors influencing the recycling of batteries and proposing corresponding policy insights. Firstly, a large amount of existing literature suggests that sound policies and regulations are the basis for promoting battery recycling (Melin et al., 2021). It is recommended that the government formulate and implement special laws and regulations to clarify the responsibilities of producers, consumers, and recycling organizations, and to ensure compliance and transparency of the recycling process (Xiao et al., 2024a). Meanwhile, government departments or industry associations should establish an effective regulatory mechanism to regularly assess the effectiveness of waste battery recycling and penalize non-compliance in order to maintain market order (He and Sun, 2022).

Secondly, economic incentives can increase stakeholders' motivation to recycle batteries. Therefore, government departments can consider providing incentives such as tax breaks and subsidies to encourage enterprises and consumers to participate in battery recycling (Tian et al., 2021). In addition, a recycling incentive mechanism should be established to motivate the public to voluntarily recycle used batteries. Thirdly, it is also crucial to establish a convenient recycling network. The government should promote the installation of recycling points and the optimization of the logistics system to improve the convenience of recycling used batteries (Li et al., 2023b). Besides, publicity and education should be strengthened to enhance public awareness and participation in battery recycling, so as to form a favorable atmosphere for the whole society to participate. Finally, the promotion of technological research and development and innovation should not be overlooked. It is recommended to increase investment in the research and development of battery recycling technology, encourage cooperation between enterprises and scientific research institutions, promote the application of new technologies, and improve the efficiency of recycling and resource utilization.

4.3. Managerial insights

In order to effectively enhance the recycling efficiency of used electric vehicle batteries, managers should consider the following multi-dimensional management insights from a systematic and strategic perspective to ensure the efficient operation of the recycling system and the sustainable development of environmental protection.

First, cross-sectoral collaboration is the cornerstone for achieving efficient recycling of used electric vehicle batteries (Fleischmann et al., 2023). Recycling not only involves multiple sectors such as environmental protection, transport and industry, but also requires comprehensive coordination at the legal, economic and social levels (Lehtimäki et al., 2024). Managers should take the initiative to build a platform for cross-sectoral co-operation, and promote real-time communication among different sectors in terms of policy, market dynamics and technological innovation through regular co-ordination meetings and the establishment of an information-sharing mechanism. Such collaboration not only enhances the efficiency of resource integration, but also strengthens the sense of identity of each sector towards a common goal and avoids duplication and waste of resources, thus forming a synergy to promote the full implementation of battery recycling.

Secondly, setting clear and challenging recycling targets is an important driver for improving recycling efficiency (Toro et al., 2023). Managers should set specific, quantifiable recycling targets based on market demand and long-term strategies for environmental protection, and design implementation plans that take into account the actual situation in different regions. These targets should not only be operable, but also have the flexibility to be dynamically adjusted to adapt to market and technological changes to ensure the effective implementation of the measures. In addition, regular performance evaluation and feedback mechanisms should be incorporated to identify problems and optimize strategies in a timely manner.

Third, optimizing the recycling process is the key to improving efficiency. Managers should conduct a comprehensive review of the existing recycling process, identify bottlenecks and obstacles, and improve the convenience of recycling by simplifying procedures and introducing digital means (Ma et al., 2024a). For example, developing an integrated e-recycling platform, streamlining recycling applications and processes, and reducing the use of paper instruments can effectively reduce the time costs of participants and increase the enthusiasm of the public and enterprises to participate (He et al., 2024; Jian et al., 2019). Optimized processes not only enhance user experience, but also strengthen the overall efficiency of the recycling system.

Fourth, strengthening training and publicity for recycling personnel and the public is an important strategy to enhance participation (Ma et al., 2024b). Managers should develop systematic training programs to

ensure that recycling personnel have the necessary professional knowledge and skills. At the same time, public awareness of the importance of recycling used batteries should be raised through multi-channel publicity campaigns (Zhao et al., 2024b). Using social media, community activities and school education to promote the benefits of battery recycling and ways to participate can effectively mobilize all sectors of society and create a good atmosphere for the whole community to participate (Zeng et al., 2023).

Finally, encouraging technological innovation is the core driving force to improve the efficiency of waste battery recycling (Huang et al., 2018). Managers should actively promote the research and development of enterprises and research institutions in battery recycling technology, and support the application of new technologies to improve recycling efficiency and resource utilization (Lee, 2024). For example, promoting automated recycling equipment and intelligent management systems can not only improve recycling efficiency but also enhance safety. In addition, the establishment of special funds or incentives to encourage the implementation of innovative projects will provide a strong impetus to the technological progress of the entire industry.

4.4. Potential future research directions

This literature review provides recent advances in analyzing the factors influencing the recycling of used electric vehicle batteries. Although this research topic has progressed in recent years, there are still many issues that need to be further addressed. This section will discuss potential future research directions to inform the field. This is particularly important given the dramatic increase in the number of used batteries in the future.

4.4.1. Need for comprehensive influence factor studies

Combining social, economic and environmental factors, comprehensive research is urgently needed to explore how these factors interact with each other to influence the efficiency and effectiveness of battery recycling, and is a necessary measure to address the growing challenges of used battery management. The rapid popularity of electric vehicles has led to a dramatic increase in the number of used batteries, which, if not properly managed, may not only lead to a waste of resources but also have a serious impact on the environment (Zhang et al., 2018). Therefore, an in-depth analysis of the impacts of social factors such as public awareness of environmental protection, economic factors such as incentives, and environmental factors such as the chemical composition of batteries is essential to optimize the battery recycling system. Exploring the interrelationships and mechanisms of action among the factors of used battery recycling can help policy makers identify the key drivers to enhance the recycling rate. For example, understanding societal attitudes towards battery recycling can guide policy makers to develop more effective communication strategies (Hansmann et al., 2006); while analyzing the effectiveness of economic incentives can drive companies to invest in recycling technologies. Through comprehensive research, we are able to build a better battery recycling system, which will lead to the efficient use of resources and sustainable protection of the environment, and ultimately promote the sustainable development of society.

4.4.2. Need to optimize recycling network

Although numerous literatures have explored the optimization of recycling networks for used electric vehicle batteries, further research and efforts are still needed due to the large number and complexity of stakeholders involved in this field (Hou et al., 2024; Sasikumar and Haq, 2011; Tang et al., 2019). Stakeholders include governments, manufacturers, recycling companies, consumers and environmental organizations, etc., and their goals, needs and interests often differ, which makes the optimization of recycling networks even more challenging. In designing a battery recycling network, consideration needs to be given to finding a balance between promoting recycling and protecting the

environment, and developing effective incentives to attract participation from all parties. Future research should pay more attention to the optimization of multi-stakeholder recycling networks, and explore how to achieve a win-win situation in terms of efficient resource utilization and environmental protection through co-operation and co-ordination (Chirumalla et al., 2022). By comprehensively considering the interests and needs of all parties, the optimization of waste battery recycling network will be more effective and contribute to sustainable development.

4.4.3. Need to explore consumer behavior

From the published literature, there is less research literature on consumer behavior in the recycling of used electric vehicle batteries. Consequently, an important direction for future research is to conduct in-depth studies on the psychological and social factors affecting consumers' willingness to recycle, and to explore how to improve public awareness of recycling (Guo and Huang, 2023). Consumers' willingness to recycle is not only influenced by personal values and environmental awareness, but also closely related to a variety of factors such as social norms, group behavior and information dissemination. For example, public may be influenced by the behavior of those around them, and if their friends or family members are actively involved in recycling used batteries, they are more likely to take similar actions themselves. Therefore, understanding how these psychological and social factors interact can provide an important basis for developing effective recycling promotion strategies (Lizin et al., 2017). In order to study these influencing factors in depth, questionnaire surveys can be used to collect statistical data on consumers' attitudes, behaviors and perceptions towards recycling, in order to identify the main factors influencing recycling intentions (Gu et al., 2017a). Furthermore, future research can dig deeper into the details of consumers' inner motivation, social influence and cultural background through focus group discussions and in-depth interviews. Effective references and insights for increasing public awareness of recycling can also be gained by analyzing successful recycling cases and models to understand the psychological and social driving mechanisms behind them.

4.4.4. Need for policy effectiveness analysis

Assessing the impact of current policies on the recycling of used batteries is one of the important future research directions, mainly because policies play a key role in resource management and environmental protection (Joshi et al., 2021; Sommerville et al., 2021). There is very limited literature on assessing the effectiveness of the impact of existing policies on the recycling of used batteries. With the popularity of electric vehicles and the increasing number of used batteries, there is an urgent need for an effective policy framework to guide their recycling and disposal (Seika and Kubli, 2024). Evaluating existing policies can identify their effectiveness and shortcomings in promoting the recycling of used batteries. Assessing how policies affect consumers and businesses' willingness to recycle can provide policy makers with data support to help them optimize existing policies or develop new ones. Besides, the evaluation of existing policies can help to identify obstacles to policy implementation, such as shortcomings in regulations and lack of public awareness, and thus provide suggestions for solving these problems.

4.4.5. Need to explore economic and market mechanisms for recycling

Investigating the economic and market mechanism of the recycling of used electric vehicle batteries is an important research direction for the future, because the sustainable development of this field is not only based on technological innovation, but also requires effective economic incentives and market operation. With the popularity of electric vehicles, the number of used batteries has surged, and it is particularly important to establish an efficient and economic recycling system (Feng et al., 2024d). The study of the economic mechanism of the recycling of waste batteries can help to identify and quantify the cost effectiveness of

different recycling options and thus provide a scientific basis for policy makers. For example, exploring the cost structure of the recycling process and analyzing the economic benefits of each link can provide reference for recycling enterprises to formulate reasonable pricing strategies. Besides, the design of market mechanisms is crucial to promoting waste battery recycling activities. By establishing effective market incentives, such as subsidies and tax breaks, consumers and enterprises can be encouraged to actively participate in battery recycling. Explore auction-based market trading mechanism for used battery recycling through dynamic pricing, information transparency and incentives in order to improve the efficiency of used battery recycling (Ma et al., 2018). The auction mechanism can promote diversity of market participants, ensure fair prices and enhance market dynamics (Feng et al., 2024c; Xu et al., 2025). Government policy support and regulatory mechanisms will guarantee the fairness of the auction process and provide new solutions for sustainable recycling.

4.4.6. Need for full life cycle assessment

Environmental impact assessment plays an important role in the recycling process of used batteries, especially in assessing their environmental impacts through life cycle assessment (Koroma et al., 2022; Wang et al., 2022). Carrying out this analysis can help us to systematically understand the potential environmental impacts of batteries throughout the entire process from production, use to disposal (Wang et al., 2018). Life cycle assessment identifies the consumption of resources and emissions of pollutants at various stages, including the extraction of raw materials, the energy used in manufacturing, the efficiency during the use phase, and the environmental impact of final recycling and disposal. This comprehensive perspective helps to identify key aspects affecting battery recycling, optimize the recycling process and reduce environmental risks (Rey et al., 2021). By assessing the environmental impacts of different recycling technologies and methods, life cycle assessment can inform technology choices and promote more competitive recycling options (Kallitsis et al., 2022). For example, comparing the environmental performance of physical recycling with chemical recycling can guide the industry to adopt low-impact and high-efficiency recycling technologies. In addition, life cycle assessment will also help to raise public and corporate environmental consciousness, and make it easier to recycle batteries. With transparent data and analyzed results, policy makers can develop more targeted policies to encourage sustainable battery management practices. Therefore, future research should include a life cycle analysis of the recycling process of spent batteries.

4.4.7. Need for case studies

It is essential to conduct more case studies for future research on used electric vehicle battery recycling. Firstly, by comparing the actual application cases of different battery recycling technologies, the cost-effectiveness and environmental impacts can be analyzed in depth, so as to identify best practices and promote technological innovation. Secondly, studying case studies of battery recycling policies and regulations in different countries can reveal their implementation effects and impacts on the industry, providing valuable references for policy optimization (Levänen et al., 2018). In addition, analyzing the successful cases of leading companies in battery recycling can help to understand their operation models and market strategies, which in turn can provide lessons for other companies to learn from (Levänen et al., 2018). Meanwhile, the case studies can also assess public awareness and participation in battery recycling, and explore ways to enhance social acceptance so as to strengthen the recycling rate. Investigating the cases of different regions in implementing the circular economy model can analyze the actual impacts on resource efficiency and environmental protection, and promote the application of the circular economy in battery recycling. Finally, by combining life cycle assessment and case studies, the environmental impacts and economic benefits of different recycling programs can be quantified to provide a scientific basis for

decision-making. Bottom line, the rich case studies will support the sustainable development and green transformation of the industry by providing important data and lessons learned for the practice of spent battery recycling.

4.4.8. Need for battery life data

Future research directions should also work towards the creation of a comprehensive information marketplace that focuses on the integration of transaction data and related information on batteries. Battery life data will help recycling companies to accurately assess the residual value and recycling potential of batteries, and thus optimize their recycling strategies (Sulzer et al., 2021). The establishment of an information marketplace will facilitate data sharing and trading between electric vehicle manufacturers, users, recyclers and research organizations (Feng et al., 2024d). This flow of information will enhance all parties' understanding of battery condition, service life and recycling value, thereby driving the industry as a whole. In addition, future research will focus on the development and formulation of harmonized data standards to ensure interoperability and comparability of information from different sources, including battery performance, usage environment and charging/discharging history, which will significantly enhance data availability and reliability. In addition, privacy and security issues are important factors that cannot be ignored in the development of the information market (Brighente et al., 2023; Zhang et al., 2023b). Protecting user privacy and data security is a basic requirement in the process of data transaction, therefore, studying how to achieve effective sharing and utilization of data while ensuring user information security will be an urgent challenge to be solved.

Another research topic that deserves attention is how to collect battery life data. Firstly, manufacturers can embed intelligent monitoring systems in the battery production process in order to record in real time the number of charging and discharging cycles, temperature, humidity and other key parameters of the battery, which can reflect the state of use of the battery and its decline (Xiong et al., 2018). Second, through cooperation with electric vehicle users, apps or in-vehicle systems can be used to collect users' driving habits and charging behaviors, and this information can help analyze battery performance and lifespan under different conditions of use. Third, when recycling companies acquire used batteries, they can assess their remaining life by testing indicators such as the voltage and internal resistance of the batteries. In addition, conducting long-term tracking studies to monitor changes in the performance of the same batch of batteries in actual use can also provide valuable references for the collection of life data. By combining these methods, a comprehensive and reliable battery life data collection system can be established to provide a scientific basis for battery recycling and reuse.

4.4.9. Need for cross-sectoral cooperation

Existing studies have given less consideration to cross-industry collaboration in the recycling of used electric vehicle batteries. Cross-industry co-operation refers to the fact that the process of electric vehicle battery recycling involves not only various segments within the automotive industry (e.g., automobile manufacturers, battery producers, parts suppliers, recyclers, etc.), but also co-operation with other related industries. For example, co-operation with professional waste battery recycling companies to ensure that batteries can be recycled in an environmentally friendly and efficient manner, and co-operation with material manufacturers to research and develop battery materials that are easier to recycle, so as to improve the efficiency and economy of recycling. With the rapid expansion of the electric vehicle market, battery recycling faces multiple technical, economic and policy challenges. Cross-industry co-operation can effectively integrate resources and expertise from different fields, thus promoting the innovation and implementation of recycling technologies (Machín et al., 2024). On the one hand, co-operation among vehicle manufacturers, recycling companies, policy makers and research institutes can facilitate information

sharing and resource integration, and enhance the efficiency and economy of battery recycling. Attempts can be made to study the establishment of a cross-industry alliance, where all parties can work together to develop more advanced recycling technologies, reduce recycling costs and increase the recycling rate. On the other hand, research into the development of common standards and norms is crucial for waste battery recycling. Cross-industry co-operation can prompt all parties to participate in the development of technical standards and operational procedures for battery recycling to ensure the safety and efficiency of the recycling process. In conclusion, cross-industry co-operation is of strategic importance in the recycling of used electric vehicle batteries. Future research should focus on exploring how to establish an effective co-operation mechanism to achieve win-win benefits for all parties and promote the sustainable development of the battery recycling industry.

4.5. Common misconceptions and downsides of electric vehicle battery recycling

Electric vehicles, as an environmentally friendly mode of transport, have received much attention in recent years. However, misconceptions and potential drawbacks about electric vehicle battery recycling still exist, and these factors may affect public acceptance of electric vehicle and their sustainable development. Firstly, a common misconception is that electric vehicle batteries will be completely discarded at the end of their useful life, causing environmental pollution. In fact, the recycling technology of modern electric vehicle batteries is quite mature. Precious metals such as lithium, cobalt and nickel in batteries can be extracted through professional recycling processes and reused in the production of new batteries (Zante et al., 2020). Such recycling not only reduces the need for new resources, but also lowers the environmental burden. Secondly, some recycling companies consider the cost of battery recycling to be too high and are thus reluctant to invest in reducing the environmental impact of the battery recycling process. While it is true that battery recycling requires a certain amount of investment, the cost of recycling is gradually decreasing as technology advances and large-scale production is realized. In addition, many countries and regions have begun to develop policies and incentives to promote the development of the battery recycling industry, which will further improve the economics of recycling (Li et al., 2024a). Thirdly, there is also a misconception that the environmental risks in the battery recycling process are underestimated (Rizos and Urban, 2024). Although batteries contain some hazardous substances, formal recycling organizations adopt stringent safety measures to minimize the impact on the environment. Through an efficient recycling process, hazardous substances in batteries can be safely disposed of, thus reducing pollution caused by soil and water sources. Finally, the public believes that battery recycling is the responsibility of enterprises, and there is still a lack of awareness of battery recycling, as well as a lack of understanding of the recycling process and its effectiveness (Wang et al., 2020). This requires the joint efforts of the government, enterprises and the community to raise public awareness and promote the benefits and importance of battery recycling. In summary, battery recycling needs to further dispel misconceptions, overcome challenges, and improve recycling technologies and public awareness, thus paving the way for the development of a circular economy.

4.6. Research limitations

Although some important findings have been obtained through the systematic literature review, there are still several limitations in this paper in the course of the research as follows. The first limitation is the scope of literature coverage. Although the systematic literature review aims to cover a wide range of literature in the relevant field, it may not be able to comprehensively cover all important studies due to time, resource or language constraints, for example, if the literature review is

limited to English language literature, important studies published in other languages may be missed, and such language constraints may lead to an incomplete understanding of recycling practices and influencing factors in a particular regional or cultural context. As a result, limited literature this may lead to certain key studies or emerging trends being missed, thus compromising the comprehensiveness of the study. The second limitation is that this paper relies on qualitative literature and lacks a quantitative assessment of the barriers to battery recycling. This means that the study fails to measure the severity and impact of different barriers through statistical data or quantitative indicators. Qualitative studies, while providing rich context and insights, often struggle to specifically quantify the impact of barriers. For example, it is not possible to determine the specific impact of a particular barrier on recovery rates or its relative importance in different contexts.

5. Conclusions

This study analyses the key factors influencing the recycling of used electric vehicle batteries and highlights the importance of optimizing recycling strategies. The results of the study indicate that the number of end-of-life electric vehicle batteries will increase dramatically in the future as the sales of electric vehicles grow significantly, which makes it particularly critical to identify and overcome the barriers to recycling of used batteries. Only through effective recycling strategies can we pave the way for a circular economy in terms of efficient resource utilization, environmental protection and sustainable economic development. Through a systematic review of the existing literature, this paper finds that current research focuses on supply chain network optimization, recycling incentive policies and economic and environmental benefit analysis of waste battery recycling. These studies tend to analyze the barriers to recycling from a single perspective and lack a systematic and comprehensive exploration of the factors affecting the recycling of used batteries. Therefore, this study fills this gap by systematically identifying the barriers in used battery recycling and providing a new perspective for optimizing used battery recycling strategies for electric vehicles.

This paper emphasizes that used battery recycling not only involves technical and economic considerations, but is also closely related to policies and regulations, public awareness and industry cooperation. For example, many countries and regions have started to formulate specific laws and regulations on battery recycling to promote the increase of recycling rate. Understanding these policy contexts will help the industry grasp the current and future state of battery recycling in a more comprehensive manner. In addition, public awareness and participation in battery recycling have a direct impact on the recycling results; therefore, it is crucial to increase public awareness and willingness to participate in environmental protection. Although existing studies cover a wide range of aspects, they are still insufficient in integrating various research results and exploring more systematic and comprehensive solutions. Future research should proactively seek solutions to problems rather than passively waiting for them to emerge. More critically, there is a need to comprehensively consider the interrelationships and mechanisms of the various factors affecting the recycling of used batteries. For example, the advancement of recycling technology can not only improve the recycling efficiency of waste batteries, but also reduce the recycling cost; at the same time, the economic factors such as market demand and material value will also directly affect the direction and investment of technology research and development. In a word, this study constructs a comprehensive knowledge framework for recycling of waste batteries, covering multiple factors affecting the recycling of waste batteries. This framework not only provides a clear research path for researchers, but also provides an important reference for practitioners to understand the current status and development trend of the field. Therefore, an in-depth understanding of these factors and their interactions will lay the foundation for effective management and policy formulation of waste battery recycling in the future, thus contributing to the realization of a circular economy.

CRedit authorship contribution statement

Jianghong Feng: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Wenjing Liu:** Supervision, Methodology, Investigation, Conceptualization. **Feng Chen:** Writing – review & editing, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A recycling mechanism for used electric vehicle batteries by integrating affine maximizer auction and fuzzy axiomatic design method

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ABSTRACT

Given that the various attributes of retired electric vehicle batteries play a critical role in determining their recycling value, this paper aims to construct a multi-attribute auction mechanism for retired electric vehicle batteries based on fuzzy axiomatic design. The proposed method in this paper, through a phased design, effectively optimizes resource allocation efficiency and transaction matching accuracy. Considering a transaction market composed of one buyer, one auctioneer, and multiple sellers, this paper proposes a two-stage auction method based on multi-attributes. In the first stage, the fuzzy axiom design method is applied to calculate the sellers' information content regarding the attributes of retired electric vehicle batteries and constructs a linear mathematical model to minimize the sellers' information content. Additionally, the study introduces a control parameter to the model to regulate the number of sellers participating in the auction. Sellers who are successfully matched in the first stage will proceed to the second stage, which uses an affine maximizer auction method to determine the winning bidder and the amount each winning seller should receive. In our auction, weighting coefficients are introduced to capture the degree of matching between sellers' retired battery attributes and buyers' functional requirements for battery attributes. Finally, a series of numerical experiments were carried out to validate the effectiveness of the proposed method, as outlined in this paper. A sensitivity analysis shows that the control parameter, the weighting coefficients, and the attribute weights have a significant influence on the outcomes of the auction. Notably, this paper provides management insights for applying this method to the battery recycling market management, derived from the theoretical experience of this paper, which is expected to contribute to electric vehicle battery recycling.

1. Introduction

Many countries have introduced policies and incentives to encourage consumers to choose electric vehicles due to their potential benefits in reducing greenhouse gas emissions [1,2]. These include subsidizing the purchase of vehicles, reducing taxes, and developing electric vehicle charging infrastructure [3–5]. As awareness of climate change and the need for environmental protection grows, an increasing number of consumers are choosing environmentally friendly transport options, such as electric vehicles. These factors are driving the rapid growth of the electric vehicle market [6]. Batteries are a critical component of electric vehicles, and while they play a vital role in promoting clean energy and sustainable transport, they can have a negative impact on the environment when disposed of due to the rare metals and materials they contain [7]. In 2022, there are over 26 million electric vehicles on the

road, marking a 60 % increase from 2021 and more than five times the number in 2018 [8]. By 2040, it is projected that the number of waste batteries will reach 1336.5 GWh [9]. The number of waste batteries will increase dramatically over the next few years as the volume of electric vehicles continues to grow. The issue is therefore one of urgency, with the need for immediate attention to meet the challenge of managing the large number of waste batteries that will be generated.

The effective recycling and reuse of retired electric vehicle batteries is crucial as they have significant economic, social, and environmental value [10–12]. In addition to minimizing lithium battery waste and addressing resource depletion, recycling electric vehicle batteries helps to reduce pollution and the impact of battery waste on soil and water sources [13]. The recycling rate of electric vehicle batteries is an important indicator for measuring the efficiency and sustainability of recycling efforts. However, the electric vehicle batteries recycling rate

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remains relatively low [14,15], primarily due to several key factors. First, the wide variety of electric vehicle batteries with different specifications poses technical challenges to the recycling process, resulting in a lower recycling rate [16]. Second, issues such as information asymmetry, dispersion of resources, insufficient information sharing, and lack of effective cooperation within the battery recycling chain have limited the overall recycling rate [10]. It is worth noting that information asymmetry will have a significant impact on the battery recycling market. First, information asymmetry leads to differences in the perceived value of batteries between sellers (battery holders) and buyers (recycling companies). Sellers may not know enough about the true state of the battery (e.g., remaining charge, degree of aging), while buyers may lack information about the potential recycling value of the battery. This difference in information prevents the market price from accurately reflecting the true value of the battery, which may lead to undervaluation of high-quality batteries and overvaluation of low-quality batteries, thus affecting the fairness of the transaction. Second, with asymmetric information, both parties to a transaction may need to spend more time and resources on information collection and verification, resulting in a complex and inefficient transaction process. Additionally, an incomplete market mechanism for battery recycling and a lack of incentives and standards have reduced recycling companies' enthusiasm and motivation. Consequently, the design of an effective trading mechanism to address the issues of recycling incentives, information asymmetries, and valuation difficulties arising from the multi-attribute nature of batteries has emerged as a key strategy to increase the battery recycling rate.

Recent research has shown that some scholars have delved into the design of power battery recycling networks [17–19]. However, accurate assessment and pricing are challenging due to the diverse characteristics of batteries such as capacity, number of cycles and state of health. Different battery types also have different reuse values after recycling, leading to information opacity and uncertainty in the recycling process. These factors reduce recyclers' motivation to participate and hamper recycling efficiency. To address these challenges, Xu et al. [20] and Feng et al. [15] have introduced auction theory into the field of battery recycling. Auction theory holds potential for optimizing resources allocation and incentivizing active participation in the recycling process. The auction mechanism not only demonstrates the real-time market value of end-of-life batteries, but also stimulates competition among recyclers. This, in turn, will improve recycling efficiency and resource utilization, ultimately driving the development of the battery recycling industry and promoting a circular economy.

The multi-attribute characteristics of retired power batteries make a difference in their recycling value. As a result, the multi-attribute characteristics of used battery batteries make the auction process complex and challenging. For example, differences in battery performance, safety, environmental friendliness, economics, and reusability can lead to a diversity of battery recycling values, so the auction process must consider and trade off the relationship between these attributes. Besides, recycling enterprises with different professional qualifications need to choose to recycle waste power batteries that meet their capacity range according to their own technical and equipment conditions. For example, high-capacity batteries, which can be recycled by companies in the ladder business, would not be suitable for a company that specializes in recycling metal from spent batteries. However, existing battery recycling auctions fail to consider the multi-attribute characteristics of batteries, leading to inefficient and inequitable resource allocation. An auction system which does not consider the multi-attribute characteristics of the battery can lead to a situation where recyclers focus only on the price and ignore the actual quality.

This study is motivated by the multi-attribute auction problem of battery recycling mentioned by Xu et al. [20] in the literature. To address this problem, this paper proposes a novel auction mechanism that incorporates the multi-attribute characteristics of batteries. By integrating the performance of the batteries, the environmental impact, the cost effectiveness, and other relevant attributes into the auction

process, the true value of the batteries can be accurately represented. This approach facilitates optimal resource allocation and increases recycling efficiency by encouraging participants to prioritize battery quality and reuse potential. Specifically, this paper focuses on the following research questions: (1) How can an efficient auction mechanism be designed to take into account the multi-attribute characteristics of end-of-life batteries, to ensure an efficient allocation of resources and to maximize the societal benefits? (2) What is the appropriate methodology to assess the multi-attribute characteristics of waste power batteries? (3) How will the results of the auction be affected by variations in the parameters of the proposed methodology?

To answer the aforementioned research questions, the objective of this paper is to construct a multi-attribute auction framework for the waste power battery recycling by introducing a method based on the fuzzy axiomatic design principle for evaluating the multi-attribute characteristics of power batteries. Fuzzy axiomatic design has been used in many fields as a method for measuring how well systems meet their requirements [21,22]. To deal with ambiguity and subjective information, fuzzy axiomatic design incorporates fuzzy logic principles into the design process. Furthermore, this paper expresses the qualitative criteria assessment in the participants' battery attributes using triangular fuzzy numbers. First, this paper identifies the attributes (e.g., remaining capacity, self-discharge rate, physical state, safety performance, environmental impact, and economic value) for evaluating waste power batteries through literature analyses and expert opinions, and then uses fuzzy axiomatic design methods to evaluate the attributes of waste power batteries. Since some attributes may involve subjective judgment or uncertain data, fuzzy logic can represent and process this information effectively. Finally, the evaluated values are incorporated into an auction framework to ensure that recyclers are able to acquire waste power batteries that meet their requirements.

The contributions of this study are highlighted in the following three aspects. i) This paper develops a novel approach to electric vehicle battery recycling by integrating two important concepts, multi-attribute auctions and fuzzy axiomatic design. The paper contributes to the existing body of knowledge in the field by providing a comprehensive and systematic framework for decision making in the process of recycling waste batteries. To the best of our knowledge, this is the first paper that integrates a fuzzy axiomatic design approach into auction theory to solve a multi-attribute auction problem. ii) This paper considers the various attributes of waste power batteries, providing a structured approach to evaluating and selecting the optimal recycling solution. It applies multi-attribute auctions and fuzzy axiomatic design principles to offer a novel decision-making framework for the waste battery recycling industry, enabling more informed and effective decisions. iii) The paper investigates the robustness of the relevant input parameters of the auction mechanism, and provides a numerical validation of the performance of the proposed scheme under different scenarios, as well as a comparison with existing methods. This paper also provides management insights drawn from key findings that are of practical relevance to industry stakeholders, policy makers, and researchers involved with electric vehicle battery recycling.

The rest of the study is structured as follows. Section 2 presents a systematic literature review on multi-attribute auctions, fuzzy axiomatic design, and waste battery recycling. Section 3 describes the research methodology of this paper. Section 4 illustrates the effectiveness of the proposed methodology through a numerical study, along with sensitivity and comparative analyses. Section 5 discusses the merits of the proposed methodology, theoretical insights, managerial insights, measures to implement the proposed methodology, and the significance of the study. Finally, conclusions, study limitations and potential future research directions are summarized in Section 6.

2. Literature review

This section is dedicated to reviewing the three main streams

relevant to the research, namely multi-attribute auction, fuzzy axiomatic design, and waste battery recycling.

2.1. Multi-attribute auction

The first stream of literature is multi-attribute auction. Several studies have focused on multi-attribute auctions in the past few years [23,24]. Che [25] developed a two-dimensional auction model for use in government procurement, where companies bid on both price and quality, and bids are evaluated according to scoring rules designed by the platform or buyer. Branco [26] further extended the Che's model with special scenarios of correlation on the firm's costs, which provides a valuable reference for subsequent multi-attribute auctions. For example, Kostamis et al. [27] considered cost-adjusted auction methods reflecting non-price attributes such as logistics costs and comparatively analyzed the results in two scenarios, a first-price auction and a reduced-price public auction and the study provided new perspectives and methodologies for multi-attribute auctions. Liu et al. [28] studied the problem of multi-attribute procurement auctions involving risk-averse suppliers and found that the equilibrium bid in the first-price auction decreases while the equilibrium bid in the second-price auction remains the same as the number of suppliers increases or as the suppliers become more risk-averse. The paper contributed to a deeper understanding of the impact of suppliers' risk-averse behavior on the auction mechanism. Wang [29] proposed a multi-attribute auction approach different from scoring auctions, called constant payment auction mechanism. This mechanism allows bidders to focus their bids not only on price but also on a combination of other non-price attributes, such as quality of service, delivery time and reputation. Besides, the more comprehensive analysis of the relevant literature can be found in Pham et al. [30].

Recently, several studies have focused on multi-attribute auctions for the transport services procurement [31–33], data markets [34], grouped joint learning schemes [35], and the problem of choosing between first-score and the second-score multi-attribute auction in the presence of supply disruptions [36]. For example, in contrast to other studies on multi-attribute single-sided Vickery-Clarke-Groves (VCG), Yu et al. [37] explored the multi-attribute multi-unit double auction problem in logistics service transactions and demonstrated that the proposed auction mechanism is incentive-compatible, individually rational, progressively efficient, and budget-balanced. Vergamini et al. [38] investigated the performance of multi-attribute auctions in terms of agri-environmental payments and cost-effectiveness, providing a theoretical basis for agri-environmental policy development. Lu et al. [39] developed a multi-attribute auction method to address the issue of third-party logistics selection, evaluating potential suppliers based on price and delivery time attributes, thereby providing a new approach to supplier selection. Xiao et al. [40] studied the multi-attribute auction problem for single and multiple units in crowdsourced delivery and developed a second priority scoring VCG auction, and the proposed method outperforms single-attribute auctions and *fixed-rate* mechanisms. Quiroga and Aldunate [41] extended the standard *non-parametric approach* for first-price auctions to multi-attribute quasi-linear scoring auctions and demonstrated the effectiveness of the proposed approach. Lorentziadis [42] studied the problem of multi-attribute auctions with different cost structures and predetermined qualities, focusing on auctions of single items without considering the efficiency of the auctions. Albano et al. [43] carried out experiments to study the problem of multi-attribute scoring auctions in the context of competitive procurement contracts. Two experimental conditions were set up based on the relative weight of quality and price in the scoring rules. The study found that different quality-price weights can greatly change the strategic environment and affect efficiency. Huang et al. [44] incorporated prospect theory into multi-attribute auction and used crisp values, interval numbers, and linguistic variables to describe attributes. Incorporating prospect theory into auction models has enabled researchers to better predict the

psychological responses of bidders when confronted with different attributes, and such models are able to capture the irrational behavior of bidders in the decision-making process. This paper summarizes the literature on multi-attribute auction, as shown in Table 1.

2.2. Fuzzy axiomatic design

The second stream is fuzzy axiomatic design. Axiomatic design is a method for evaluating a system's functionality in meeting functional requirements, with two key concepts [45]. The first concept is the independence axiom, which mandates that the design process must ensure independence between functional requirements [46]. The second concept is that among products or solutions that meet all the system's functional requirements, the one with the least information content is considered the optimal solution. Since axiomatic design considers the probability that a functional requirement will satisfy the system function, it is widely used in various fields [47]. For example, Kannan et al. [48] used a fuzzy axiomatic design approach to achieve optimal supplier-manufacturer matching, i.e. taking into account both the supplier's functional requirements for the attributes and the manufacturer's system design requirements for the attributes. Chen et al. [49] applied the fuzzy axiomatic design approach to investigate the matching problem between the supply side and demand side of knowledge. Li et al. [50] integrated the fuzzy axiomatic design method into multi-attribute decision-making and verified the effectiveness of the proposed method through the person-job matching problem in the recruitment process.

The existing literature related to fuzzy axiomatic design focuses on aspects such as facility location [22], alternative selection [51], and supplier selection [48]. These studies demonstrate that the fuzzy axiomatic design approach can effectively address qualitative and quantitative criteria in problem-solving. Furthermore, its flexibility enables it to be adapted to diverse scenarios and problem requirements, enabling it to solve practical problems more effectively. Consequently, compared with other methods, the fuzzy axiomatic design method is more suitable for multi-attribute auctions for waste battery recycling. One advantage of fuzzy axiomatic design is its consideration of the probability of attributes matching success between buyers and sellers, facilitating agreement. Additionally, fuzzy axiomatic design enhances decision-making process, enabling participants to understand the impact of each attribute on the final result more clearly and thus increasing their trust in the auction's outcome. However, to date, no studies have applied the fuzzy axiomatic design approach to further explore the multi-attribute matching problem in waste battery recycling. As a result, this paper incorporates fuzzy axiomatic design into the auction method, constructing a theoretical framework for multi-attribute auctions for the recycling of end-of-life electric vehicle batteries and filling a research gap.

2.3. Waste battery recycling

The third stream is waste battery recycling. Recently, there has been an increasing focus on recycling used batteries [52–54]. Regarding the policy and recycling strategy aspects of waste battery recycling, scholars mostly use optimization or game theory methods to explore the improvement of the waste battery recycling rate. For instance, Kannan et al. [55] constructed a multi-cycle and multi-product optimization model for the product recycling problem and validated the model using battery recycling as an example. Li et al. [56] investigated the differences between power battery recycling with or without cross-network co-operation by constructing a non-linear optimization model, and the results provide useful references for related stakeholders to formulate policies. Tang et al. [57] employed a game theory approach to study waste battery recycling, introduced a reward and punishment mechanism to improve the battery recycling rate, and considered different recycling channel models in the model. Chen et al. [58] considered a network consisting of new energy vehicle manufacturers and battery

Table 1
Summary of primary literature related to multi-attribute auction.

References	Method	Field of research	Attributes	Market composition
Kostamis et al. [27]	First-price sealed-bid auction and descending open-bid auction	Procurement issue	Price and fixed cost adjustments	One buyer, multiple sellers
Liu et al. [28]	First-score auction and second-score auction	Procurement issue	Cost and quality	One buyer, multiple sellers
Wang [29]	Contingent payment auction mechanism	Procurement issue	Price and quality	One buyer, multiple sellers
Huang et al. [44]	Sealed-bid single-stage reverse auction	Procurement issue	Benefits, opportunities, cost, and risk	One buyer, multiple sellers
Vergamini et al. [38]	Discriminatory price auction	Agri-environmental scheme	Agri-environmental payments and environmental outcome	Auctioneer and multiple farmers
Lorentziadis [42]	Asymmetric multidimensional auction	Procurement issue	Price and quality	One buyer, multiple sellers
Xiao et al. [40]	Second-preferred-score and a Vickrey-Clarke-Groves score auction	Crowdsourced delivery	Price and weight	Multiple couriers and multiple requesters
Yu et al. [37]	Multi-attribute multi-unit double auction mechanism	Logistics service transactions	Price and non-price attributes	Multiple shippers and multiple carriers
Albano et al. [43]	Scoring auctions	Procurement contracts	Price and quality	One buyer, multiple sellers
This paper	Affine maximizer auction based on fuzzy axiomatic design	Waste battery recycling	Multiple non-price attributes	One buyer, multiple sellers

manufacturers, and applied the well-known game theory approach to compare the recycling effects in different policy scenarios. Sun et al. [59] explored three recycling models for waste batteries, namely retailer recycling, manufacturer recycling and mixed recycling, through a game-theoretic approach, and systematically analyzed related parameters such as carbon trading policies and advertising effects. He and Sun [60] explored the waste batteries recycling through a system dynamics model, and the results showed that a dynamic reward and punishment mechanism is conducive to motivating consumers and new energy vehicle manufacturers to participate in the waste battery recycling. Furthermore, some studies have focused on the location problem in the battery recycling process. For example, Lin et al. [61] developed an online optimization analysis method and integrated it into the system to determine the number of recycling stations that need to be built in the region, and validated the effectiveness and feasibility of the proposed method. Hezam et al. [62], Sherif et al. [63] and Puviarasu et al. [64] have studied the location problem of waste battery recycling plants through a multi-attribute decision-making method. Haynes et al. [65] primarily applied machine learning methods to determine the optimal location of lithium battery recycling facilities. Du et al. [66] have developed a linear programming model to solve the problem of battery recycling and remanufacturing center site selection, considering the uncertainty of the quantity and capacity of waste battery recycling, which provides an important theoretical basis for waste battery recycling site selection.

Regarding the price of recycling spent batteries, existing work has focused on determining their price using optimization and game theory methods [67]. For example, Zhao et al. [68] and Zhang et al. [69] investigated the optimal pricing strategies for recycling waste batteries under different recycling channels, and found that government subsidies are conducive to the waste battery recycling. Tang et al. [70] investigated the willingness to recycle waste batteries using empirical methods and the results confirmed that the recycling price has a significant effect on the residents' willingness, providing theoretical evidence for designing an effective battery recycling pricing mechanism to increase the recycling rate. Besides, a dynamic optimization model was developed for battery recycling platform supply and demand mismatch problems, providing useful decision support for platform recycling prices and platform fees [71]. To further improve the waste battery recycling efficiency, Xu et al. [20] introduced the auction theory to waste battery recycling to explore the resource allocation and waste battery recycling pricing, and designed a battery recycling trading mechanism that can motivate relevant stakeholders to participate in battery recycling. On this basis, Feng et al. [15] further explored a two-stage auction for the waste power batteries recycling, introducing an affine-maximizer mechanism method to increase platform revenue. The auction-based method described above provides a new solution idea for waste battery recycling. Wu et al. [72] applied a game theory approach to explore

the used batteries recycling channel model and verified the impact of deposit refund strategy on supply chain performance. This paper summarizes the literature on waste battery recycling, as shown in Table 2.

2.4. Literature summary

Previous studies on multi-attribute auction have primarily focused on price and quality attribute. However, representing these attributes with scoring functions may not fully capture the diversity and complexity of commodities, resulting in insufficient information for decision-making. Little attention has been paid to the problem of multi-attribute matching of commodities between buyers and sellers, and it also fails to fully consider the individual needs of different buyers, resulting in an auction process that may not be able to satisfy the specific needs of buyers and affecting the effectiveness of the transaction. Therefore, this study aims to fill the existing research gap by exploring the multi-attribute auction matching problem for electric vehicle batteries, providing better decision support for buyers and sellers, and improving transaction efficiency and satisfaction.

The above literature review indicates that existing methodological research on waste battery recycling has primarily focused on optimization methods, game theory, and multi-attribute decision-making methods to explore the subsidy policy, recycling network optimization, facility location, and pricing strategies. This paper is close to Xu et al. [20] and Feng et al. [15]. However, Xu et al. [20] and Feng et al. [15] do not consider the multi-attribute characteristics of waste batteries. Indeed, since the value of waste batteries largely depends on the remaining battery capacity and battery type, etc., to this end, it is very necessary to consider the multi-attribute characteristics of waste battery recycling. However, to the best of our knowledge, the existing literature has not explored the multi-attribute auctions for waste batteries recycling, nor has it constructed a multi-attribute theoretical framework. In view of this, this paper fills the current research gap by investigating the multi-attribute auction problem of waste battery recycling to make theoretical and practical contributions to the sustainable development of battery recycling.

3. Methodology

This section will present the problem statement, the fuzzy axiomatic design method and the affine maximizer VCG auction and an example illustration.

3.1. Problem statement

In the waste battery recycling multi-attribute auction problem, the waste battery recycler is the buyer and the seller is the waste battery owner. Waste battery recyclers usually consider price factors in addition

Table 2
Summary of primary literature related to waste battery recycling.

References	Method	Objective	Verification method
Tang et al. [57]	Stackelberg game theory	Exploring the impact of reward-penalty mechanisms and policies on the retired batteries recycling.	Case study
Sun et al. [59]	Stackelberg game theory	Investigate the impact of carbon trading policies, endurance capacity, and advertising effects on the selection of recycling channels.	Case study
Chen et al. [58]	Game theory	Exploring the recycling of retired batteries under different incentive policies.	Case study
Zhang et al. [69]	Stackelberg game theory	Exploring the selection of waste battery recycling models and carbon emission reduction decision-making issues	Case study
Tang et al. [70]	Structural equation and agent-based model,	Investigating factors influencing residents' willingness to participate in electric vehicle battery recycling	Case study
Xu et al. [20]	Double auction	Exploring resource allocation and pricing issues	Numerical study
Li et al. [56]	Mixed integer nonlinear programming	Determine the location of the facilities and transportation	Case study
Haynes et al. [65]	An unsupervised machine learning clustering heuristic	Site selection for retired battery disposal facilities	Case study
Du et al. [66]	Mixed-integer linear programming model	Battery recycling and remanufacturing center site selection issues	Case study
Feng et al. [15]	Two-stage auctions	Information matching and resource allocation	Numerical study
Wu et al. [72]	Stackelberg game theory	Exploring the performance of used battery recycling under different recycling models and deposit refund strategies	Numerical study
This paper	Affine maximizer auction based on fuzzy axiomatic design	Exploring the issue of multi-attribute auctions for the recycling of waste batteries	Numerical study

to other attributes of the waste battery, such as remaining capacity, physical state, and safety performance. Therefore, this paper aims to address the following practical problems faced by the waste battery recycling market. First, the lack of transparent information between waste battery holders and recycling companies leads to misunderstandings about the status and value of batteries, which affects pricing and transaction efficiency. Second, due to information asymmetry and the lack of effective incentive mechanisms, high-quality batteries fail to receive reasonable returns, while poor-quality waste batteries may be sold at a high price, which affects the overall health of the market. Third, due to the imperfect recycling mechanism, many batteries are not effectively recycled, resulting in waste of resources and environmental pollution. In this paper, we consider a waste battery recycling network consisting of an auctioneer, a buyer, and multiple sellers, as shown in Fig. 1. The buyer gives attribute values based on the waste batteries attributes, such as remaining capacity, physical state, and safety performance, etc., while the seller's attribute values of waste batteries are given by the platform or a professional third-party appraisal company based on the actual condition of the batteries. For example, if the buyer requires the remaining capacity of the battery to be in the range of [70 %, 100 %], and the remaining capacity of a seller's

battery is [60 %, 69 %], then the seller will not be able to match with the buyer. Consequently, this paper constructs a methodological framework to solve the multi-attribute auction problem for waste battery recycling, where the first step is the multi-attribute matching stage of waste batteries, while the second step is the auction stage of waste batteries.

Assume that there are n sellers, each seller of which $i (i \in I = 1, 2, \dots, n)$ has one unit of waste battery to sell, and the buyer can either determine the number of winning sellers ex ante. Indeed, a seller may have more than one waste battery for sale, and the assumption that each unit of waste battery corresponds to one seller is made herein to simplify the complexity of the problem. For example, a seller with multiple units of waste batteries submits the sealed bids and attributes information of each unit of waste batteries separately, and the system automatically assigns numbers to the waste batteries, each of which reveals a seller. Seller i submits a sealed bid price $s_i (i \in I)$ for each of the waste batteries. Let H denote the set of waste batteries attributes, and each attribute $h (h \in H)$ can be a crisp value, an interval value, or a linguistic variable. Let the attribute weight h be w_h , which is determined by the buyer. Let b_i denote the value of the information content of the waste battery attributes of the seller i with the functional requirements of the attributes defined by the buyer. Furthermore, in this study, based on research needs, it is assumed that buyer demand is known. This assumption has certain practical significance. For example, buyers can determine demand positioning based on their own processing capacity, production plans, or resource allocation. Such a setting makes the assumption more relevant to actual application scenarios and provides a reasonable basis for model establishment. The notations used in this paper are summarized in Table 3.

The first step is to calculate the information content of the seller's waste batteries using the fuzzy axiomatic design method to filter the attributes that meet the buyer's requirements for waste batteries. Assuming that the number of sellers meeting the buyer's attribute requirements in the first step is $L (L \in I)$, then the second step is to construct a winner determination set to determine the number of sellers participating in the final transaction. Assume that the buyer determines ex ante the quantity of waste batteries to be purchased as X , and that seller i 's reservation price $\hat{s}_i$ is private information. It should be noted that the number of waste batteries referred to later in this paper corresponds to the number of sellers unless otherwise stated, since one seller corresponds to one unit of waste battery. Each seller is a selfish participant and only considers maximizing his/her own benefits. Seller i 's utility u_i is the difference between the payment received and the reservation cost $\hat{s}_i$. For example, if a seller has a reservation price of \$5 and receives a payment of \$8, then his utility is $8 - 5 = 3$. Also, the utility of a seller who does not participate in the transaction is zero.

3.2. Attribute selection

In this paper, six dimensional attributes of waste power batteries, namely, remaining capacity, self-discharge rate, physical state, safety performance, environmental impact, and economic value, are selected. The remaining capacity of a waste power battery is its ability to store and release electrical energy. By measuring the actual capacity of a waste power battery, it is possible to assess its remaining electrical energy and service life. Self-discharge rate refers to the rate of decrease of the capacity of the battery during storage, i.e. the rate of capacity loss due to self-discharge of the battery when it is not loaded, which indicates the characteristics of the capacity change of the battery after it is put aside. By measuring the self-discharge rate, the stability of the battery and the degree of loss can be assessed. The self-discharge rate can be expressed in terms of the amount of charge lost by the battery per unit of time, usually at a daily, weekly or monthly rate. The physical state of waste batteries can usually be described and assessed from a number of aspects such as battery appearance and size. By observing and evaluating the physical state of waste batteries, it is possible to gain a

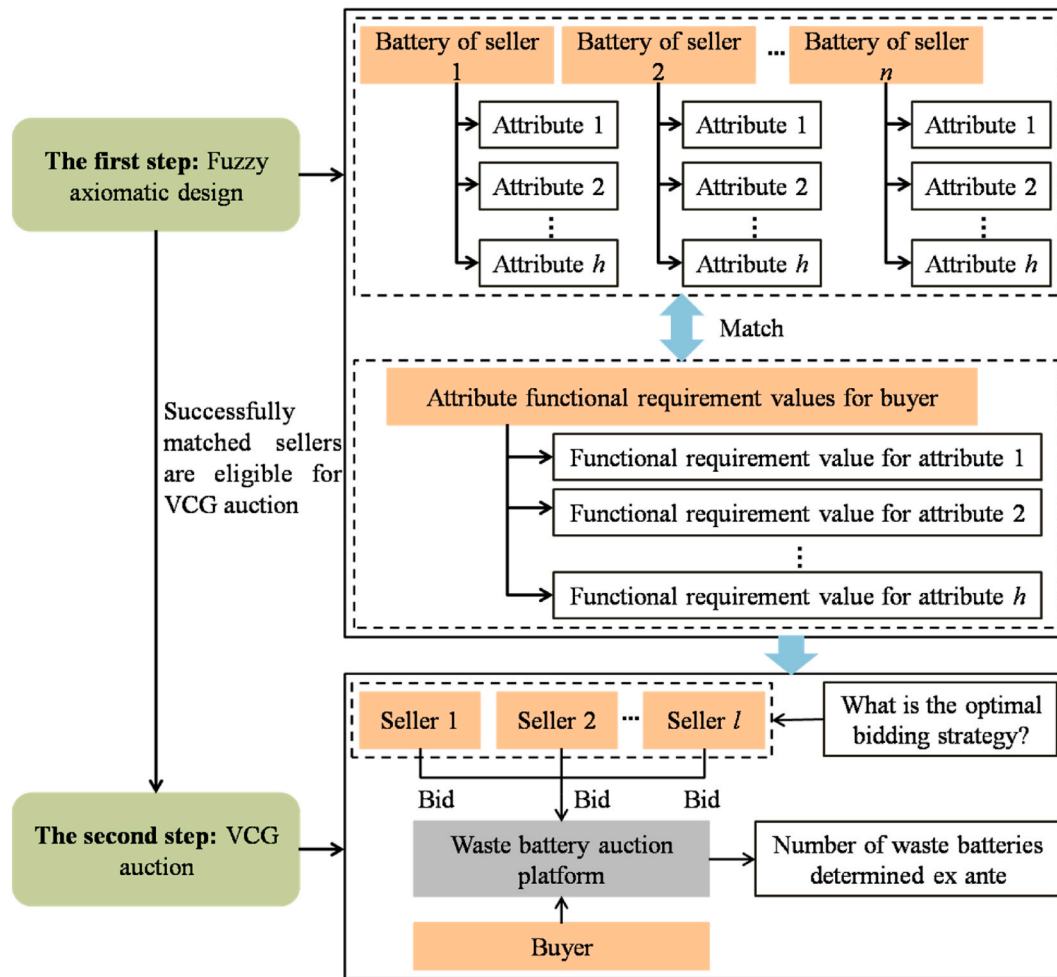


Fig. 1. Waste battery recycling multi-attribute auction problem description.

Table 3

Notations.

Symbol	Definition
I	The set of sellers.
H	The set of waste batteries attributes.
L	The set of sellers entering the auction $L = \sum_{i \in I} \psi_i$.
b_i	The value of the information content of the waste battery attributes of the seller i with the functional requirements of the attributes defined by the buyer.
s_i	Seller i 's sealed bid price.
$\hat{s}_i$	Seller i 's reservation price.
w_h	Attribute h 's weight.
X	Ex ante the quantity of waste batteries determined by the buyer.
IC_{ih}	Seller i 's information content of the waste battery attribute h .
p_{ih}	The probability that seller i 's waste power battery attribute h satisfies the buyer's functional requirements.
IC_i	Information content of seller i .
ψ_i	A binary variable where $\psi_i = 1$ indicates that seller i enters into the auction, otherwise, $\psi_i = 0$.
τ	Scale control parameter.
η_i	The bid price weighting factor for seller i .
x_l	A binary variable where $x_l = 1$ indicates that seller l wins the auction, otherwise, $x_l = 0$.
ϕ_l	Externalities of seller l .

preliminary understanding of the battery's usage history, health, and disposal. Different treatment and recycling methods may be required for different types of waste batteries to ensure environmental friendliness and effective use of resources. The safety performance of waste power

batteries refers to their safety performance during use and treatment, including explosion-proof, leakage-proof, and short-circuit-proof. The safe handling and recycling of waste batteries can be ensured by assessing the safety performance. The environmental impact, on the other hand, is to assess the content of hazardous substances (e.g. heavy metals, acids, etc.) in the batteries, so that appropriate treatment measures can be taken during the recycling process to avoid environmental pollution, and the environmental impacts of the recycling process also need to be taken into account, including the energy consumption and emissions of transport, treatment and reuse. Besides, another important attribute is to assess the economic value of used batteries, first, to assess the cost of recycling used batteries, including the cost of collection, transport, sorting, and treatment; and second, to assess the market value of recyclable materials in batteries (e.g. lithium, cobalt, nickel, etc.) in order to determine the economic benefits of recycling.

Of the six attributes selected, residual capacity and self-discharge rate are described using quantitative quantities, while the remaining four attributes are difficult to describe using quantitative data due to the large amount of battery information content they contain, and are assessed in this paper through qualitative linguistic terms. The linguistic terms and the corresponding triangular fuzzy numbers are shown in Table 4.

3.3. Fuzzy axiomatic design method

The fuzzy axiomatic design approach requires that all attributes satisfy the design requirements, otherwise, the product or design corresponding to that attribute is eliminated. Let IC_{ih} denote the informa-

Table 4
Linguistic terms and the corresponding triangular fuzzy numbers.

Linguistic terms	Triangular fuzzy numbers
Very good (VG)	(0.9,1,1)
Good (G)	(0.6,0.8,1)
Fair (F)	(0.3,0.5,0.7)
Poor (P)	(0,0.2,0.4)
Very poor (VP)	(0,0,0.1)

tion content of the attribute h of the waste battery of seller i , and p_{ih} denote the probability that seller i 's waste power battery attribute h satisfies the buyer's functional requirements. Then we can get the expression of IC_{ih} as

$$IC_{ih} = \log_2 \left(\frac{1}{p_{ih}} \right), \forall i \in I, \forall h \in H \quad (1)$$

In the fuzzy axiomatic design method, the value of the buyer's requirement for the attribute is called the system range, while the value of the seller's attribute assessment is called the design range, and the overlap between the system range and the design range is called the common range, as shown in Fig. 2. It is worth mentioning that the attribute assessment values considered in this paper are interval values or linguistic variables which can be transformed into triangular fuzzy numbers. If the common range does not exist, then the waste power battery of seller i does not meet the buyer's requirements and cannot be matched. Thus, p_{ih} can be expressed by the ratio of the common range to the area of the system range with the following expression

$$p_{ih} = \frac{\text{Area of comon range}}{\text{Area of system range}}, \forall i \in I, \forall h \in H \quad (2)$$

For ease of understanding, a simple example is given to illustrate the process of calculating p_{ih} and IC_{ih} . Assuming that the buyer requires the remaining capacity attribute range of the waste battery to be [70%, 100%] (system range), and the evaluated value of the remaining capacity attribute of the waste battery of the seller i is [60%, 75%] (design range), then the common range is 75% – 70% = 5%. Thus, we can obtain $P = \frac{5\%}{100\% - 70\%} = \frac{1}{6}$ and $IC = \log_2(6) = 2.58$.

Given that different attributes have different importance, the weighted information content of the waste battery needs to be calcu-

lated. Recall that the weight of attribute h is w_h , then the weighted information content of the waste battery of seller IC_i can be determined by the following expression

$$IC_i = \sum_{h \in H} IC_{ih} w_h, \forall i \in I \quad (3)$$

Apparently, the smaller the information content IC_i , the better the match between seller i and buyer. After obtaining the information content IC_i for each seller i , the number of sellers participating in the auction needs to be determined. In this paper, we define $\tau (\tau > 1)$ as the scale control parameter, which can effectively control the number of sellers entering the auction transaction. In practical applications, the parameter τ can be dynamically adjusted based on real-time market conditions to ensure the flexibility and practicality of the auction mechanism. Therefore, for the scale control parameter τ , a reasonable range of values for τ can be determined through statistical analysis based on the platform's historical transaction data (such as the number of sellers, transaction success rate, price volatility, etc.). This paper constructs the following linear model P1 to determine the number of sellers entering the auction.

$$P1 : \min IC = \sum_{i \in I} IC_i \psi_i \quad (4)$$

$$s.t \sum_{i \in I} \psi_i \geq \tau X \quad (5)$$

$$\psi_i \in \{0, 1\}, \forall i \in I \quad (6)$$

ψ_i is a binary variable where $\psi_i = 1$ indicates that seller i enters into the auction, otherwise, buyer i is excluded. X denotes ex ante determined the quantity of waste power batteries. The objective function (4) denotes the minimization of the information content of all sellers entering into the auction; the constraints (5) denote the number of sellers entering into the auction and are not less than the τX .

3.4. Affine maximizer VCG auction

3.4.1. The model

If one of seller l 's waste battery attributes does not meet the buyer's needs, then seller l is not eligible to enter the auction platform to match with the buyer. For example, if the buyer needs lithium batteries and seller l sells lead-acid batteries, then seller l is not eligible to match the buyer. Besides, all sellers who meet the buyer's needs can be matched with the buyer, and the platform can control the number of sellers matched with the buyer through parameter τ . The parameter τ is important because it adjusts the number of sellers and thus affects the outcome of the auction transaction.

Indeed, in the affine maximizer VCG auction, the number of sellers participating in the auction is $L (L = \sum_{i \in I} \psi_i)$, and the bid price of seller l is s_l . Recall that it is common knowledge that any seller l has a quantity y_l of waste batteries and a buyer has a pre-determined quantity X of waste batteries to recycle. It is worth noting that y_l in this paper is a unit quantity of batteries, i.e., $y_l = 1$. Let η_l be the bid price weighting factor for seller l , which is related to the information content of seller l in Section 3.3. In this paper, the information content of the seller's used batteries refers to the degree of deviation between the actual characteristics of the used batteries sold by the seller (such as battery capacity, health status, etc.) and the buyer's expectations. The smaller the information content, the closer the seller's battery characteristics align with the buyer's expectations; the larger the information content, the greater the discrepancy between the seller's battery characteristics and the buyer's expectations. By applying a weighted treatment to sellers' quotes, η_l can guide the auction mechanism to prioritize sellers whose offerings better match buyer demands, thereby optimizing auction efficiency and fairness. For example, the smaller the information content of a seller, which indicates that the waste batteries sold by that seller are

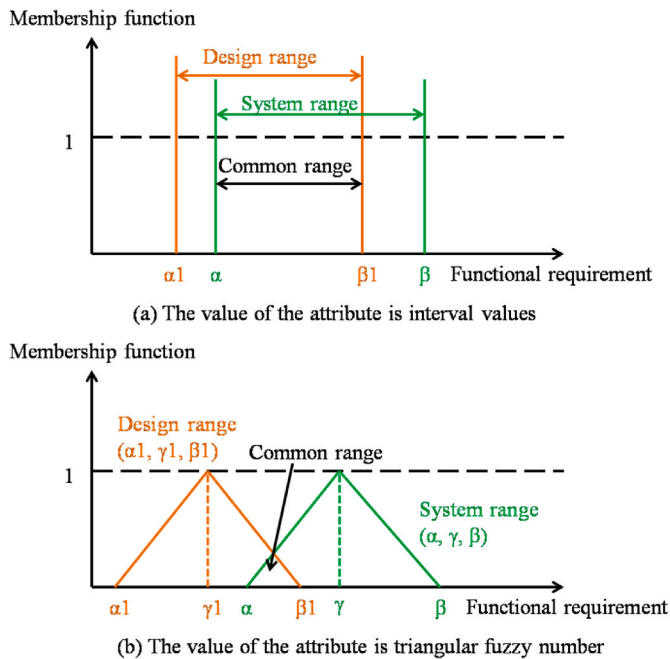


Fig. 2. Relationship between system, design and common range.

very much in line with the buyer's expectations, the smaller the bid price weighting factor η_l for seller l . Obviously, consideration of the weighting factor facilitates transactions in waste battery auctions, and better match the buyer's expectations. Assume that each seller l has an externality on the other sellers, denoted by ϕ_l . Considering the above information, the problem of minimizing total cost can be formulated as the following P2 model:

$$P2 : \pi(L) = \min \sum_{l \in L} \eta_l s_l x_l + \phi_l \quad (7)$$

$$s.t. \quad \sum_{l \in L} x_l \geq X \quad (8)$$

$$x_l \in \{0, 1\}, \forall l \in L \quad (9)$$

$$\eta_l > 0, \forall l \in L \quad (10)$$

x_l is a binary variable where $x_l = 1$ indicates that seller l wins the auction, otherwise, seller l is excluded. Assume that the value of model P2 is $\pi(L)$, while $\pi(L \setminus \{l\})$ denotes the value after excluding seller l from the model. The objective function (7) denotes the minimization of the total purchase cost; the constraints (8) denote that the buyer's demand can be met.

3.4.2. Mechanism

Let $\pi(L)$ be the optimal value of the objective function (7), while $\pi(L \setminus \{l\})$ denotes the optimal value of the objective function (7) after excluding the seller l . It is worth noting that the system is assumed to still have the optimal value of model P2 after excluding seller l . Then if seller l becomes the winner of model P2, the expression for the payment P_l he/she will receive is as follows

$$P_l = \frac{1}{\eta_l} \{ \eta_l s_l + \phi_l - [\pi(L) - \pi(L \setminus \{l\})] \} \quad (11)$$

Eq. (11) can be written as $P_l = s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l}$. Then the utility μ_l of seller l can be expressed as

$$\mu_l = \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l} \quad (12)$$

Indeed, the buyer has a reservation price, defined as RP , for the purchase of a quantity of waste batteries, X . The buyer is then required to pay a payment of BP , which is expressed as follows

$$BP = \sum_{l=1}^X \left\{ s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l} \right\} \quad (13)$$

If $BP \leq RP$ holds, then the trade succeeds, otherwise, the trade fails. As a result, based on the above analysis, the affine maximizer VCG auction mechanism procedure proposed herein is as follows:

- 1) Collect the seller's bid price s_l and the buyer's ex ante determined quantity X of waste batteries.
- 2) Collect the number of sellers $L = \sum_{i \in I} \psi_i$ eligible to enter the auction obtained from model P1.
- 3) The optimal value is computed from model P2 and the payment received by seller l is calculated by Eq. (11).
- 4) Calculate the buyer's payment BP from Eq. (13) and compare it with RP . If $BP \leq RP$ holds, then the auction is successful, otherwise, the auction fails.

3.4.3. Properties

Theorem 1. In affine maximizer VCG auction, seller l 's dominant strategy is to bid truthfully.

Proof. If seller $l (l \in L)$ submits a truthful reservation price of s_l , then s/he expects to receive payment $P_l = s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l}$ when s/he wins

the auction, and the utility of seller l is $\mu_l = \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l}$. Thus, the result welfare is

$$\pi(L) = \sum_{l \in L} \eta_l s_l x_l + \phi_l \quad (14)$$

If $s'_l \neq s_l$ holds, then s/he expects to receive payment P'_l

$$P'_l = s'_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi'(L)}{\eta_l} \quad (15)$$

where $s'_l \neq s_l$ denotes that seller l 's reservation value s_l is not equal to the bid price s'_l . And the result welfare is

$$\pi'(L) = \eta_l s'_l + \phi_l + \left(\sum_{k \in L \setminus \{l\}} \eta_k s_k x_k + \phi_k \right) \quad (16)$$

where, x_k denote the optimal solution to $\pi'(L)$. If it is more beneficial for the seller l to misrepresent the bid price, then it must be satisfied that the

$$P'_l = s'_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi'(L)}{\eta_l} > P_l = s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l} \quad (17)$$

Simplification of inequality (17) yields

$$\pi(L) > \eta_l s_l + \phi_l + \left(\sum_{k \in L \setminus \{l\}} \eta_k s_k x_k + \phi_k \right) \quad (18)$$

This contradicts the fact that $\pi(L)$ is an efficient allocation. It is clear that seller l 's misrepresentation of the bid price does not lead to an increase in utility. Thus, seller l 's optimal strategy is to bid truthfully.

Theorem 2. The affine maximizer VCG auction is individually rational and budget balance.

Proof. If seller l wins, then s/he has utility $\mu_l = \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l}$ and receives payment $P_l = s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l}$. Apparently, as long as seller l bids truthfully and wins, then s/he always has positive utility, even if seller l bids truthfully and fails to be the winner, his/her utility is zero. Thus, the proposed mechanism is individually rational. Furthermore, in affine maximizer VCG auction, the buyer's payment BP is $BP = \sum_{l=1}^X \left\{ s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l} \right\}$ and the buyer has a reservation value RP . If $BP \leq RP$ holds, then the auction is successful, otherwise, the auction fails. Thus, the affine maximizer VCG auction is budget balance.

Proposition 1. In the affine maximizer VCG auction, if the seller l has a larger weight factor η_l , the smaller the payment received, and conversely, the larger the payment received.

Proof. Assume that seller l has weight η_l and wins the auction, then s/he receives payment $P_l = s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l}$. If her/his weighting factor changes to η_l^* , then s/he will receive a payment of $P_l^* = s_l + \frac{\phi_l + \pi(L \setminus \{l\}) - \pi^*(L)}{\eta_l^*}$. Suppose $0 < \eta_l < \eta_l^*$ holds, then

$$P_l - P_l^* = \frac{\phi_l + \pi(L \setminus \{l\}) - \pi(L)}{\eta_l} - \frac{\phi_l + \pi(L \setminus \{l\}) - \pi^*(L)}{\eta_l^*} \quad (19)$$

where

$$\pi^*(L) = \eta_l^* s_l + \phi_l + \left(\sum_{k \in L \setminus \{l\}} \eta_k s_k x_k + \phi_k \right) \quad (20)$$

$$\pi(L \setminus \{l\}) = \sum_{k \in L \setminus \{l\}} \eta_k s_k x_k + \phi_k \quad (21)$$

$$\pi(L) = \eta_l s_l + \phi_l + \left(\sum_{k \in L \setminus \{l\}} \eta_k s_k x_k + \phi_k \right) \quad (22)$$

Bringing Eqs. (20)–(22) into Eq. (19) yields

$$P_l - P_l^* = \frac{(\eta_l^* - \eta_l)}{\eta_l \eta_l^*} \left(\sum_{k \in L \setminus \{l\}} \eta_k s_k x_k - \sum_{k \in L \setminus \{l\}} \eta_k s_k x_k' \right) \quad (23)$$

It is worth noting that since the number of sellers is determined ex ante, there is $x_k > x_k'$ holds in Eq. (23). Therefore, it is obvious that $\sum_{k \in L \setminus \{l\}} \eta_k s_k x_k - \sum_{k \in L \setminus \{l\}} \eta_k s_k x_k' > 0$ holds. Furthermore, $\eta_l^* - \eta_l > 0$ holds by the known conditions ($0 < \eta_l < \eta_l^*$). As a result, Eq. (23) is greater than zero holds, i.e., $P_l - P_l^* > 0$. Proposition 1 indicates that as long as the attributes of seller l 's waste battery match the buyer's demand more closely, the smaller the weight is, the easier it is for seller l to become the winner and receive a larger payment. Indeed, this phenomenon is very much in line with the real world scenario where, in practice, if the seller's battery attributes match the buyer's expectations, even if the seller's bid price is slightly higher, it can be regulated by the weighting coefficients and become a winner.

3.5. Framework for the proposed methodology

This paper constructs an integrated analytical framework model for the waste battery recycling, as shown in Fig. 3. The auction rules are

announced by the platform before the auction starts. The seller submits the bidding information for waste power batteries, and the buyer submits the number of waste batteries to be purchased for this auction. The battery attribute information submitted by the seller will be evaluated by the platform or a third-party evaluation company and the evaluation report will be uploaded. The buyer submits the functional requirements of the waste batteries attributes, and then the system calculates the information content of waste batteries between each seller and the buyer. Then the platform determines the parameter τ and determines the number of sellers participating in the auction L ($L = \sum_{i \in I} \psi_i$) by model P1. Then the winner determination set is determined by model P2 and the payment that the buyer needs to pay to each winning seller is calculated. Finally, the total payment from the buyer is calculated and if the total payment is less than or equal to the buyer's reservation value, the transaction succeeds; otherwise, the transaction fails.

3.6. An example

A simple example is used in this section to illustrate the calculation process of the proposed method. Assuming an auction network consisting of one auctioneer, one buyer, and six sellers, each seller has one waste battery for sale, and the buyer's pre-determined quantity of

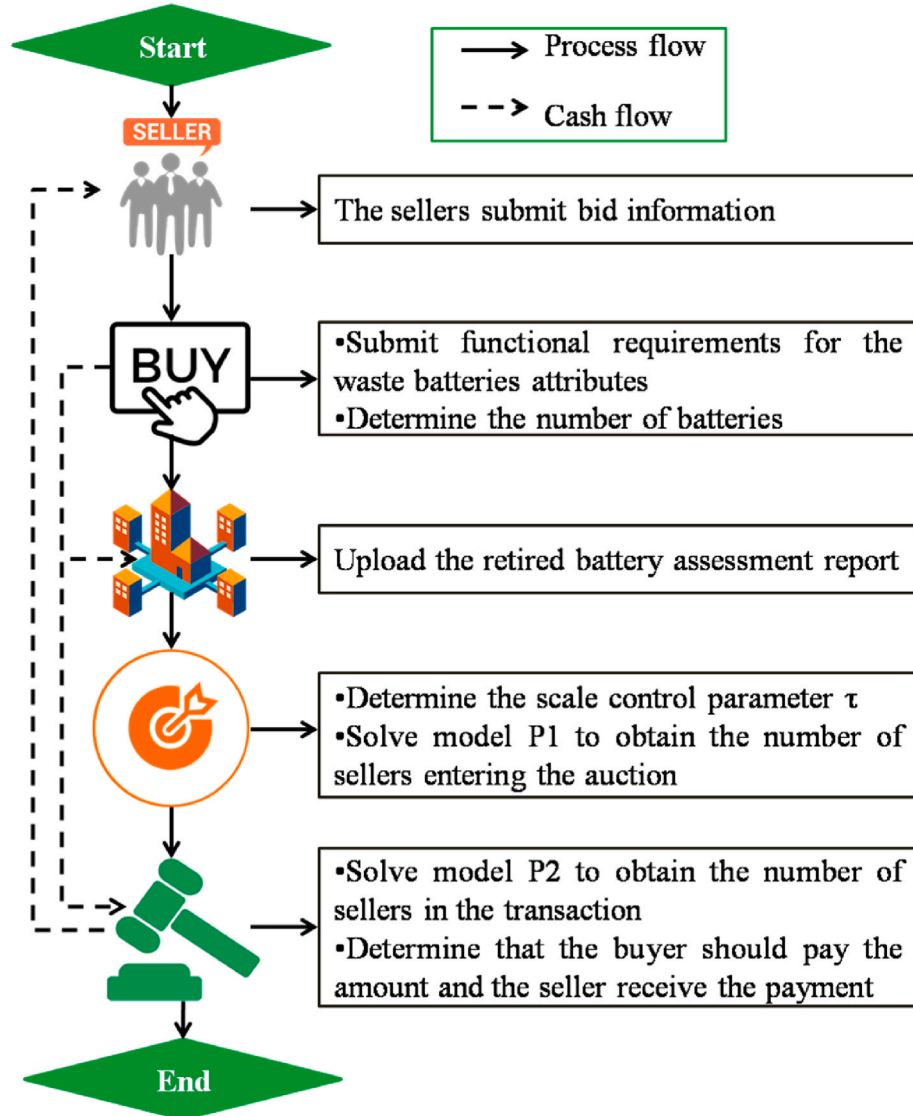


Fig. 3. Implementation steps of the proposed method.

batteries to be recycled is $X = 2$. The value of parameter τ is 1.6, and the evaluation information of the waste battery attribute is shown in Table 5. The functional requirements of the buyer for the residual waste battery power attribute are the interval value [70 %, 100 %], for the self-discharge rate attribute is a monthly self-discharge rate of the interval value [0, 1 %], and for the physical condition, safety performance, environmental impact, and economic value is (0.6, 1, 1). The buyer assigns a weight of $w_h = (0.21, 0.15, 0.18, 0.15, 0.16, 0.15)$ to the attributes. Besides, the bid information, bid weight coefficients and externality information for each seller i are shown in Table 6.

In this paper, we illustrate the calculation process of the fuzzy axiomatic design method by calculating the remaining capacity information content of seller 1 as an example. The buyer requires the remaining capacity attribute range of the waste battery to be [70%, 100%] (system range), and the evaluated value of the remaining capacity attribute of the waste battery of the seller 1 is [65%, 73%] (design range), then the common range is $73\% - 70\% = 3\%$. Thus, we can obtain $P = \frac{3\%}{100\% - 70\%} = \frac{1}{10}$ and $IC = \log_2(10) = 3.32$. As a result, the information content of each seller i 's waste battery attributes can be obtained, as shown in Table 4. Finally, the weighted information content of each seller i is calculated, for example, taking seller 1 as an example, its weighted information content is $IC_1 = 3.32 \times 0.21 + 0 \times 0.15 + 0.58 \times 0.18 + 0 \times 0.15 + 0 \times 0.16 + 0.58 \times 0.15 = 0.89$. The sellers' weighted information content is shown in Table 7. Note that the remaining capacity of seller 6's waste battery does not satisfy the buyer's functional requirements, so seller 6's information content is infinite, and to this end, seller 6 is eliminated.

Taking the above information content values of sellers 1 to 5 into model P1, it can be obtained that sellers 1 to 4 will enter the auction stage and seller 5 is eliminated due to his/her large information content, i.e., $L = \sum_{i \in I} \psi_i = 4$. Bringing the data information for sellers 1 to 4 from Table 6 into model P2 yields the optimal value $\pi(4) = 13.4$. Sellers 1 and 4 win, and seller 1 will receive payment $P_1 = s_1 + \frac{\phi_1 + \pi(4) - \pi(1)}{\eta_1} = 9 + \frac{0.8 + 13.4 - 13.4}{0.6} = 10.5$ with utility $\mu_1 = 1.5$; while seller 4 will receive payment $P_4 = s_4 + \frac{\phi_4 + \pi(4) - \pi(4)}{\eta_4} = 12 + \frac{0.3 + 13.4 - 13.4}{0.5} = 12.6$ with utility $\mu_4 = 0.6$.

4. Numerical study

In this section, the validity and rationality of the proposed method will be explored through a numerical study.

4.1. Data collection

To simplify the calculation process, it is assumed that there are 90 sellers, and the results of the information content of the waste battery attribute h of seller i , calculated by Eqs. (1) and (2) introduced in Section 3.3, are shown in Table A1 in Appendix A. The corresponding weights of each attribute take the values of $w_1 = 0.21$, $w_2 = 0.15$, $w_3 = 0.18$, $w_4 = 0.15$, $w_5 = 0.16$ and $w_6 = 0.15$. Besides, the bid information s_i , bid weight coefficients η_i and externality information ϕ_i for each seller i are shown in Table A2 in Appendix A. Recall that in the previous section, it was assumed that each seller corresponds to one waste battery for sale, and therefore, the number of waste batteries to be purchased by the

Table 6

Bid information, bid weight coefficients and externality information.

Seller	1	2	3	4	5	6
s_i	9	10	7	12	15	13
η_i	0.6	0.8	0.9	0.5	1	0.9
ϕ_i	0.8	0.7	0.2	0.3	-1.3	0.7

buyer determined ex ante is $X = 30$. The parameter τ takes the value of 1.5.

4.2. Determine the set of sellers entering the auction

The information content of each seller i in Table A1 is calculated by Eq. (3), and then the relevant data is substituted into model P1, which can get the information of sellers participating in the auction, as shown in Table 5. Note that the seller numbers matched by model P1 in Table 8 are the corresponding seller numbers in the original Table A1. For example, in the first column of Table 8, the seller numbers 1, 10 and 11, etc. matched by model P1 correspond to sellers 1, 10 and 11, etc. in the original Table A1. In model P2, the numbering sequence of the sellers in columns 1, 6, and 11 of the table are reordered from 1 to 45, respectively.

4.3. Determine the set of winning sellers

Then the corresponding data information in Table 8 is substituted into model P2, from which the optimal value $\pi(L)$ can be obtained as 162.94. The utility and payments received by each winning seller are shown in Table 9. The buyer has to pay a total cost of 582.1, while the seller's total utility (STU) has a value of 237.13. Let AC represent the unit cost of the recycled waste batteries for the buyer, i.e. $AC = \frac{582.1}{30} = 19.4$. Let AU represent the average utility of the winning seller, i.e. $AU = \frac{237.13}{30} = 7.9$. Let AIC represent the average information content of waste power batteries of the winning seller, i.e. $AIC = \frac{34.64}{30} = 1.15$.

4.4. Sensitivity analysis

In this section, the sensitivity analysis of the proposed method is performed in several dimensions, including the impact of the change in the number of sellers on the outcome, the impact of the change in the attribute weights on the outcome, and the impact of the change in τ on the outcome.

4.4.1. Impact of changes in the number of sellers on results

In this paper, seller numbers 1 to 45, 1 to 60, 1 to 75, and 1 to 90 in Table A1 are selected for sensitivity analyses of changes in the number of sellers, and the results of the calculations are shown in Table 10 and Fig. 4. Noticeably, as the number of sellers increases while the number of waste batteries purchased by buyers, X , remains constant, the optimal value of model P2, $\pi(L)$, will decrease. This is because as the number of sellers participating in the bidding increases, the supply of waste electric vehicle batteries also increases, which leads to increased price competition among sellers, and thus the platform can select the seller with the lower bid for the transaction. Besides, as the number of waste batteries

Table 5

Waste battery attributes evaluation information.

Seller	Remaining capacity	Self-discharge rate	Physical state	Safety performance	Environmental impact	Economic value
1	[65 %, 73 %]	[0.5 %, 0.8 %]	G	VG	VG	G
2	[70 %, 78 %]	[0.7 %, 1.2 %]	VG	G	G	VG
3	[66 %, 73 %]	[0.6 %, 1.1 %]	F	VG	VG	VG
4	[72 %, 80 %]	[0.4 %, 0.8 %]	VG	G	F	G
5	[64 %, 71 %]	[0.8 %, 1.4 %]	F	G	VG	F
6	[49 %, 52 %]	[0.9 %, 1.5 %]	G	G	F	F

Table 7

Waste battery attributes information content.

Seller	Remaining capacity	Self-discharge rate	Physical state	Safety performance	Environmental impact	Economic value	IC_i
1	3.32	0	0.58	0	0.00	0.58	0.89
2	1.91	1.74	0	0.58	0.58	0.00	0.84
3	3.32	0.74	4.58	0	0.00	0.00	1.63
4	1.58	0	0	0.58	4.58	0.58	1.24
5	4.91	2.32	4.58	0.58	0.00	4.58	2.98
6	∞	3.32	0.58	0.58	4.58	4.58	∞

Table 8

The seller number matched by model P1 and the corresponding model P2 seller number.

SN	SN*	s_i	η_i	ϕ_i	SN	SN*	s_i	η_i	ϕ_i	SN	SN*	s_i	η_i	ϕ_i
1	1	5.31	0.57	-0.37	37	16	19.77	0.37	-1.96	69	31	12.23	0.60	1.61
10	2	16.99	0.45	0.33	40	17	5.44	0.57	1.95	73	32	5.99	0.65	1.32
11	3	15.88	0.51	-1.15	42	18	11.28	0.48	-0.46	74	33	14.54	0.55	-0.09
12	4	16.14	0.68	-1.42	45	19	6.41	0.36	-0.75	76	34	8.78	0.50	-0.60
13	5	18.95	0.62	0.05	46	20	8.54	0.47	0.89	77	35	18.01	0.60	-1.04
14	6	5.51	0.64	-0.75	47	21	11.81	0.59	-1.97	79	36	19.30	0.61	1.62
17	7	7.59	0.52	0.58	49	22	14.18	0.69	-0.55	80	37	19.71	0.62	1.62
19	8	8.32	0.63	-1.67	51	23	14.19	0.71	-1.72	81	38	10.61	0.17	0.33
27	9	19.69	0.39	-1.90	55	24	11.53	0.62	-1.02	82	39	13.27	0.34	1.75
28	10	6.96	0.40	1.89	59	25	8.05	0.35	1.22	83	40	17.38	0.51	1.10
30	11	9.88	0.53	-1.95	60	26	15.44	0.64	-0.93	84	41	19.18	0.57	1.93
31	12	19.64	0.63	1.61	61	27	12.85	0.63	0.96	85	42	16.59	0.70	-0.32
33	13	12.12	0.72	-0.69	62	28	13.96	0.47	1.74	86	43	11.32	0.57	0.34
35	14	19.55	0.43	1.81	66	29	19.70	0.64	0.21	88	44	7.52	0.57	-1.18
36	15	15.44	0.49	-1.50	67	30	19.93	0.24	0.59	90	45	14.90	0.58	-0.88

Note: SN denotes the seller number matched by model P1; SN* denotes the seller number in model P2.

Table 9

Utility and payments received by each winning seller.

SN	SN*	P_i	μ_i	SN	SN*	P_i	μ_i	SN	SN*	P_i	μ_i
1	1	15.22	9.91	36	15	17.60	2.16	62	28	18.39	4.43
10	2	19.20	2.21	37	16	23.35	3.58	67	30	36.29	16.36
11	3	16.94	1.06	40	17	15.17	9.73	69	31	14.41	2.17
14	6	13.48	7.97	42	18	18.02	6.74	73	32	13.31	7.32
17	7	16.64	9.05	45	19	24.09	17.67	74	33	15.71	1.17
19	8	13.67	5.35	46	20	18.42	9.88	76	34	17.23	8.45
27	9	22.17	2.48	47	21	14.62	2.82	81	38	51.84	41.23
28	10	21.74	14.77	55	24	13.95	2.42	82	39	25.39	12.12
30	11	16.35	6.46	59	25	24.91	16.86	86	43	15.14	3.82
35	14	20.07	0.53	61	27	13.70	0.85	88	44	15.08	7.56

Table 10

Result affected by changing number of sellers.

Number of sellers	τ	X	$\pi(L)$	BP	AC	STU	AU	AIC
45	1.5	30	222.15	598.46	19.95	251.03	8.37	1.60
60			191.64	599.51	19.98	257.09	8.57	1.40
75			177.14	583.54	19.45	240.37	8.01	1.28
90			162.94	582.10	19.40	237.13	7.90	1.15

increases, the buyer is better able to match the suitable waste batteries, primarily because as the number of used batteries increases, the buyer has more choices and can more easily identify the required number of waste batteries. It is noticeable that despite the increase in the number of sellers, the average price at which buyers purchased waste batteries and the utility received by sellers did not change much, as can be seen from the values of AC and AU in Table 10. Overall, however, the BP (Buyers' payments), AC and AU values decrease slightly as the number of batteries waste increases. This may be related to the bid weight coefficients of each seller and the externality between sellers.

4.4.2. Impact of changes in attribute weights on results

This subsection aims to investigate how different combinations of

attribute weights impact auction results. This paper selects four different weight combinations (e.g. scenario 1 is (0.21, 0.15, 0.18, 0.15, 0.16, 0.15), scenario 2 is (0.11, 0.25, 0.18, 0.15, 0.16, 0.15), scenario 3 is (0.2, 0.15, 0.28, 0.15, 0.16, 0.15), and scenario 4 is (0.2, 0.15, 0.28, 0.25, 0.16, 0.15)), and the information and results are presented in Table 11 and Fig. 5. It is worth noting that in this paper, the rules for determining attribute weights were established through consensus reached after multiple rounds of discussions among buyer experts, combining the actual needs of the battery recycling market with expert experience. As can be seen from Table 11 and Fig. 5, different weight combinations have a significant impact on auction results. This is because the fuzzy axiomatic design method calculates the information content of each used battery, which is affected by different weight combinations. This,

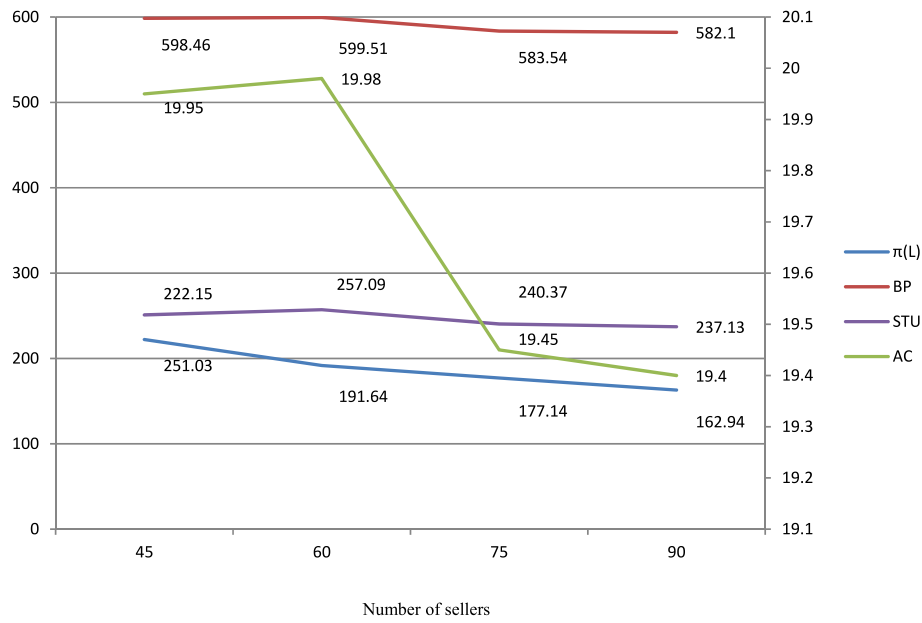


Fig. 4. The impact of changes in the number of sellers on the results.

Table 11
Result affected by changing attribute weights.

Scenarios	Number of sellers	τ	X	$\pi(L)$	BP	AC	STU	AU	AIC
Scenario 1	90	1.5	30	162.94	582.10	19.40	237.13	7.90	1.15
Scenario 2				164.94	532.08	17.74	205.34	6.84	1.18
Scenario 3				161.79	558.36	18.61	222.74	7.42	1.10
Scenario 4				166.34	530.55	17.69	200.25	6.68	1.19

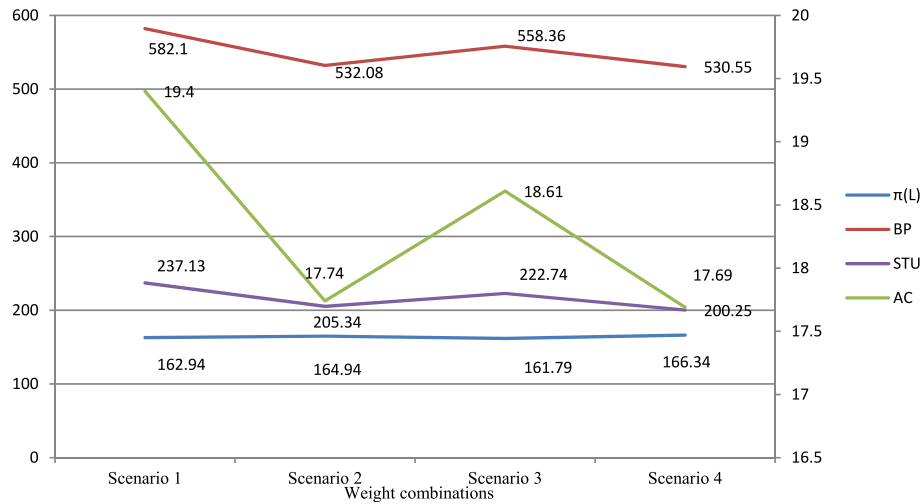


Fig. 5. The impact of changes in attribute weights on the results.

in turn, affects whether the seller participates in the auction or not. This is also more realistic. For example, a waste battery secondary utilization operator may be more concerned with remaining capacity attributes than a battery dismantler. Different concerns about the recycling value of waste batteries are held by different recyclers and therefore different attribute weights need to be assigned.

4.4.3. Impact of changes in the parameter τ on results

In this section, the effect of the variation of the control parameter τ on the results of the auction is further investigated. Taking the values of

Table A1 and Table A2 in Appendix A as an example, the results are shown in Table 12 and Fig. 6, assuming that the parameter τ takes the values 1.1, 1.5, 1.9, 2.3, 2.5, and 2.7, respectively. An interesting finding is that as the control parameter τ increases, the model P2 optimal value $\pi(L)$ first decreases and then increases, but the increase is not significant. While BP, AC, and AU decrease to a specific value as parameter τ increases, their values do not change regardless of how parameter τ changes. AIC increases as parameter τ increases and then increases to a specific value where AIC remains constant. This is because as the control parameter τ increases, it means that the number of sellers entering the

Table 12Result affected by changing the parameter τ .

τ	X	$\pi(L)$	BP	AC	STU	AU	AIC
1.1	30	185.37	802.40	26.75	420.64	14.02	1.13
1.5		162.94	582.10	19.40	237.13	7.90	1.15
1.9		162.31	519.67	17.32	203.49	6.78	1.23
2.3		158.28	488.23	16.27	184.74	6.16	1.26
2.5		160.17	488.23	16.27	184.74	6.16	1.26
2.7		160.35	488.23	16.27	184.74	6.16	1.26

auction increases, leading to a competitive incentive in the seller's market, where buyers are able to purchase waste batteries at a lower price. Although as the parameter τ increases it helps to reduce the total recycling cost of the buyer, there is a gap between the attributes of the recycled waste batteries and the buyer's needs. In other words, the more the buyer pays for recycling if the attributes of the used batteries the buyer wishes to purchase match the used batteries provided by the seller, the higher the recycling fee the buyer pays.

4.5. Comparative analysis

In this section, the proposed method is compared with the auction method that does not consider the fuzzy axiomatic design and the auction method that does not consider the weighting coefficients and externalities. In comparison with auction methods that do not consider fuzzy axiomatic design, assuming that the waste batteries attributes are not considered, the data in Table A2 is directly brought into model P2 for auction. Besides, assuming that the seller's weight coefficients and externalities are not considered, the auction model is constructed as follows:

$$P3 : \pi(L) = \min \sum_{l \in L} s_l x_l \quad (24)$$

$$\sum_{l \in L} x_l y_l \geq X \quad (25)$$

$$x_l \in \{0, 1\}, \forall l \in L \quad (26)$$

The results obtained from model P1 are substituted into model P3 to obtain the final transaction results. And the comparison results of the above two scenarios are shown in Table 13. The following three key findings can be derived from Table 13 i) Although the total cost paid by the buyer of the method without considering the fuzzy axiomatic design

is lower than that of the method proposed in this paper, due to the lack of consideration of the multi-attribute characteristics of waste batteries, this makes the recycled waste batteries may not be able to satisfy the buyer's functional requirement for waste batteries. Nevertheless, the method proposed herein costs the buyer more, but the buyer is able to match more suitable waste batteries, which is especially important for the secondary use of waste battery recyclers, as matching suitable waste batteries can bring more value to the utilization of waste batteries. ii) Although an auction method that does not consider weighting factors and externalities reduces the buyer's cost of purchasing waste batteries, there is a significant difference in the attribute match between the used batteries that the buyer ultimately purchases and the used batteries that it expects to receive, e.g., 1.27 in Table 13 is greater than 1.15. This may be due to the fact that, in the design method that does not consider the fuzzy axiom, the buyer's bid fails to reflect the attribute requirements of the retired batteries, resulting in the selected batteries not matching the expected attributes. iii) The method proposed herein is more incentive-based for sellers because the average utility of the seller who gets a deal is greater than the auction method that does not consider weighting factors and externalities, e.g., 7.9 in Table 13 is greater than 5.48. This is because externalities in auction mechanisms may influence sellers' decisions to sell, thereby increasing sellers' expected returns when auction methods that account for externalities are employed. Additionally, the auction method proposed herein may encourage sellers to provide higher-quality goods or more accurate product information by optimizing incentive mechanisms, thereby increasing sellers' utility.

5. Discussion

The purpose of this section is to discuss the merits of the proposed method, theoretical implications, managerial insights, measures to implement the proposed methodology, and the significance of the study.

5.1. Merits of the proposed method

This paper highlights the merits of the proposed method through sensitivity analysis and a comparative evaluation with other methods.

First, this paper considers sellers' weights and externalities. Introducing a weight coefficient allows for more accurate measurement of each seller's influence on the auction results, enhancing decision-making effectiveness. Seller relationships—whether cooperative, competitive, or otherwise—can influence both the auction outcome and

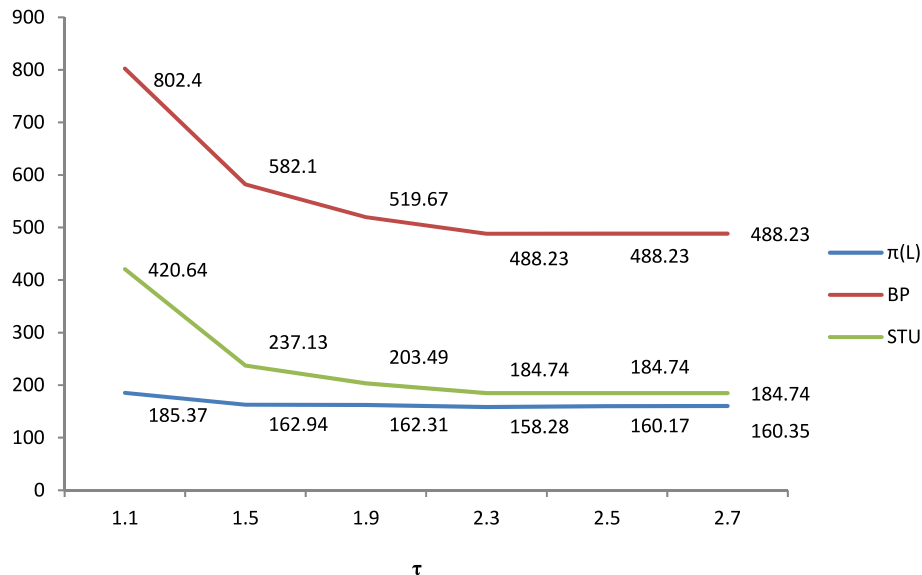


Fig. 6. The impact of changes in different control parameters on the results.

Table 13
Comparison results.

Scenarios	Number of sellers	X	τ	$\pi(L)$	BP	AC	STU	AU	AIC
The proposed method	90	30	1.5	162.94	582.10	19.40	237.13	7.90	1.15
The method without fuzzy axiomatic design			–	159.26	476.19	15.87	184.48	6.15	–
The method without weight coefficients and externalities			1.5	319.87	484.16	16.14	164.29	5.48	1.27

the decision-making process. Thus, incorporating externalities and weight coefficients helps capture these interactions, improving our understanding of the auction market's complexity.

Second, the proposed method considers the multi-attribute characteristics of waste batteries. By evaluating sellers' waste batteries against the buyer's recycling standards, it can ensure that the buyer's expectations are met, thereby improving buyer satisfaction. This, in turn, can incentivize more buyers to participate in the battery recycling auction platform. Even if the proposed method involves higher purchase costs, buyers will be able to recycle waste batteries in line with their expectations.

Third, the proposed method enhances utility compared to traditional auction. Consequently, from the perspective of incentive compatibility, the method effectively motivates sellers with waste batteries to join the auction platform. This paper introduces the control parameter τ , which regulates the number of sellers entering the auction—an important factor, as the number of participants influences auction outcomes. Thus, the number of participants can be adjusted using the control parameter τ .

5.2. Theoretical implications

Previous studies have focused on auctions for recycling waste batteries, for example, Xu et al. [20] designed a double auction method for recycling waste batteries, and Feng et al. [15] constructed a two-stage auction method for recycling waste batteries. However, few studies have focused on multi-attribute auctions for waste battery recycling. For this reason, this paper explores multi-attribute auctions for waste battery recycling from both theoretical and practical perspectives.

Traditional multi-attribute auctions are typically based on a score function [73], which is a commonly used evaluation method for determining the final outcome of the auction by scoring the multi-attribute characteristics of the services or goods offered by the participants. Although score functions are widely used in traditional multi-attribute auctions, score function-based multi-attribute auctions do not consider the degree of match between buyer and seller with respect to the good or service, i.e., the probability that the seller's good or service meets the buyer's needs. The paper fills this research gap by introducing the fuzzy axiomatic design approach, which considers the probability that the seller's good or service satisfies the buyer's demand. In particular, the method proposed herein is able to capture the uncertainty and ambiguity of the attributes of waste batteries assessed by experts, and is fault-tolerant to changes and uncertainties in the attribute values, making the decision-making results more robust and stable. Therefore, from this perspective, the method proposed herein provides a new solution for multi-attribute auctions of waste batteries and offers a potential avenue for research on multi-attribute auctions based on fuzzy axiomatic design.

More importantly, this paper introduces the weight coefficient η_1 to portray the matching degree between the seller's waste battery assessment result and the buyer. The higher the matching degree, the smaller its weight coefficient, and theoretically proves that the smaller the seller's weight coefficient η_1 , then the larger the payment she receives. The finding aligns with real-world observations, e.g., if the service or item provided by the seller matches the buyer's requirements the better, then the buyer is more willing to pay more price to buy it. Besides, this paper also introduces the control parameter τ to adjust the number of sellers participating in the auction, and from the numerical analyses, it is

also obtained that the control parameter τ has an impact on the auction results. Specifically, the price paid by the buyer decreases firstly with the increase of parameter τ and then stays the same, while the information content of the buyer's and seller's waste battery matching increases firstly and then stays the same.

5.3. Managerial implications

This paper provides several management insights into a multi-attribute for waste power batteries based on fuzzy axiomatic design, offering practical guidance for managers seeking to apply the proposed methodology.

First, the auction method proposed herein is different from the traditional second price auction. In this paper, we introduce the seller's weight factor, which is a parameter determined by the system based on the content of the seller's waste battery evaluation information. Specifically, if a seller's waste batteries are very much in line with the buyer's demand, i.e., the smaller the information content, then the platform gives the seller a certain weight based on the value of that information content. Furthermore, the smaller the weighting factor, the larger the payment received by the seller. As a result, the platform or administrator must pay particular attention to how well the waste power battery matches between the seller and the buyer.

Second, this paper introduces a control parameter τ to adjust the number of sellers participating in the auction. Although an increase or decrease in the number of participants does not affect the auction mechanism, they may affect the level of competition and the outcome of the auction. To this end, in practice, managers should consider the impact of participant numbers on the auction outcome, especially when resource allocation is involved and competition is high. In such cases, the manager may need to take measures to attract more participants or limit the number of participants to ensure the effectiveness and fairness of the auction. Controlling the number of participants helps screen those who best meet the auction's needs, improving the accuracy and quality of the results. It also motivates participants, enhancing auction efficiency and ensuring the reasonableness of the transaction price. To this end, the platform or management needs to set the value of control parameter τ according to the number of participants.

Last but not least, the numerical analyses reveal that the criteria weights of waste battery attributes have an impact on the auction results. In practice, managers need to understand the importance of different attributes in the market based on market demand and industry standards. Industry experts or relevant stakeholders should be invited to participate in the discussion to jointly determine the weight allocation of waste power battery attributes. More importantly, managers should conduct multi-party consultations and trade-offs, considering the needs and interests of all parties when making decisions on weight allocation.

5.4. Measures to implement the proposed methodology

In exploring the practical application of auction mechanisms in the used battery recycling market, it is crucial to consider how theory can be translated into practical, operational scenarios to ensure feasibility. This includes addressing the infrastructure needed for large-scale collection, validation, and analysis of battery properties. First, a well-established infrastructure must be established, with specialized collection points for used batteries, involving battery manufacturers, retailers, and waste management companies to create a widespread collection network.

Meanwhile, an efficient logistics system should be developed to ensure the timely and safe transportation of collected batteries to recycling centers, potentially in collaboration with third-party logistics providers or through specialized transport solutions. Second, collection points and recycling centers should be equipped with testing equipment to assess the chemical composition, remaining capacity, aging, and physical condition of the batteries. In addition, developing a standardized testing and assessment process will ensure that all collected batteries are evaluated consistently, ensuring data reliability. Furthermore, market participants—including consumers, recycling companies, and inspectors—should be trained through education and outreach programs to improve their understanding of the recycling process and auction mechanism. Last but not least, a centrally managed information platform is essential to record battery attributes, test results, and transaction histories, providing the necessary data to support the auction mechanism.

5.5. Significance of the study

The recovery of waste power batteries is essential for promoting resource recycling, reducing environmental pollution, and advancing green and sustainable development. Achieving this goal requires joint efforts from academia, industry, and government. Thus, this paper aims to investigate the multi-attribute auction problem of waste power battery recycling based on fuzzy axiomatic design from both theoretical and practical levels. The significance of this study is reflected in the following aspects: i) From the theoretical level, the numerical study has illustrated the effectiveness and applicability of the proposed method. By studying the application of fuzzy axiomatic design in the multi-attribute auction of waste power battery recycling, this paper promotes the innovation and development of auction theory, and provides new ideas and theoretical methods for waste power battery recycling. ii) From a practical point of view, the proposed multi-attribute auction mechanism not only better aligns demand and resources between battery suppliers and recyclers but also encourages greater participation from both parties in the recycling process. This, in turn, promotes the rational use of resources, reduces environmental pollution, and supports the sustainable development of the waste power battery recycling industry.

6. Conclusions

The development of the waste power battery recycling industry has become a global consensus. However, waste battery recycling is still facing some major challenges in the actual promotion process, such as a single recycling channel, lack of a perfect recycling network, price fluctuation, uncertainty, and information asymmetry. With respect to the multi-attribute problem in the recycling auction of waste power batteries, this paper proposes a multi-attribute auction based on the fuzzy axiomatic design for recycling waste electric vehicle batteries. Besides, a numerical study is carried out to illustrate the effectiveness of the proposed method, followed by a sensitivity analysis to assess its robustness. Finally, two key findings are obtained through comparative analysis. i) The proposed method can motivate more sellers participate in the waste battery recycling auction system. It increases the seller's utility while ensuring that buyers can recycle batteries that meet their needs, offering advantages over traditional auction methods. ii)

Compared with the traditional multi-attribute auction based on scoring function, the proposed method effectively handles the ambiguity and uncertainty in evaluating used battery attributes, enhancing the scientific accuracy of auction decision-making. This, in turn, promotes the development of the recycling market and improves resource utilization efficiency. Moreover, this paper also summarizes the proposed methods in terms of both theoretical and managerial implications, so that managers and scholars can understand and further apply these methods.

The limitations of this work include the following. First, although this paper illustrates the effectiveness of the proposed method through numerical studies, the lack of sufficient real data may limit the model's ability to accurately reflect the actual conditions of the used power battery recycling market. Second, although attribute weights significantly influence auction outcomes, this paper assumes that they are subjectively assigned by decision-makers rather than determined through quantitative methods, which may affect the final results. Finally, this paper only considers a market with one buyer and multiple sellers, without considering competition among multiple buyers. Additionally, the lack of further validation across different scenarios limits the generalizability of the study's key findings. Nevertheless, the present work can provide a new idea for subsequent research work on multi-attribute auctions, and thus we highlight important future research directions. First, it is necessary and challenging to extend the proposed approach to scenarios with multiple sellers and multiple buyers in future research. The complexity of the auction in this scenario will be greatly increased and more factors and interactions need to be considered. Second, an important direction for future research is the empirical study of collusion in the analysis of auction mechanisms, examining the mechanisms by which collusion occurs and its impact on the outcome of auctions through the analysis of actual auction cases. Third, the introduction of a model of strategic bidding is considered to analyze the performance of different auction mechanisms in the face of strategic bidding, and to explore how to optimize the design of auctions to reduce the occurrence of misconduct. Finally, future research should further validate the effectiveness of the methods proposed in this paper under different application scenarios and the new insights they may bring.

CRedit authorship contribution statement

Jianghong Feng: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Feng Chen:** Writing – review & editing, Software, Resources, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Information content.

Seller	IC_{i1}	IC_{i2}	IC_{i3}	IC_{i4}	IC_{i5}	IC_{i6}	Seller	IC_{i1}	IC_{i2}	IC_{i3}	IC_{i4}	IC_{i5}	IC_{i6}
1	1.98	0.86	0.29	1.89	1.01	1.98	46	1.57	1.56	0.03	0.96	0.85	1.72
2	1.83	3.35	0.84	3.32	2.50	2.99	47	2.74	1.26	0.14	0.97	0.79	2.31
3	1.43	3.8	0.98	3.07	2.62	2.78	48	2.7	3.94	0.88	2.56	2.46	3.45
4	2.88	2.87	0.76	0.79	1.47	2.70	49	0.22	2.78	0.18	3.34	2.10	2.00
5	2.02	2.61	0.79	1.2	1.53	2.22	50	2.28	2.36	0.08	2.98	1.81	3.01
6	2.89	3.74	0.51	1.61	1.95	3.29	51	1.17	2.47	0.56	2.37	1.80	2.08
7	2.05	2.91	0.46	3.45	2.27	3.11	52	1.83	3.99	0.13	3.51	2.54	3.40
8	2.33	3.5	0.19	1.96	1.88	3.05	53	2.41	0.51	0.87	3.23	1.54	2.42
9	2.51	2.32	0.51	2.98	1.94	3.04	54	0.39	3.68	0.06	3.3	2.35	2.39
10	0.27	3.15	0.2	0.59	1.31	1.28	55	1.39	0.41	0.95	3	1.45	1.68
11	0.84	0.24	0.79	2.97	1.33	1.33	56	2.75	2.1	0.89	3.99	2.33	3.35
12	1.23	3.38	0.92	0.86	1.72	1.85	57	2.18	2.03	0.48	2.63	1.71	2.65
13	1.8	3.02	0.39	0.41	1.27	2.06	58	1.78	2.09	0.7	2.56	1.78	2.36
14	2.6	1.5	0.48	1.07	1.02	2.25	59	0.08	1.58	0.24	1.4	1.07	0.92
15	2	3.09	0.78	2.8	2.22	2.86	60	1.42	1.38	0.75	2.37	1.50	1.85
16	2.42	1.99	0.57	2.98	1.85	2.87	61	2.12	0.76	0.62	2.2	1.19	2.06
17	0.17	1.24	0.81	2.82	1.62	1.19	62	1	1.5	0.76	1.13	1.13	1.25
18	2.96	3.54	0.19	3.79	2.51	4.01	63	2.41	2.18	0.03	2.89	1.70	3.02
19	1.21	1.14	0.74	2.82	1.57	1.79	64	0.34	3.29	0.81	2.48	2.19	1.82
20	0.56	3.84	1	3.35	2.73	2.35	65	2.32	2.23	0.31	2.79	1.78	2.88
21	1.98	3.83	0.81	1.34	1.99	2.62	66	2.01	3.07	0.43	0.27	1.26	2.15
22	1.03	2.24	0.87	2.92	2.01	2.03	67	0	0.47	0.52	1.34	0.78	0.45
23	2.58	2.13	0.58	1.72	1.48	2.62	68	2.91	2.43	0.98	0.31	1.24	2.38
24	0.76	3.19	0.78	2.88	2.28	2.17	69	0.82	3.06	0.93	0.86	1.62	1.50
25	1	3.59	0.78	3.51	2.63	2.64	70	0.87	3.96	0.68	2.78	2.47	2.47
26	2.09	3.76	0.71	2.38	2.28	3.01	71	2.36	2.81	0.86	2.44	2.04	2.86
27	0.1	0.52	0.04	2.99	1.18	1.14	72	0.02	3.63	0.15	3.41	2.40	2.17
28	0.61	2.27	0.51	0.34	1.04	1.06	73	0.09	1.26	0.98	3.98	2.07	1.47
29	2.92	0.35	0.07	3.79	1.40	3.02	74	2.98	0.59	0.99	0.23	0.60	1.82
30	1.56	0.03	0.64	2.56	1.08	1.60	75	2.83	3.92	0.6	0.51	1.68	2.94
31	1.13	0.68	0.23	3.78	1.56	2.01	76	1.28	2.03	0.01	1.19	1.08	1.77
32	0.2	3.52	1	3.77	2.76	2.17	77	2.75	2.21	0.15	0.02	0.79	2.31
33	0.9	1.84	0.68	3.32	1.95	1.99	78	1.24	2.82	0.59	3.92	2.44	2.71
34	2.8	2.5	0.59	3.26	2.12	3.34	79	0.87	2.65	0.47	1.74	1.62	1.78
35	2.78	0.43	0.3	0.09	0.27	1.76	80	2.36	0.97	0.17	1.94	1.03	2.28
36	1.78	0.18	0.89	1.63	0.90	1.43	81	0.14	0.72	0	0.68	0.47	0.52
37	1.24	1.41	0.28	0.37	0.69	1.24	82	1.61	0.84	0.41	0.13	0.46	1.18
38	2.39	3.84	0.96	2.43	2.41	3.17	83	0.1	0.97	0.19	3.56	1.57	1.43
39	1.34	3.25	0.1	2.27	1.87	2.50	84	1.43	0.9	0.02	2.75	1.22	1.99
40	1.94	1.48	0.59	1.11	1.06	1.84	85	2.38	1.39	0.15	2.24	1.26	2.52
41	2.97	3.15	0.72	0.13	1.33	2.64	86	2.43	1.17	0.4	1.01	0.86	2.05
42	0.59	1.55	0.43	1.92	1.30	1.34	87	2.54	3.14	0.92	0.34	1.47	2.40
43	2.96	1.57	0.13	3	1.57	3.17	88	1.59	0.87	0.83	2	1.23	1.66
44	2.89	2.79	0.02	2.05	1.62	3.24	89	2.31	1.87	0.85	3.22	1.98	2.78
45	2.4	0.19	0.04	0.29	0.17	1.58	90	1.88	2.06	0.09	1.07	1.07	2.08

Table A2
Bid information, bid weighting factors and externality information for all sellers.

Seller	s_i	η_i	ϕ_i	Seller	s_i	η_i	ϕ_i	Seller	s_i	η_i	ϕ_i
1	5.31	0.57	-0.37	31	19.64	0.63	1.61	61	12.85	0.63	0.96
2	8.39	1.01	1.25	32	12.84	0.88	-0.57	62	13.96	0.47	1.74
3	11.34	0.99	0.23	33	12.12	0.72	-0.69	63	19.92	0.84	-1.66
4	18.64	0.82	1.68	34	11.19	1.01	0.55	64	12.74	0.72	1.35
5	14.63	0.73	-1.57	35	19.55	0.43	1.81	65	17.86	0.85	-0.66
6	15.58	0.97	-0.64	36	15.44	0.49	-1.50	66	19.70	0.64	0.21
7	10.39	0.97	0.11	37	19.77	0.37	-1.96	67	19.93	0.24	0.59
8	14.80	0.89	1.95	38	12.80	1.05	0.95	68	10.19	0.74	0.05
9	8.78	0.92	1.68	39	18.27	0.76	1.07	69	12.23	0.60	1.61
10	16.99	0.45	0.33	40	5.44	0.57	1.95	70	12.95	0.88	1.77
11	15.88	0.51	-1.15	41	7.37	0.78	1.82	71	19.59	0.93	-1.10
12	16.14	0.68	-1.42	42	11.28	0.48	-0.46	72	16.64	0.76	1.84
13	18.95	0.62	0.05	43	16.36	0.87	-1.80	73	5.99	0.65	1.32
14	5.51	0.64	-0.75	44	13.70	0.88	0.76	74	14.54	0.55	-0.09
15	15.16	0.94	0.68	45	6.41	0.36	-0.75	75	11.90	0.88	-1.42
16	18.11	0.88	-0.91	46	8.54	0.47	0.89	76	8.78	0.50	-0.60
17	7.59	0.52	0.58	47	11.81	0.59	-1.97	77	18.01	0.60	-1.04
18	7.50	1.17	-1.89	48	11.12	1.10	-1.65	78	9.92	0.92	0.50

(continued on next page)

Table A2 (continued)

Seller	s_i	η_i	ϕ_i	Seller	s_i	η_i	ϕ_i	Seller	s_i	η_i	ϕ_i
19	8.32	0.63	−1.67	49	14.18	0.69	−0.55	79	19.30	0.61	1.62
20	17.41	0.92	0.34	50	11.75	0.86	−1.52	80	19.71	0.62	1.62
21	11.16	0.87	1.75	51	14.19	0.71	−1.72	81	10.61	0.17	0.33
22	15.59	0.75	−1.33	52	16.41	1.04	0.73	82	13.27	0.34	1.75
23	19.29	0.78	−1.71	53	13.33	0.77	1.57	83	17.38	0.51	1.10
24	17.10	0.80	−1.06	54	15.24	0.79	−0.01	84	19.18	0.57	1.93
25	19.33	0.94	−0.24	55	11.53	0.62	−1.02	85	16.59	0.70	−0.32
26	15.35	0.97	−0.95	56	5.21	1.07	1.45	86	11.32	0.57	0.34
27	19.69	0.39	−1.90	57	14.25	0.81	1.09	87	9.19	0.77	1.43
28	6.96	0.40	1.89	58	7.29	0.78	1.42	88	7.52	0.57	−1.18
29	7.00	0.81	0.87	59	8.05	0.35	1.22	89	12.60	0.90	−1.25
30	9.88	0.53	−1.95	60	15.44	0.64	−0.93	90	14.90	0.58	−0.88

Data availability

Data will be made available on request.

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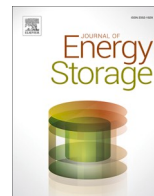
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通讯作者论文



Research papers

Self-building or sharing? The strategy analysis of building charging stations

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ABSTRACT

Charging station sharing, as a new business model, can effectively reduce the building of unnecessary public charging stations and promote sustainable urban development. This study discusses whether the manufacturers introduce a charging station sharing strategy and identify the introduction conditions. We develop a strategic competition model where the two manufacturers engage in electric vehicles (EVs) and charging stations. The results show that charging stations have a facilitating effect on the EV market. In a sharing strategy, the low-end vehicle manufacturer can profit more when the contract cost is smaller. Comparing the strategies of self-building and sharing, the manufacturers should choose a self-building strategy when the cost coefficient of building the station, the brand advantage, and the contract cost are all larger. However, when the brand advantage and the contract cost are smaller, or both in the medium, the manufacturers should choose a sharing strategy. In addition, we also find that the substitutability of EVs and the cross-sensitivity of EVs and charging stations can lead to lower market demand for EVs. In a monopoly production scenario, encroachment by both the platform and the service provider leads to lower profits for the manufacturer. Therefore, it is more favorable for the manufacturer to self-build charging stations in the no-invader condition. Our analysis provides insights into when charging station sharing may be beneficial and when it may be detrimental to vehicle manufacturers.

1. Introduction

The transportation sector is confronted with significant challenges amid the ongoing energy transition and warming climate [1–3]. Studies show that the transportation sector accounts for >23 % of global carbon dioxide emissions, which is expected to rise to 50 % by 2050 [4]. Responding to these challenges, the imperative of decarbonizing transportation has become a central focus of national and international policies [5,6]. Electric vehicles (EVs), with their environmentally friendly attributes, are driving an unprecedented revolution in transportation [7,8]. Projections from the International Energy Agency indicate an anticipated surge in the number of EVs, reaching 350 million by 2030 [9]. Some cities and transportation agencies are also committed to achieving a fleet-wide shift to EVs in the future [10]. While increasing the electrification of transportation is a key step towards sustainability, the widespread adoption of EVs hinges on the presence of sustainable and convenient charging infrastructure [11,12]. McKinsey also indicates that the coverage and accessibility of charging infrastructure is a

significant concern for consumers [13]. Without a high-density charging network and convenient charging options, consumers will suffer from charging anxiety, which will affect the popularity of EVs [14,15]. Therefore, the development of a robust charging infrastructure is significant to ensure the successful evolution of EVs [16,17].

The significantly increasing adoption of EVs is creating new opportunities and development in the charging stations market [18,19]. Although many countries and enterprises are actively building charging infrastructures, the current number of charging infrastructures still fails to meet the charging demand for EVs, which seriously hinders the promotion and adoption of EVs¹. For example, the UK government expects to own at least 300,000 public chargers by 2030 [15]. The U.S. Bipartisan Infrastructure Law (BIL) allocated \$7.5 billion for the installation of 500,000 public chargers across the country, and these public chargers are compatible with other EVs and technologies.² Despite a gradual decrease in the vehicle-to-station ratio, it remains significantly below the international standard of 1.5:1. Fig. 1 presents the changes in new energy vehicles and charging stations in China from 2015 to 2023.

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¹ <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/europes-ev-opportunity-and-the-charging-infrastructure-needed-to-meet-it>.

² <https://www.mckinsey.com/industries/public-and-social-sector/our-insights/building-the-electric-vehicle-charging-infrastructure-america-needs>.

However, the slow development of charging infrastructure has created an imbalance between the supply and demand for charging services, posing a significant obstacle to the widespread adoption of EVs [20]. To break through this obstacle and promote the transition of transportation electrification, China, the United States, and France have implemented relevant policies and committed resources to the development of charging infrastructure [21]. However, the progress of EV charging infrastructure is impeded by economic, social, environmental, and technological challenges [22–24].

Currently, the construction and operation of charging stations are characterized by two predominant features. **First**, there is a significant high-cost investment in charging stations [10,17,25]. Charging operators face substantial initial capital investments, and the swift recovery of these costs is crucial for investors. However, challenges in recouping these investments hinder capital inflow into the market, thereby impeding the development of the charging market [26]. The limitation of charging stations and the high cost of charging also pose a huge challenge for vehicle owners to charge their vehicles [27,28]. Therefore, automakers must focus on maximizing the net revenue derived from the investment and operating costs associated with charging stations. **Second**, the low utilization of charging stations is another key feature, particularly in the early stages [29]. This underutilization is exemplified by a mismatch between the number of charging stations and the actual demand for charging. Consequently, charging hotspots are challenging to locate, while charging stations in remote areas remain unused for extended periods. Increasing charging power has been identified as a means to alleviate charging resource constraints [27]. Furthermore, the utilization of charging stations with integrated high and low power is significantly better than the utilization of charging stations with high power alone [30,31]. In addition, while workplace charging stations can significantly increase EVs availability, there are still public charging stations that are seldom used by pure EV users, who primarily employ home charging [32]. This paper aims to address these challenges by exploring strategies to reduce the building costs of charging stations and concurrently increase their utilization.

Notably, there is a diversification of EV brands in the market. However, different automakers are also deploying charging stations to dominate the market and enhance their corporate image. Although the

charging market is growing significantly, given the cost of construction and the recovery period, there are still some automakers that are not keen on building charging stations. These automakers are taking a wait-and-see position or are sharing charging infrastructure with other automakers to minimize market uncertainty [15]. For instance, both Tesla and NIO are actively constructing their proprietary charging stations, reinforcing their commitment to a comprehensive EV ecosystem. However, in the case of BYD, it hardly builds charging stations and instead shares charging stations with NIO [33]. Consequently, the matter of charging station sharing has received a lot of attention.

According to the 2023 China Electric Vehicle User Charging Behavior Research Report, >90 % of users have cross-operator charging behavior. Therefore, owners who choose BYD can still choose to charge with other charging operators. For charging stations that do not support Tesla's charging requirements, owners can also charge by choosing a compatible third-party charging platform. The third-party charging station operators, represented by Star Charge and Tercel, account for about 40 % of the market share in the charging market. Chen et al. [34] also argue that the production of compatible charging stations contributes to business profitability and social welfare. Therefore, under the condition of charging compatibility, this paper investigates the charging station sharing of different vehicle manufacturers. In addition, the emergence of wireless charging and 5G charging technologies not only affects the efficiency of charging stations [35,36] but also leads to the emergence of various types of charging station operators, which brings more challenges and competition to vehicle manufacturers. While the phenomenon of cross-operator charging provides consumers with more charging flexibility, it has also raised concerns among manufacturers about potential entrants.

Furthermore, the intensified competition within the market has significantly disrupted the monopoly once held by companies over public charging infrastructure. A potential win-win situation emerges when companies prioritize enhancing charging services and simultaneously reducing the number of charging stations [33]. Charging station sharing is identified as a strategy that can boost utilization, lower costs, minimize material consumption, and accelerate the transition to the electrification of transportation [37]. Beyond the operational advantages, charging station sharing also contributes to positive image

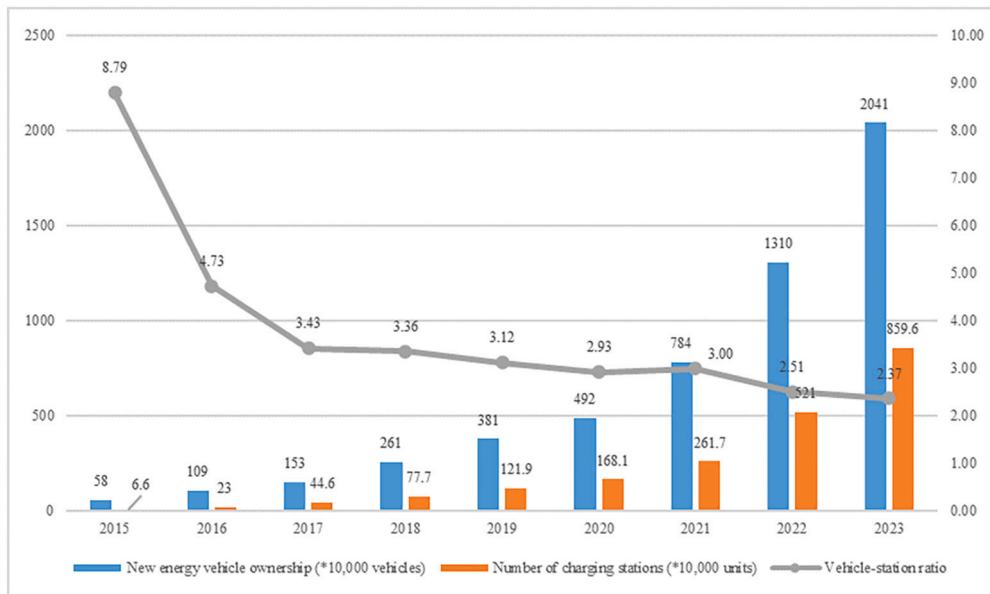


Fig. 1. China's new energy vehicle ownership, charging station ownership and vehicle-to-station ratio from 2015 to 2023.

Data source: Ministry of Public Security, China Charging Alliance, National Development and Reform Commission, Ministry of Commerce, China Association of Automobile Manufacturers, China Securities Research Department, Guanyan Report Network "China Low-voltage Electrical Appliances Industry Development Status Research and Investment Prospects Fanisi Report (2022–2029)".

building and reinforces a sense of social responsibility among companies. On the other hand, charging station self-building demonstrates companies' independence and ability to provide full service. In addition, the vehicle companies self-building charging stations can further improve the competitiveness of the market. For companies, how they make strategic choices depends on the market demand for EVs and the revenue of the companies. However, the current studies have mainly focused on the deployment and location of charging infrastructures [38–41], power distribution [42], charging strategies [25], and battery swapping [43]. However, there has been limited research on how to maximize the impact of charging infrastructure on the promotion of EVs and the competitive dynamics among companies in the charging sector.

Considering the differences between different manufacturers, we explore the possibility of charging station sharing. This paper aims to answer the following research questions:

1. How does the brand advantage of EVs affect production and pricing of EVs and the building of charging stations?
2. Should low-end vehicle manufacturer deploy charging stations and how should the high-end vehicle manufacturer set contract cost?
3. How do low-end vehicle manufacturer trade off a self-building strategy versus a sharing strategy for charging stations?

To address these questions, we develop a supply chain game-theoretic model with two competing vehicle manufacturers. Specifically, the two manufacturers compete completely in the EVs field, while there is competition or cooperation in the charging stations field. When the low-end vehicle manufacturer chooses to self-build charging stations, the charging stations become the manufacturers' competitive leverage; When the manufacturers share charging stations, the number of charging stations contributes to the market demand for EVs from both manufacturers. Therefore, the game-theoretic model can comprehensively characterize the competition and cooperation between two vehicle manufacturers in the supply chain.

We highlight some of the major findings from our results. **First**, the high-end vehicle manufacturer does not always realize a larger profit in the market in the charging station sharing strategy. The outcome depends on factors such as building cost and brand advantage. Specifically, when the cost coefficient of building the station and the contract cost are smaller or the cost coefficient of building the station is larger but the brand advantage and the contract cost are relatively smaller, the low-end vehicle manufacturer gets a bigger business pie instead. **Second**, when the cost coefficient of building the station, the brand advantage of EVs, and the contract cost are larger, the charging station self-building strategy is more favorable to manufacturers. Conversely, the two competing manufacturers should adopt a charging station sharing strategy if and only if the brand advantage of EVs and the contract cost are smaller, or in the medium. The conditions create diverse scenarios where a win-win situation can be achieved for manufacturers of different brands. **Third**, the encroachment by both the platform and the service provider harms the manufacturer's revenue, making the strategy of self-building more profitable for the manufacturer.

The main contributions of our work are as follows. **First**, we introduce a contract to characterize the motivations of supply chain members to cooperate and show how charging stations drive the development of EVs and influence the decisions of vehicle manufacturers. Whereas most of the previous studies in the literature only focus on the facility planning of charging stations and the competition of EVs, few related scholars study the cooptation of vehicle manufacturers in the field of charging stations. We provide important references and a decision-making basis for stakeholders to promote the rapid development and popularity of the EV market. **Second**, we identify threshold conditions for manufacturers to choose different strategies. In addition, we analyze the impact of platform and service provider encroachment in a monopoly scenario, examine the manufacturer's trade-off between self-building and cooperating with a service provider, and synthesize

strategies for operating charging stations. **Third**, our study helps to enrich the field of charging stations and the theory of the sharing economy and advances academic research. The results of the study provide valuable recommendations for the development of charging stations.

The remainder of this paper is organized as follows. In Section 2, we review the related literature. We introduce two strategies of self-building and sharing of charging stations in Section 3. In Section 4, we discuss our findings from computational experiments and analysis. We extend the relevant models in Section 5 and conclude the paper in Section 6. All proofs are presented in the Appendix.

2. Literature review

The review covers two extensive streams of literature: the first captures the charging station sharing. The second includes operational cooptation. We elaborate on each of these two in detail in the subsequent paragraphs.

2.1. Charging station sharing

The sharing economy, also known as cooperative consumption, is defined as the process by which individuals renting, trading, or exchanging goods, services, or space, thereby increasing the utilization of goods and achieving certain economic benefits [44,45]. Charging station sharing is essentially a new model of the sharing economy. Companies or individuals do not need to own the product to enjoy the product or service in common with others [46].

Sharing economy business models have many ecological, economic, and social benefits [47]. Therefore, charging station sharing, as a new commercial service, can effectively ease the balance between charging supply and demand and reduce the construction of unnecessary public charging stations. Zhao et al. [48] examine EV charging services with private charging station sharing through a bilateral bargaining game and examine charging service pricing. Hu et al. [33] also study the private charging station sharing model and find that the sharing model can provide a win-win solution for charging post owner consumers, non-owner consumers, electricity distributors, and public charging infrastructure operators. Chen et al. [49] investigate private charging station sharing through a sharing model of a generalized Nash game and propose a hierarchical scheduling model for EVs considering charging station sharing. Wang et al. [50] study the fair distribution of benefits from private charging station sharing through an improved Shapley value model for the promotion of private charging station programs. Melander and Wallström [37] show that sharing electric freight vehicle (EFV) charging infrastructure has economic and environmental benefits, e.g., providing a new source of revenue, lowering investment costs, increasing the utilization of charging stations, and environmental sustainability. Yang et al. [51] investigate the potential for private home charging station sharing through a data-driven microsimulation approach. The results show that private home charging station sharing reduces the dependence of private EV users on public charging stations. Charging station sharing is a new way to move EV charging services forward. However, almost all studies only consider charging station location planning and private charging station sharing. Therefore, in this research context of public charging stations, we study the interaction of interests between companies and explore the operation mode of the charging stations.

2.2. Operational cooptation

Cooptation is cooperation and competition between rivals [52]. Cooptation brings advantages to different business markets and management, including profits from market sharing among rivals [53]. Therefore, companies need to explore cooptation in depth to recognize the complexities associated with cooptation [54].

In our study, a coopetition relationship occurs when one manufacturer leases a key product from another manufacturer. Chen et al. [55] examine two competing manufacturers' coopetition through wholesaling coopetition or license coopetition and find that the optimal coopetition strategy depends on power relationship and production efficiency. Narayan and Tidström [56] argue that coopetition can enable firms to transition to a circular economy and use tokens in the blockchain to operationalize and optimize coopetition. Li et al. [57] explore the optimal information sharing strategy choices in online markets with different competitive intensities. Cheng and Fan [58] investigate fuel vehicle (FV) automaker and new energy vehicle (NEV) automaker competition and coopetition strategy production under the dual credit policy. Li and Zhao [59] find that competing suppliers always favor coopetition when supplier-initiated investments are effective and that process improvement incentives promote the emergence of coopetition. Sun et al. [60] find that the cost-quality benefit ratio of high-quality and low-quality products determines whether brand manufacturers prefer a competition or coopetition strategy. Yang et al. [61] investigate the customer's patience to wait and that the competitor's product quality affects a manufacturer of a proprietary component's optimal competition strategy selection. Pei et al. [62] find that when preventive maintenance capabilities are high, manufacturers with coopetition strategy generate higher revenues from royalties and sales. In the field of supply chain management, sustainability is becoming increasingly important in practice, but research on sustainability-driven coopetition is relatively limited. Similar to the literature focused on the coopetition strategy, this paper explores how competing vehicle manufacturers cooperate in supply chains to provide sustainable supply chain cooperation mechanisms for automakers.

Our paper contributes to the literature as follows. We focus on the coopetition and competition game between manufacturers and explore different operational strategies for charging stations. Not only that, by analyzing it, we enrich the literature from theory and practice.

3. Model settings

We develop a model consisting of two competitive vehicle manufacturers A (*he*) and B (*she*). Self-building charging stations can enhance brand image and provide a better charging experience for vehicle owners, so high-end EV manufacturer A chooses to self-build charging stations. Considering the building cost and the market potential, low-end EV manufacturer B has two strategic choices: (1) self-building charging stations (Strategy D), or (2) leasing manufacturer A's charging stations and sharing the charging stations with manufacturer A (Strategy S). The relevant diagram of the structure is shown in Fig. 2. The notations are summarized in Table 1. Without loss of generality, according to the research of Mantovani and Ruiz-Aliseda [63] and Liu et al. [3], we normalize the manufacturers' production cost to zero.

The manufacturer's decision sequence is shown in Fig. 3. In the first stage, manufacturer B chooses between self-building or sharing strategy for charging stations. In the second stage, if the self-building strategy is chosen, manufacturers A and B decide the number of charging stations, respectively; If the sharing strategy is selected, manufacturer A first sets the contract cost f , and then manufacturer A decides the number of charging stations. In the third stage, manufacturers A and B decide on the demand of EVs, respectively.

3.1. Self-building strategy (Strategy D)

The two manufacturers build their own charging stations. The number of charging stations in the market can affect consumers' charging anxiety. When the consumers' charging anxiety is resolved, the consumers' willingness to pay for EVs increases accordingly. This assumption is consistent with the setup of Yu et al. [64] and Pi et al. [65] on the inverse demand function for EVs. Although manufacturers of self-building charging stations can increase the price of private-label EVs,

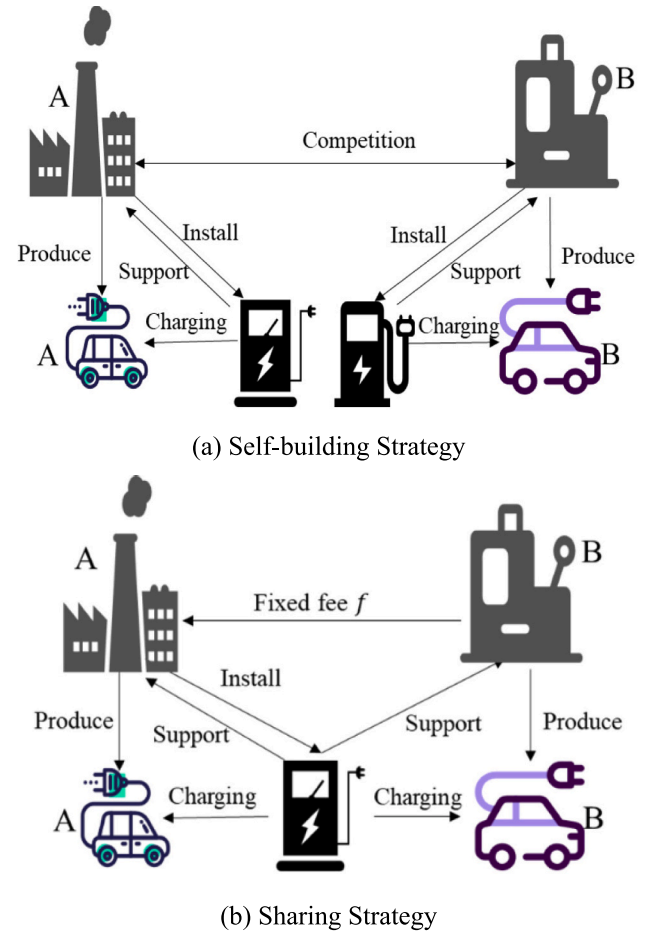


Fig. 2. Structure of charging station building.

Table 1
Notations.

Parameters	Descriptions
a	The market potential of B-type EVs
θ	Brand advantage of the manufacturer A
k	Cost coefficient of building the charging station
f	Contract cost of the manufacturer B
Decision variables	
q_i	The quantity of EV i , $i \in \{A, B\}$
n_i	The number of charging station i , $i \in \{A, B\}$
Superscripts	
p_i	Price of the unit EV i , $i \in \{A, B\}$
π_i	The profit of manufacturer i , $i \in \{A, B\}$

We use Cournot model to formulate the market competition between the two manufacturers.

they act as a disincentive to competitors' EV price [34]. The main reason for this phenomenon is that manufacturers compete in the field of charging stations. Therefore, the inverse demand functions of the two manufacturers are, respectively

$$p_A^D = (1 + \theta)a - q_A^D + n_A^D - q_B^D - n_B^D \quad (1)$$

$$p_B^D = a - q_B^D + n_B^D - q_A^D - n_A^D \quad (2)$$

The two manufacturers' profit functions in Strategy D are as follows:

$$\pi_A^D = p_A^D q_A^D - k(n_A^D)^2 \quad (3)$$

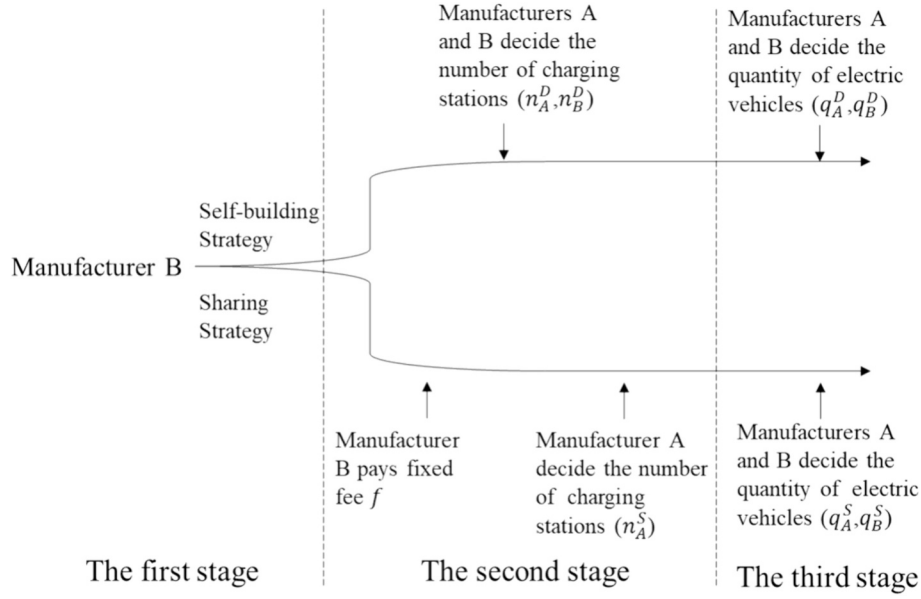


Fig. 3. Manufacturer's decision sequence diagram.

$$\pi_B^D = p_B^D q_B^D - k(n_B^D)^2 \quad (4)$$

where a denotes the market potential for B-type EVs. Due to the brand advantage of A-type EVs, the market potential is $(1 + \theta)a$. n_A^D and n_B^D denote the number of charging stations built by the two manufacturers, respectively, and their impact on the price of EVs is as described above. q_A^D and q_B^D denote the market demand of EVs, respectively, and that market demand plays a negative effect on the price of EVs [66–68]. Since the building of charging stations is uneconomical in scale, $k(n_A^D)^2$ and $k(n_B^D)^2$ denote the total cost of building the charging stations, respectively, according to Yu et al. [64] and Tang et al. [25]. To ensure all outputs are positive, we assume $k > 2$ and $0 < \theta < \frac{k-2}{k+1}$. By backward induction, we summarize our equilibrium outputs in Table 2.

3.2. Sharing strategy (Strategy S)

Although BYD has its own public charging stations, these charging stations are for city buses, cabs, and other operating vehicles, and owners can hardly see charging stations for personal charging on the road. The main reason is that public charging stations have large investments, long profitability periods, and higher risks [69,70].

Table 2
The equilibriums in both strategies.

	Strategy D	Strategy S
q_A	$\frac{a(k-2-\theta+2k\theta)}{3(k-2)}$	$\frac{3ak(1+2\theta)}{9k-1}$
q_B	$\frac{a(k-2-\theta-k\theta)}{3(k-2)}$	$\frac{a(3k-3k\theta+\theta)}{9k-1}$
n_A	$\frac{a(k-2-\theta+2k\theta)}{3k(k-2)}$	$\frac{a(1+2\theta)}{9k-1}$
n_B	$\frac{a(k-2-\theta-k\theta)}{3k(k-2)}$	/
p_A	$\frac{a(k-2-\theta+2k\theta)}{3(k-2)}$	$\frac{3ak(1+2\theta)}{9k-1}$
p_B	$\frac{a(k-2-\theta-k\theta)}{3(k-2)}$	$\frac{a(3k-3k\theta+\theta)}{9k-1}$
π_A	$\frac{a^2(k-1)(k-2-\theta+2k\theta)^2}{9k(k-2)^2}$	$\frac{ka^2(1+2\theta)^2}{9k-1} + f$
π_B	$\frac{a^2(k-1)(k-2-\theta-k\theta)^2}{9k(k-2)^2}$	$\frac{a^2(3k-3k\theta+\theta)^2}{(9k-1)^2} - f$

Companies won't invest in infrastructure until more consumers use EVs [71]. To solve the charging problem of vehicle owners, manufacturer B will sign a strategic agreement with manufacturer A and lease charging stations. However, manufacturer B has to pay contract cost f . If $f \geq k(n_A^S)^2$, manufacturer B would prefer to self-build charging stations. Therefore, we assume $0 < f < k(n_A^S)^2$. Similar to Strategy D, the inverse demand functions of two manufacturers are, respectively

$$p_A^S = (1 + \theta)a - q_A^S + n_A^S - q_B^S \quad (5)$$

$$p_B^S = a - q_B^S + n_A^S - q_A^S \quad (6)$$

The difference is that there is cooperation between the two manufacturers in the field of charging stations. As a result, the number of charging stations contributes to both EVs, thus favoring the manufacturers' pricing. The two manufacturers' profit functions in Strategy S are as follows:

$$\pi_A^S = p_A^S q_A^S - k(n_A^S)^2 + f \quad (7)$$

$$\pi_B^S = p_B^S q_B^S - f \quad (8)$$

where $k(n_A^S)^2$ denotes the cost of building the stations in Strategy S for manufacturer A. The equilibrium EVs, charging stations, prices, and profits in Strategies D and S are shown in Table 2.

Proposition 1. (1) $q_A^D > q_B^D$, $n_A^D > n_B^D$, $p_A^D > p_B^D$, $\pi_A^D > \pi_B^D$.

(2) $q_A^S > q_B^S$, $p_A^S > p_B^S$.

(3) If one of the following conditions is satisfied, $\pi_A^S > \pi_B^S$.

- i) $k \in (2, k_0)$, $f \in \left(f_1, \frac{a^2 k(1+2\theta)^2}{(9k-1)^2}\right)$;
- ii) $k \in (k_0, +\infty)$, $\theta \in (0, \theta_1)$, $f \in \left(f_1, \frac{a^2 k(1+2\theta)^2}{(9k-1)^2}\right)$;
- iii) $k \in (k_0, +\infty)$, $\theta \in \left(\theta_1, \frac{k-2}{k+1}\right)$.

If one of the following conditions is satisfied, $\pi_A^S < \pi_B^S$.

- iv) $k \in (2, k_0)$, $f \in (0, f_1)$;

v) $k \in (k_0, +\infty)$, $\theta \in (0, \theta_1)$, $f \in (0, f_1)$.

Proposition 1(1) shows that the equilibrium outputs of manufacturer B are always smaller than that of its rival in Scenario D (as shown in Fig. 4(a)–(c)). This is due to the brand advantage of manufacturer A. With the increase in brand advantage, the gap between manufacturers A and B is larger. In Strategy S, **Proposition 1(2)** is similar to **Proposition 1(1)**. The brand advantage of manufacturer A can further increase market demand and pricing for EVs.

Proposition 1(3) shows a surprising discovery. The cost coefficient of building the charging station, the contract cost, and the brand advantage will affect manufacturers' profits (as shown in Fig. 5). In Strategy S, although the manufacturer A has more market demand due to his brand advantage, it is possible for the low-end vehicle manufacturer B to gain more than manufacturer A. Specifically, when the cost coefficient of building the station and the contract cost are relatively smaller, or when the cost coefficient of building the station is larger, but the brand advantage and the contract cost are relatively smaller. This is because the smaller contract cost allows manufacturer B to make smaller fixed payments, which reduces the loss of revenue. When the cost coefficient of building the station is smaller, manufacturers will build more charging stations, which will increase the sales and price of the B-type EVs. When the cost coefficient of building the station is larger, manufacturer A will reduce the building of charging stations. However, the lower brand advantage also makes manufacturer A less competitive in the market, thus allowing manufacturer B to gain a bigger business pie. The profit that manufacturer A obtains will be higher than that of manufacturer B only if there is a larger contract cost or a significant brand advantage.

4. Comparative analysis

In this section, we provide detailed analysis of the results in Table 2. Specifically, we compare the outcomes in self-building and sharing charging stations. We find that brand advantage (θ) and contract cost (f) are important factors influencing manufacturers' strategic choice

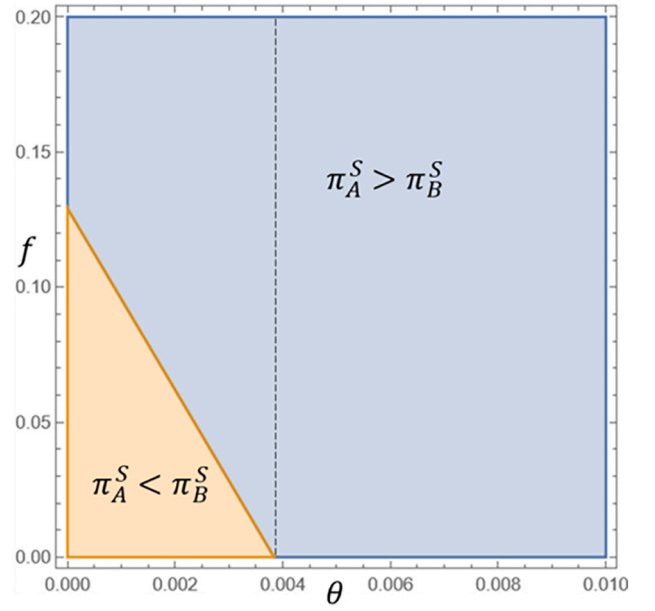


Fig. 5. The impact of contract cost and brand advantage on manufacturers' profits in Strategy S ($a = 10$, $k = 5$).

preferences. Therefore, we analyze these two factors further.

4.1. Comparison of EV and charging station quantity

By comparing the optimal outputs in two strategies, we get **Proposition 2**:

Proposition 2. (1) When $\theta \in \left(\frac{k-2}{25k+1}, \frac{k-2}{k+1}\right)$, $q_A^D > q_A^S$; otherwise, $q_A^D < q_A^S$; $q_B^D < q_B^S$.
(2)

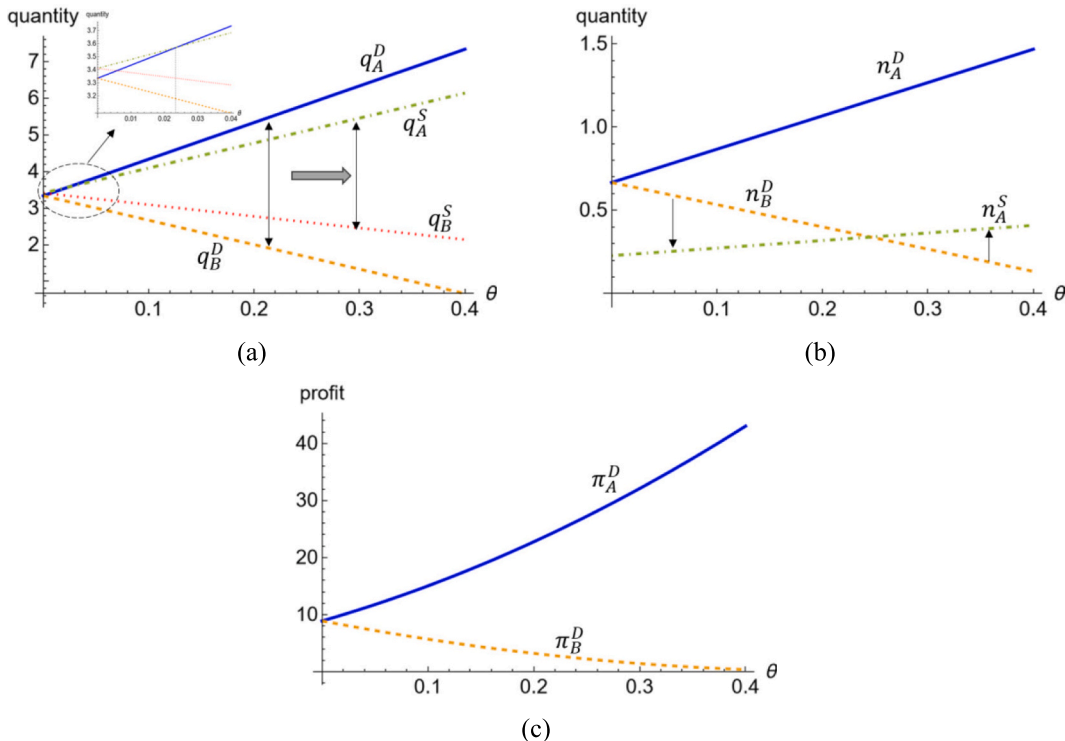


Fig. 4. The impact of brand advantage on the optimal decisions of manufacturers in Strategy D ($a = 10$, $k = 5$).

$$n_A^D > n_A^S.$$

- (3) $q_A^D + q_B^D < q_A^S + q_B^S$, $n_A^D + n_B^D > n_A^S$. **Proposition 2(1)** shows that A-type EVs have more market demand in Strategy D only if the brand advantage is larger. Conversely, Strategy S is more favorable to the sales of A-type EVs when the brand advantage is smaller (as shown in Fig. 4(a)). This is because, in Strategy S, a smaller brand advantage makes the EVs of manufacturers A and B more homogeneous, resulting in weaker competition between them. Additionally, manufacturer A has two sources of profit (one is the sale of EVs, and the other is the income from the contract), and these two sources of profit mean that any change in brand advantage can lead to the re-division of the market share. Therefore, Strategy D can be more favorable to the sales of A-type EVs only when manufacturer A's brand advantage is significant. Otherwise, manufacturer A should consider signing a charging station sharing agreement with manufacturer B. Furthermore, even though manufacturer B does not self-build charging stations, once consumers' charging anxiety is resolved, manufacturer B can still capture more market share in Strategy S compared to Strategy D.

Comparing Propositions 2(1) and (2), we find that the development of EVs and charging stations is not synchronized. Although manufacturer A builds more charging stations in Strategy D, he sells more EVs in Strategy S when the brand advantage is smaller. This is because, on one hand, the gap between the two manufacturers is reduced, and on the other hand, charging station sharing enables stronger cooperation between the two manufacturers, thus promoting the sales of EVs. In a fiercely competitive environment, charging stations are growing at a greater rate with brand advantage ($\frac{\partial n_A^D}{\partial \theta} > \frac{\partial n_A^S}{\partial \theta}$) (as shown in Fig. 4(b)). Therefore, $n_A^D > n_A^S$.

Proposition 2(3) shows that although the total number of charging stations built by manufacturers in Strategy D is larger, the overall EV market demand is relatively smaller. This is because there is both EV and charging station competition in Strategy D, which leads to a less favorable market environment.

Since the demand for EVs and the number of charging stations are influenced by brand advantage, we get **Lemma 1**.

Lemma 1. (1) $\frac{\partial q_A^D}{\partial \theta} > 0$, $\frac{\partial q_A^S}{\partial \theta} > 0$, $\frac{\partial q_A^D}{\partial \theta} > \frac{\partial q_A^S}{\partial \theta}$.

$$(2) \frac{\partial q_B^D}{\partial \theta} < 0, \frac{\partial q_B^S}{\partial \theta} < 0, \left| \frac{\partial q_B^D}{\partial \theta} \right| > \left| \frac{\partial q_B^S}{\partial \theta} \right|.$$

$$(3) \frac{\partial n_A^D}{\partial \theta} > 0, \frac{\partial n_A^S}{\partial \theta} > 0, \frac{\partial n_A^D}{\partial \theta} > \frac{\partial n_A^S}{\partial \theta}.$$

(4)

$$\frac{\partial n_B^D}{\partial \theta} < 0.$$

Lemma 1 reflects the variation in the number of EVs and charging stations with brand advantage. Whatever the strategy, a larger brand advantage for A-type EVs leads to increased market demand, giving manufacturer A a larger market share. In **Proposition 2**, we find that $q_A^D < q_A^S$ when the brand advantage is smaller, but the sales growth rate of manufacturer A's EVs is larger in Strategy D. The possible reason is that in Strategy D, manufacturers A and B operate in a perfectly competitive market. Whereas in Strategy S, competition between manufacturers is reduced. As a complementary energy infrastructure, the variation in the number of charging stations is similar to the variation in EVs due to branding factors.

For manufacturer B, the sales of B-type EVs decrease as brand advantage increase, with a faster decline in Strategy D. This is because manufacturer B's fixed fee effectively promotes cooperation and avoids

head-to-head competition between manufacturers. In addition, we find that although the manufacturers share charging stations in Strategy S and the number of charging stations built by manufacturer A increases with brand advantage, the sales of B-type EVs continue to decrease with brand advantage. This situation is similar to that in Strategy D. The main reason is that the impact of brand advantage on B-type EVs is larger than the impact of charging stations, as indicated by the formula $q_B^S = \frac{\alpha(1-\theta)+n_A^S}{3}$. This leads to a decrease in the sales of B-type EVs. Through Fig. 4(a), we find that the gap between the sales of A-type and B-type EVs gradually narrows as the market shifts from a competition to a cooperation market, which reflects the weakening of competition between manufacturers.

4.2. Comparison of electric vehicle retail price

By comparing the prices in two strategies, we get **Proposition 3**.

Proposition 3. When $\theta \in \left(\frac{k-2}{25k+1}, \frac{k-2}{k+1}\right)$, $p_A^D > p_A^S$; otherwise, $p_A^D < p_A^S$; $p_B^D < p_B^S$.

Comparing **Proposition 3** and **Proposition 2**, we find that the number and price of EVs change in synchronization. **Proposition 3** indicates that when the brand advantage is larger, manufacturer A sells more EVs in Strategy D, but the price of the EV does not decrease as a result; instead, manufacturer A charges a higher retail price to increase the profit. Similarly, when the brand advantage is smaller, manufacturer A sells more EVs in Strategy S, and the price of the EVs increases accordingly. This is due to the fact that manufacturer A has an incentive to set a higher price when the market demand for EVs increases. Since manufacturer B has a lower brand advantage, product selling is the main source of profit for manufacturer B. In addition, to offset losses due to fixed cost, manufacturer B has a stronger incentive to raise the prices in Strategy S to achieve profitability equilibrium.

In **Lemma 2**, we consider how cooperation relationship between manufacturers affects manufacturers' retail price.

Lemma 2. (1) $\frac{\partial p_A^D}{\partial \theta} > 0$, $\frac{\partial p_A^S}{\partial \theta} > 0$, $\frac{\partial p_A^D}{\partial \theta} > \frac{\partial p_A^S}{\partial \theta}$.

$$(2) \frac{\partial p_B^D}{\partial \theta} < 0, \frac{\partial p_B^S}{\partial \theta} < 0, \left| \frac{\partial p_B^D}{\partial \theta} \right| > \left| \frac{\partial p_B^S}{\partial \theta} \right|.$$

The underlying reasons for **Lemma 2** are similar to those for **Lemma 1**. **Lemma 2(1)** demonstrates that a larger brand advantage extends pricing flexibility, but also increases competition for the EVs, leading to a decrease in the price of B-type EVs. Since EVs and charging stations are complementary, in Strategy S, although manufacturer B does not build charging stations, she can utilize the charging stations built by manufacturer A. Moreover, when the brand advantage is larger, manufacturer B can access more charging stations than in Strategy D ($n_A^S > n_B^D$, if $\frac{6k^2-13k+2}{15k^2-4k-1} < \theta < \frac{k-2}{k+1}$). In this scenario, manufacturer B pays less costs than Strategy D, which is undoubtedly the best choice for manufacturer B. Therefore, manufacturer B also has an incentive to produce more EVs in Strategy S, and the price of the EVs has been relatively slow to decline in the market.

4.3. Comparison of profits of manufacturers

By comparing the analyses, we derive the choices of the two manufacturers in different strategies. Thus, **Proposition 4** reflects the manufacturer A's strategy preference.

Proposition 4. (1) If one of the following conditions is satisfied, $\pi_A^D > \pi_A^S$.

i) $\theta \in (\theta_2, \theta_3)$, $f \in (0, f_2)$;

ii)

$$\theta \in \left(\theta_3, \frac{k-2}{k+1}\right).$$

(2) If one of the following conditions is satisfied, $\pi_A^D < \pi_A^S$.

iii)

$$\theta \in (0, \theta_2);$$

iv) $\theta \in (\theta_2, \theta_3)$, $f \in \left(f_2, \frac{ka^2(1+2\theta)^2}{(9k-1)^2}\right)$. **Proposition 4** shows that

manufacturer A's strategic preference is influenced not only by the EV brand advantage but also by the contract cost. Specifically, **Proposition 4**(1) i) indicates that manufacturer A will choose Strategy D when the brand advantage of the EV is in the medium and the contract cost is smaller. That is because, while manufacturer A's brand advantage decreases, competition for its products remains fierce. In Strategy, A-type EVs achieve higher sales and prices, leading to increased revenue for manufacturer A. In contrast, although manufacturer A's revenue includes both EV sales and contract income in Strategy S, the building of charging stations requires larger investment and the lower rental income reduce overall profitability. Not only that, when manufacturer A has a larger brand advantage, A-type EVs have a higher retail prices and market demand in Strategy D. Although the cost of building the charging stations is larger, the revenue is sufficient to offset the loss incurred by the cost. Therefore, manufacturer A also prefers Strategy D.

In addition, **Proposition 4**(2) iii) demonstrates that manufacturer A can make more profit in Strategy S, thus driving he to choose Strategy S. This is due to the fact that manufacturer A sells more and prices higher in Strategy S when the brand advantage is smaller. **Proposition 4**(2) iv) suggests that when the brand advantage of manufacturer A is in the medium range and the contract cost is larger, manufacturer A will be more motivated to choose the Strategy S by compensating for the decrease in sales revenue and the increase in the cost of building the stations.

Proposition 5 reflects the manufacturer B's strategy preference.

Proposition 5. (1) If the following condition is satisfied, $\pi_B^D > \pi_B^S$.

$$i) k \in \left(\frac{13+3\sqrt{17}}{2}, +\infty\right), \theta \in \left(\theta_4, \frac{k-2}{k-1}\right), f \in \left(f_3, \frac{ka^2(1+2\theta)^2}{(9k-1)^2}\right);$$

(2) If one of the following conditions is satisfied, $\pi_B^D < \pi_B^S$.

$$ii) k \in \left(2, \frac{13+3\sqrt{17}}{2}\right);$$

$$iii) k \in \left(\frac{13+3\sqrt{17}}{2}, +\infty\right), \theta \in (0, \theta_4);$$

$$iv) k \in \left(\frac{13+3\sqrt{17}}{2}, +\infty\right), \theta \in \left(\theta_4, \frac{k-2}{k-1}\right), f \in (0, f_3).$$

Different from the findings of **Proposition 4**, we further observe that manufacturer B's strategy preference is not only affected by the brand advantage of EVs and the contract cost but also the cost coefficient of building the charging station. **Proposition 5**(1) i) shows that manufacturer B will choose Strategy D when both the cost coefficient of building the charging station and the contract cost are larger. The larger cost of building the station causes the manufacturer B to reduce the number of charging stations, diminishing her competitive advantage. In Strategy S, despite the market demand and pricing for B-type EVs are relatively higher, the higher contract cost reduces manufacturer B's revenue. The negative forces eliminate manufacturer B from joining the charging

station sharing alliance, thus choosing Strategy D.

Proposition 5(2) ii)–iv) shows that even if manufacturer B does not build charging stations, she can still achieve higher profit in Strategy S. **Proposition 5**(2) ii) shows that, regardless of the brand advantage and the effect of the contract cost, Strategy S is more suitable for manufacturer B only when the cost coefficient of building the charging station is smaller. This is because the smaller cost of building stations allows manufacturers A to build more charging stations, which in turn benefits manufacturer B. The manufacturer B can pay a smaller cost to use the same value of the charging station, which increases her willingness to choose Strategy S. When the cost coefficient of building the charging station is larger, there are two cases of **Proposition 5**(2) iii) and iv). **Proposition 5**(2) iii) shows that when the brand advantage of EVs is smaller, competition between EVs weakens and the market size of manufacturer A decreases. In this case, $n_B^D > n_A^S$, meaning manufacturer B would need to invest more in building stations, which is unfavorable to manufacturer B. Therefore, manufacturer B prefers to sign a contract with manufacturer A rather than build charging stations independently. **Proposition 5**(2) iv) shows that manufacturer B will choose Strategy S only when both a larger brand advantage and a smaller contract cost are satisfied. This is because while the larger brand advantage increases competition between manufacturers and puts manufacturer B at a disadvantage position, a smaller contract cost allows manufacturer B to address the charging issue effectively. Thus, the combination of these factors makes Strategy S the best option for manufacturer B.

Comparing **Propositions 4** and **5**, we find that when the cost coefficient of building the charging station, the brand advantage, and the contract cost are all larger, both manufacturers A and B will choose Strategy D simultaneously. Conversely, when the brand advantage and the contract cost are the smaller or in the medium, both manufacturers A and B will choose Strategy S. These scenarios allow manufacturers A and B to achieve a win-win situation, as shown in **Fig. 6**.

4.4. Comparison of carbon footprints of manufacturers

To assess the sustainability of the supply chain, we use environmental index (*EI*) to depict environmental performance [72,73]. We assume that the carbon emissions from the production of a unit of EV is e_1 and the carbon emissions from a new unit of charging station is e_2 .

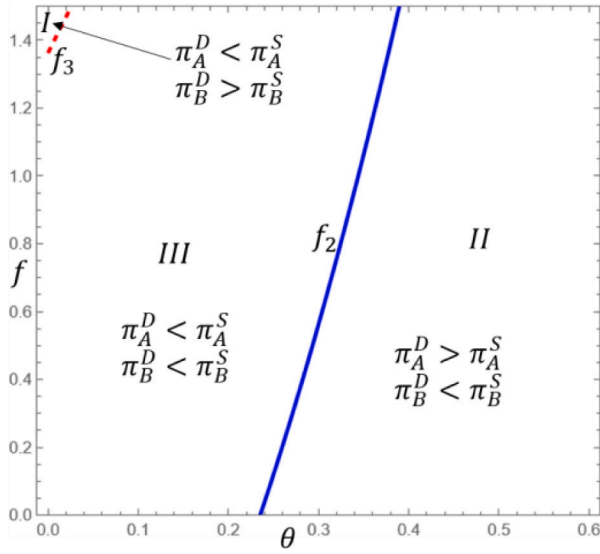
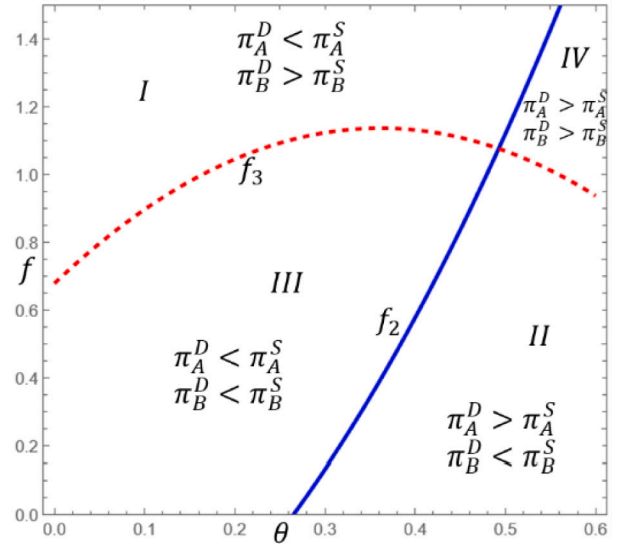
Thus, the total carbon emissions of manufacturers during the production of EVs and building of charging stations are as follows:

$$EI^j = e_1(q_A^j + q_B^j) + e_2(n_A^j + n_B^j) \quad (9)$$

where $j \in \{D \text{ or } S\}$. In Strategy S, since manufacturer B does not build charging stations, $n_B^S = 0$. We can derive **Proposition 6**.

Proposition 6. When $e_2 > \frac{2k(1+2\theta)e_1}{3k(5+\theta)-(2+\theta)}$, $EI^D > EI^S$; otherwise, $EI^D < EI^S$.

Proposition 6 shows that when the carbon emissions per unit of charging station building are higher, the manufacturers' production in Strategy S is more sustainable. On the contrary, the manufacturers' production in Strategy D is more sustainable. This is due to the fact that manufacturers build the highest number of total charging stations in Strategy D, thus producing more carbon emissions. If the carbon emissions per unit of charging station building are lower, the total carbon emissions are primarily come from EVs production, and manufacturers have the highest total number of EVs in Strategy S. Therefore, when manufacturers aim at the production of environmental performance, they should strictly control the carbon emissions from building charging stations and from EVs production. Thus, the economic and environmental objectives are harmonized.

(a) $k = 10$ (b) $k = 20$ Fig. 6. Manufacturers' strategic preferences considering brand advantage and contract cost ($a = 10$).

5. Extensions

In this section, we explore several extensions. First, we analyze the impact of EVs substitutability on manufacturers' decision-making. Second, we investigate the cross-sensitivity between EVs and charging stations. Third, we examine the monopoly scenario involving self-building by the manufacturer, platform encroachment, and commission-based station building. The relevant results are in the Appendix.

5.1. Impact of EVs substitutability

In previous research, we assume that different brands of EVs are completely substitutable. However, there are still similarities between different brands of EVs. According to Liu et al. [74], we use γ ($0 < \gamma < 1$) to represent the partial substitutability of EVs. The larger γ is, the greater the substitutability of the two brands of EVs is and the more intense the market competition is. $\gamma = 0$ indicates that the two types of EVs are independent of each other. Similar to Models 3.1 and 3.2, we use the superscripts DS and SS to distinguish the optimal decision. In Strategy DS, the inverse demand functions of the two manufacturers are, respectively:

$$p_A^{DS} = (1 + \theta)a - q_A^{DS} + n_A^{DS} - \gamma q_B^{DS} - n_B^{DS} \quad (10)$$

$$p_B^{DS} = a - q_B^{DS} + n_B^{DS} - \gamma q_A^{DS} - n_A^{DS} \quad (11)$$

In Strategy SS, the inverse demand functions of the two

manufacturers are as follows:

$$p_A^{SS} = (1 + \theta)a - q_A^{SS} + n_A^{SS} - \gamma q_B^{SS} \quad (12)$$

$$p_B^{SS} = a - q_B^{SS} + n_A^{SS} - \gamma q_A^{SS} \quad (13)$$

The manufacturers' profit functions in Strategies DS and SS are the same as Eqs. (3)–(4) and Eqs. (7)–(8), respectively. We will not repeat them. The equilibration results of the manufacturer are in the appendix. Due to the complexity of the results, different strategies are numerically explored and the corresponding results are given in Table 3 and Fig. 7. We assume $\theta = 0.4$, $f = 0.4$, $a = 10$, $k = 10$.

Table 3 show that, in Strategy DS, the number of charging stations built by manufacturer A increases with the substitutability of EVs, while manufacturer B exhibits the opposite result. In Strategy SS, the number of charging stations built by manufacturer A decreases with the EVs substitutability. Comparing Strategies DS and SS, we find that the number of charging stations built by manufacturer A in Strategy SS is always smaller than that in Strategy DS. This is because the market is in a perfect competition in Strategy DS, and manufacturer A needs to build more charging stations to enhance his competitiveness. In Strategy SS, if manufacturer A builds more charging stations, it also provides a significant promotion to the sales of B-type EVs. In addition, we find that manufacturer A is more profitable in Strategy SS when the substitutability of EVs is smaller. When the substitutability of EVs is larger, manufacturer A is more profitable in Strategy DS. The possible reason for this is that manufacturer A has a lower pricing in Strategy SS, which leads to a reduction in the profit. Comparing the profits of manufacturer

Table 3
Decision-making results under different strategies.

γ	Strategy	n_A	n_B	q_A	q_B	p_A	p_B	π_A	π_B
0.1	Strategy DS	0.359	0.242	6.829	4.600	6.829	4.600	45.339	20.573
	Strategy SS	0.330	/	6.924	4.819	6.924	4.819	47.254	22.820
0.3	Strategy DS	0.381	0.233	6.481	3.953	6.481	3.953	40.554	15.089
	Strategy SS	0.283	/	6.517	4.164	6.517	4.164	42.069	16.940
0.5	Strategy DS	0.418	0.222	6.264	3.337	6.263	3.337	37.487	10.638
	Strategy SS	0.249	/	6.233	3.566	6.233	3.566	38.629	12.319
0.7	Strategy DS	0.476	0.208	6.189	2.699	6.189	2.699	36.042	6.856
	Strategy SS	0.225	/	6.066	2.989	6.066	2.989	36.693	8.535
0.9	Strategy DS	0.574	0.178	6.316	1.960	6.316	1.960	36.597	3.523
	Strategy SS	0.208	/	6.028	2.391	6.028	2.391	36.302	5.319

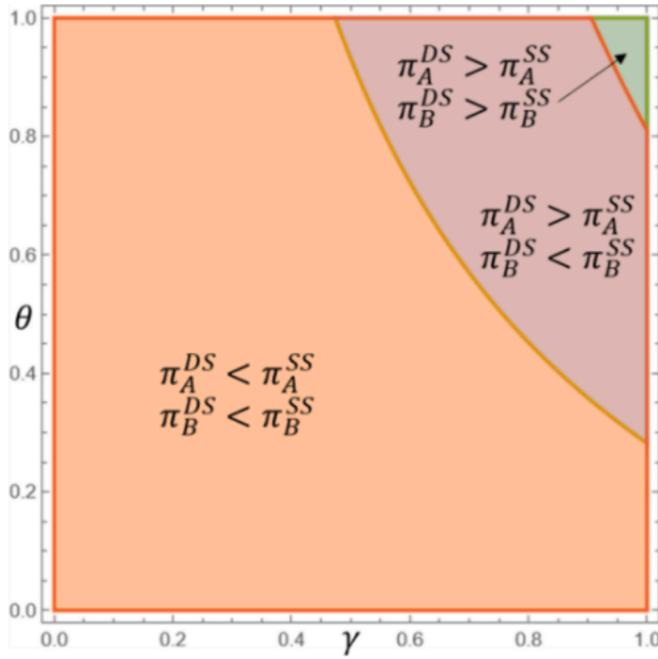


Fig. 7. Manufacturers' strategic preferences considering brand advantage and EVs substitutability ($\alpha = 10$, $k = 10$, $f = 0.4$).

B, we find that the manufacturer B is more profitable in Strategy SS. This is mainly due to the higher market demand and pricing for B-type EVs.

To further explore the impact of brand advantage and EVs substitutability, we illustrate manufacturers' strategic choices (as shown in Fig. 7). When the brand advantage of manufacturer A is smaller, both manufacturers will choose Strategy SS at the same time, thus realizing a win-win situation. This is because the two manufacturers are homogenized and the sharing of charging stations is beneficial to both manufacturers. Only when both brand advantage and the EVs substitutability are larger will the two manufacturers simultaneously choose Strategy DS. At this point, the competitive advantage of manufacturer A is more apparent. Although increased market competition leads to lower pricing and market demand for A-type EVs, the cost of building charging stations also decreases. For manufacturer B, the intense market environment results in higher pricing and market demand for EVs, thus benefiting manufacturer B. Overall, manufacturers should consider reducing brand advantage to increase the likelihood of choosing a sharing strategy.

5.2. The correlation between EV and charging station cross-sensitivity

In our previous study, we assumed that EVs and charging stations are independent of each other. According to Lai et al. [75], there may be some association between EVs and charging stations in reality, e.g., some consumers may compare the number of EVs in the market with the number of charging stations in an equal manner, thus comparing the benefits of ease of charging for themselves. In Model 3.2, since manufacturers share charging stations, we only consider EV competition among manufacturers. Whereas the reality is that manufacturer A provides charging services to manufacturer B's owners, the interaction of charging stations with EVs may also affect the production of EVs. To obtain the relationship between the cross-effects, we revise Models 3.1 and 3.2, and develop inverse demand functions for manufacturers in both the self-building and sharing strategy of charging stations. We use the superscripts D' and S' to distinguish the optimal decision in the above model.

In Strategy D' , the inverse demand functions of the two manufacturers are, respectively

$$p_A^{D'} = (1 + \theta)a - q_A^{D'} + n_A^{D'} - \beta q_B^{D'} - \beta n_B^{D'} \quad (14)$$

$$p_B^{D'} = a - q_B^{D'} + n_B^{D'} - \beta q_A^{D'} - \beta n_A^{D'} \quad (15)$$

In Strategy S' , the inverse demand functions of the two manufacturers are, respectively

$$p_A^{S'} = (1 + \theta)a - q_A^{S'} + n_A^{S'} - \beta q_B^{S'} - \beta n_A^{S'} \quad (16)$$

$$p_B^{S'} = a - q_B^{S'} + n_A^{S'} - \beta q_A^{S'} - \beta n_A^{S'} \quad (17)$$

where $0 < \beta < 1$ reflects a certain positive relationship between EV and charging station cross-sensitivity. In Strategy S' , although only manufacturer A builds charging stations, since manufacturers share charging stations, the charging stations contribute to the market demand of manufacturer B while also causing competition in the market for manufacturer A. We denote this effect by $\beta n_A^{S'}$. This hypothesis is similar to the study of Lai et al. [75]. The manufacturers' profit functions in Strategies D' and S' are the same as Eqs. (3)–(4) and Eqs. (7)–(8), respectively. We will not repeat them. The manufacturers' decision-making sequence as in Models 3.1 and 3.2.

When comparing the manufacturers' optimal decisions in Strategies D' and S' , we observe that the analytical results of β on the optimal decisions are complicated. Therefore, according to the research of Xu et al. [76] and Sun et al. [60], we conduct numerical studies for the effect β . The relevant results are curved in Fig. 8.

For manufacturer A, Fig. 8(a) and (b) shows that the number of EVs and charging stations always first decrease and then increase with the coefficient of cross-sensitivity in Strategy D' . However, for manufacturer B, both the number of EVs and charging stations decrease, with a faster decline as the coefficient of cross-sensitivity becomes larger. In Strategy S' , we find that the gap in vehicle sales is smaller compared to Strategy D' , and that the number of charging stations built by manufacturer A decreases. Fig. 8(d) illustrates that the larger coefficient of cross-sensitivity, manufacturer A's profit initially decreases and then increases, while manufacturer B's profit always declines. This result is similar to the study of Lai et al. [75]. Overall, when the cross-sensitivity coefficient is smaller, Strategy S' is more favorable to the manufacturers, potentially creating a win-win situation. In addition, as the relationship between the cross-quantity sensitivity of EVs and the charging stations strengthens, the gap between manufacturers A and B widens, intensifying competition. Therefore, manufacturers should reasonably manage the interaction between EVs and charging stations, and promptly communicate with the market to reduce consumer sensitivity to this correlation.

5.3. The potential invaders

With the diversification of charging formats in the market, third-party charging operation platforms are beginning to invade the market, thus altering the supply chain structure. In this scenario, we consider a system consisting of an EV manufacturer and a charging operation platform. In our previous study, we analyze this from the companies' perspective. According to Pi et al. [65], we further examine the company's production decision from the consumers' perspective. The consumer surplus is

$$CS = U - p_e q_e \quad (18)$$

where $U = a q_e - \frac{1}{2} q_e^2 + \tau n q_e$ denotes the consumer's utility when purchasing EVs. τ denotes the sensitivity coefficient of the charging station; a larger τ indicates that the number of charging stations has a larger impact on the consumer's purchasing decision. By solving the equation $\frac{\partial U}{\partial q_e} = 0$, we derive $p_e = a - q_e + \tau n$. However, when only the manufacturer builds the stations (Strategy DP), the manufacturer bears the full cost of building the charging stations. We set the time to one year, and

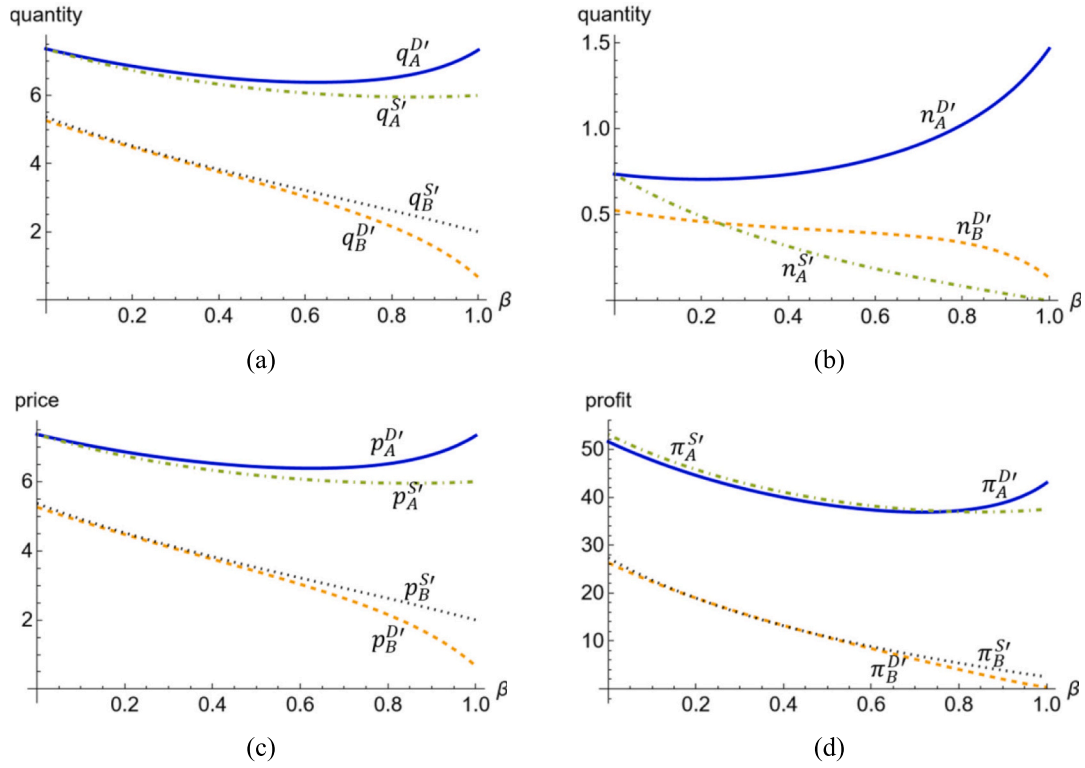


Fig. 8. Impact of cross-sensitivity coefficients on manufacturers' decisions ($k = 5, a = 10, \theta = 0.4, f = 1.5$).

the manufacturer translates the revenue and cost into annual amounts [77]. The profit function of manufacturer is as follows:

$$\pi_M^{DP} = p_e^{DP} q_e^{DP} - k(n_M^{DP})^2 + Qc q_e^{DP} \quad (19)$$

n_M^{DP} denotes the number of charging stations built by the manufacturer in Strategy DP. According to the research of relevant scholars [25,78,79], Q denotes the charging capacity of EVs, c denotes the cost per unit of electricity, and $Qc q_e^{DP}$ denotes the manufacturer's revenue in the charging field.

When platform encroachment occurs (Strategy PP), both the manufacturer and a third-party platform building stations in the market. The total number of charging stations is $n_M^{PP} + n_P^{PP}$. Both the manufacturer and the third-party platform contribute to promoting EV sales in the market, and EV owners can choose any of the charging platforms. The profit functions for the manufacturer and the platform are as follows:

$$\pi_M^{PP} = p_e^{PP} q_e^{PP} - k(n_M^{PP})^2 + \alpha Qc q_e^{PP} \quad (20)$$

$$\pi_P^{PP} = (1 - \alpha) Qc q_e^{PP} - k(n_P^{PP})^2 \quad (21)$$

Here, n_M^{PP} and n_P^{PP} denote the number of charging stations built by the manufacturer and the third-party platform in the Strategy PP, respectively. Since consumers can use charging stations across different operators, α represents the probability that a consumer chooses a charging station built by the manufacturer, while $1 - \alpha$ is the probability of choosing a charging station built by the third-party operation platform. The revenue for the charging operation platform primarily comes from consumers charging fees, so its revenue is $(1 - \alpha) Qc q_e^{PP}$. The decision sequence of manufacturer and charging operation platform is as follows: first, both manufacturer and the platform decide on the number of charging stations to build. Then the manufacturer determines the number of EVs to produce.

Comparing Strategies DP and PP, we obtain Proposition 7.

Proposition 7. $n_M^{DP} > n_M^{PP}$, $n_M^{DP} = n_M^{PP} + n_P^{PP}$, $q_e^{DP} > q_e^{PP}$, $p_e^{DP} < p_e^{PP}$,

$$\pi_M^{DP} > \pi_M^{PP}.$$

Proposition 7 shows that with platform encroachment, the manufacturer reduces the building of charging stations, but the total number of charging stations in the market remains the same. Consumers can choose between manufacturer-built charging stations and third-party charging operation platform, which reduces the manufacturer's revenue from charging. Consequently, the manufacturer has an incentive to increase the EV prices to mitigate losses. As a result, when there are multiple charging operators in the market, the manufacturer's revenue decreases.

Through the above analysis, we find that the intrusion of charging platform results in revenue loss for manufacturer. Moreover, both of the above strategies are independent and there is no cooperation between manufacturer and charging operation platform. However, vehicle manufacturers are constantly expanding into new areas within the charging field, which attracts new entrants and leads to the formation of cooperative partnerships. For instance, Didi Chuxing has interconnected data with the National Grid and invested in building charging stations. Additionally, Didi Chuxing is collaborating with BP to invest in joint charging stations.³ Similarly, Lyft and Electrify America are partnering to build charging stations in the Denver area.⁴ To distinguish from the independent strategy, we construct a supply chain consisting of a manufacturer and a service provider, and the manufacturer co-builds charging stations with the service provider (Strategy DT). We compare the limitations and effectiveness of this co-building model (Strategy DT) with the self-building model (Strategy DP). In Strategy DT, the inverse demand function for the manufacturer remains the same as in Strategy DP. The profit functions of the manufacturer and the service provider are as follows:

³ <https://www.automotive-fleet.com/337729/bp-didi-chuxing-building-ev-charge-stations-in-china?>

⁴ <https://insideevs.com/news/383450/lyft-kia-niro-ev-electrify-america/>.

$$\pi_M^{DT} = p_e^{DT} q_e^{DT} - t n_s^{DT} \quad (22)$$

$$\pi_s^{DT} = t n_s^{DT} - k (n_s^{DT})^2 + Q c q_e^{DT} \quad (23)$$

where n_s^{DT} denotes the number of charging stations built by the service provider, and t is a fixed commission per unit of charging station paid by the manufacturer to the service provider. The sequence of decisions by the manufacturer and service provider is as follows: In the first stage, the manufacturer sets the commission for the charging stations, while the service provider determines the number of charging stations to build. In the second stage, the manufacturer decides on the number of EVs to produce.

Comparing Strategies DP and DT, we get [Proposition 8](#).

Proposition 8. (1) $n_M^{DP} > n_s^{DT}$, $q_e^{DP} > q_e^{DT}$, $\pi_M^{DP} > \pi_M^{DT}$. (2) When $k > \frac{a\tau^2 + 4cQ\tau^2}{16cQ} + \frac{1}{16} \sqrt{\frac{a^2\tau^4 + 8acQ\tau^4 + 8c^2Q^2\tau^4}{c^2Q^2}}$, $p_e^{DP} < p_e^{DT}$; when $\frac{\tau^2}{4} < k < \frac{a\tau^2 + 4cQ\tau^2}{16cQ} + \frac{1}{16} \sqrt{\frac{a^2\tau^4 + 8acQ\tau^4 + 8c^2Q^2\tau^4}{c^2Q^2}}$, $p_e^{DP} > p_e^{DT}$.

[Proposition 8\(1\)](#) suggests that the manufacturer will build more charging stations in a self-building strategy. This is because the manufacturer needs to be more competitive in the market through charging stations. If the manufacturer builds fewer charging stations, that reduces the market demand for EVs, while lowering the manufacturer's charging service revenue. Despite the higher investment required for building stations in Strategy DP, the increased market demand for EVs results in higher profits for the manufacturer compared to Strategy DT.

[Proposition 8\(2\)](#) suggests that in Strategy DP, the pricing of EVs is higher when the cost coefficient of building the station is smaller. Conversely, when the cost coefficient of building the station is larger, the result is reversed. This is because a larger cost coefficient of building the station will cause both the manufacturer and the service provider to reduce the number of charging stations built. In Strategy DT, the difference is that if the service provider builds fewer charging stations, the manufacturer pays a smaller commission, resulting in only a modest reduction in EV pricing. In Strategy DP, although the manufacturer will also build fewer charging stations, the reduction is more significant, leading to a larger drop in EV prices. A smaller cost coefficient of building the station encourages both the manufacturer and the service provider to build more charging stations. In strategy DT, this results in higher commission costs for manufacturer, which in turn lowers EV pricing.

6. Conclusion

6.1. Key findings

In this paper, we develop a programmatic game-theoretic model to analyze how the low-end vehicle manufacturer makes decisions about the building of charging stations. We construct two models of charging station self-building and sharing, and comprehensively compare the optimal building strategies. The results of the study reveal that the brand advantage of A-type EVs is favorable to the revenue of high-end vehicle manufacturer, but unfavorable to the revenue of low-end vehicle manufacturer. Comparing self-building and sharing strategies, the manufacturers should choose sharing strategy when the brand advantage of the high-end vehicle manufacturer and the contract cost are smaller or both are in the medium. Additionally, when the cost coefficient of building the station, the brand advantage, and the contract cost are all larger, Self-building strategy is more favorable for the manufacturers' sustainability. In the extended model, the substitutability of EVs causes a highly competitive environment, which loses the profits of the manufacturers. When the cross-influence between EVs and charging stations is smaller, the charging station sharing strategy is more favorable to business growth. However, once consumers make a strong

connection between EVs and charging stations, manufacturers face a prisoner's dilemma. In a monopoly production scenario, the invasion of a platform and a service provider reduces the manufacturer's revenue. It is more favorable for the manufacturer to self-build charging stations than to commission them. This paper provides a comprehensive analysis of charging station building modes, offering practical insights for the management and operation of charging station and guidance for vehicle manufacturer, charging operation platform, and service provider.

6.2. Managerial insights

The key managerial implications are summarized. When the competitive advantage of the high-end vehicle manufacturers is reduced, the competition weakens. For the low-end vehicle manufacturers, the charging station sharing strategy is undoubtedly better as she can expand her market with the benefit of charging stations built by the high-end vehicle manufacturers. Whereas, when the high-end vehicle manufacturers have a significant brand advantage and the low-end EV manufacturers face higher contract costs, the low-end EV manufacturers prefer to build their own charging stations. In addition, the vehicle manufacturers should avoid publicizing the correlation between EVs and charging stations to reduce consumer reliance on charging stations. In scenario where a manufacturer holds a monopoly on production, platform intrusion, while allowing consumers to have more charging options, also leads to a reduction in the manufacturer's revenue. Similarly, although the service provider collaborates with the manufacturer, it still diminishes the manufacturer's revenue. Therefore, it is more favorable for the manufacturer to self-build charging stations in the no-invader condition.

6.3. Limitations and future research

We discuss some of the limitations of this study and directions for future research. First, this paper has only considered the horizontally competitive market of different automakers, for the vertically competitive market still needs further consideration. Second, the market size of products usually affects the investment and deployment of infrastructure. Consequently, we can consider the deployment of charging stations by manufacturers at different stages. Third, we introduce electricity market into the supply chain and examine the structure of government subsidies.

CRedit authorship contribution statement

Feng Chen: Writing – original draft, Supervision, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jianghong Feng:** Writing – review & editing, Validation, Software, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Proposition 1.

Proof: Proposition 1 can be derived by comparing the equilibrium outcomes in Strategy D and Strategy S. We have

$$q_A^D - q_B^D = \frac{ak\theta}{k-2} > 0$$

$$n_A^D - n_B^D = \frac{a\theta}{k-2} > 0$$

$$p_A^D - p_B^D = \frac{ak\theta}{k-2} > 0$$

$$\pi_A^D - \pi_B^D = \frac{a^2(k-1)\theta(2k-4-2\theta+k\theta)}{3(k-2)} > 0$$

$$q_A^S - q_B^S = a\theta > 0$$

$$p_A^S - p_B^S = a\theta > 0$$

$$\pi_A^S - \pi_B^S = \frac{2f - a^2k - 36fk + 162fk^2 - 10a^2k\theta + 54a^2k^2\theta - a^2\theta^2 + 2a^2k\theta^2 + 27a^2k^2\theta^2}{(-1+9k)^2}$$

Define $\text{expr1} = 2f - a^2k - 36fk + 162fk^2 - 10a^2k\theta + 54a^2k^2\theta - a^2\theta^2 + 2a^2k\theta^2 + 27a^2k^2\theta^2$. The sign of $\pi_A^S - \pi_B^S$ depends on expr1 . The above expression can be rewritten as $2f(9k-1)^2 - a^2k + 2a^2k(-5+27k)\theta + a^2(-1+2k+27k^2)\theta^2$, which is a quadratic function with respect to θ and a convex function of θ . expr1 is monotonically increasing in $\theta \in \left(0, \frac{k-2}{k+1}\right)$. Define $\text{expr2} = -a^2k + 2a^2k(-5+27k)\theta + a^2(-1+2k+27k^2)\theta^2$.

① When $\text{expr2} > 0$, for $\forall f \in \left(0, \frac{a^2k(1+2\theta)^2}{(9k-1)^2}\right)$ and $\theta \in \left(0, \frac{k-2}{k+1}\right)$, $\text{expr1} > 0$ always hold. Therefore, we have $\pi_A^S - \pi_B^S > 0$.

Solving $\text{expr2} = 0$, we obtain the unique valid root $\theta_1 = \frac{5k-27k^2+\sqrt{k(9k-1)^3}}{27k^2+2k-1}$ ($\theta_1 > 0$). When $\theta = \frac{k-2}{k+1}$, we have

$$\text{expr2}|_{\theta=\frac{k-2}{k+1}} = \frac{a^2(-4+31k-k^2-171k^3+81k^4)}{(1+k)^2}$$

Define $F(k) = -4+31k-k^2-171k^3+81k^4$. $F(k)$ is monotonically increasing in $k \in (2, +\infty)$; Because of $F(k=2) = -18 < 0$, there exists unique root k_0 of $F(k) = 0$ in interval $(2, +\infty)$. When $k > k_0$, we have $F(k) > 0$; when $2 < k < k_0$, we have $F(k) < 0$.

Therefore, when $k > k_0$, $\theta_1 < \theta < \frac{k-2}{k+1}$, and $0 < f < \frac{a^2k(1+2\theta)^2}{(9k-1)^2}$, we have $\pi_A^S - \pi_B^S > 0$.

② When $\text{expr2} < 0$, to satisfy $\pi_A^S - \pi_B^S > 0$, so $f > f_1$, where $f_1 = \frac{a^2(k+2k(5-\theta)\theta+\theta^2-27k^2\theta(2+\theta))}{2(9k-1)^2}$.

Therefore, when $k > k_0$, $0 < \theta < \theta_1$, and $f_1 < f < \frac{a^2k(1+2\theta)^2}{(9k-1)^2}$, we have $\pi_A^S - \pi_B^S > 0$.

Or, when $k < k_0$, $0 < \theta < \frac{k-2}{k+1}$, and $f_1 < f < \frac{a^2k(1+2\theta)^2}{(9k-1)^2}$, we have $\pi_A^S - \pi_B^S > 0$.

③ When $\text{expr2} < 0$, to satisfy $\pi_A^S - \pi_B^S < 0$, so $f < f_1$.

Therefore, when $k > k_0$, $0 < \theta < \theta_1$, and $0 < f < f_1$, we have $\pi_A^S - \pi_B^S < 0$.

Or, when $k < k_0$, $0 < \theta < \frac{k-2}{k+1}$, and $0 < f < f_1$, we have $\pi_A^S - \pi_B^S < 0$.

In summary, when $\pi_A^S - \pi_B^S > 0$, there are three cases:

$$\text{i) } 2 < k < k_0, f_1 < f < \frac{a^2k(1+2\theta)^2}{(9k-1)^2};$$

$$\text{ii) } k > k_0, 0 < \theta < \theta_1, f_1 < f < \frac{a^2k(1+2\theta)^2}{(9k-1)^2}$$

$$\text{iii) } k > k_0, \theta_1 < \theta < \frac{k-2}{k+1}.$$

When $\pi_A^S - \pi_B^S < 0$, there are two cases:

$$\text{iv) } 2 < k < k_0, 0 < f < f_1;$$

$$\text{v) } k > k_0, 0 < \theta < \theta_1, 0 < f < f_1.$$

Where $f_1 = \frac{a^2(k+2k(5-\theta)\theta+\theta^2-27k^2\theta(2+\theta))}{2(9k-1)^2}$, $\theta_1 = \frac{5k-27k^2+\sqrt{k(9k-1)^3}}{27k^2+2k-1}$, k_0 is unique root of $-4+31k-k^2-171k^3+81k^4 = 0$ when $k \in (2, +\infty)$.

Proposition 2.

Proof: The difference between q_A^D and q_A^S is:

$$q_A^D - q_A^S = \frac{a(2-k+\theta+25k\theta)}{3(k-2)(9k-1)}$$

When $\frac{k-2}{25k+1} < \theta < \frac{k-2}{k-1}$, $q_A^D > q_A^S$; otherwise, $q_A^D < q_A^S$.

The difference between q_B^D and q_B^S is:

$$q_B^D - q_B^S = -\frac{a(k-2-7\theta+29k\theta)}{3(k-2)(9k-1)} < 0$$

The difference between n_A^D and n_A^S is:

$$n_A^D - n_A^S = \frac{a(2-13k+6k^2+\theta+k\theta+12k^2\theta)}{3k(k-2)(9k-1)}$$

Define $\text{expr3} = 2-13k+6k^2+\theta+k\theta+12k^2\theta$. The sign of $n_A^D - n_A^S$ depends on expr3 . The derivation of expr3 with respect to θ is $\frac{\partial \text{expr3}}{\partial \theta} = 1+k+12k^2$. Clearly, $\frac{\partial \text{expr3}}{\partial \theta} > 0$. Therefore, expr3 is monotonically increasing in $\theta \in \left(0, \frac{k-2}{k+1}\right)$; And the values at endpoints are

$$\text{expr3}|_{\theta=0} = 2-13k+6k^2 > 0$$

$$\text{expr3}|_{\theta=\frac{k-2}{k+1}} = \frac{6k(-2-5k+3k^2)}{1+k} > 0$$

When $k > 2$, we have $\text{expr3} > 0$. Therefore $n_A^D > n_A^S$.

The difference between $q_A^D + q_B^D$ and $q_A^S + q_B^S$ is:

$$q_A^D + q_B^D - (q_A^S + q_B^S) = -\frac{2a(1+2\theta)}{27k-3} < 0$$

The difference between $n_A^D + n_B^D$ and n_A^S is:

$$n_A^D + n_B^D - n_A^S = \frac{a(3k(5+\theta) - (2+\theta))}{3k(9k-1)} > 0$$

Lemma 1.

Proof: The derivations of q_A^D, q_A^S with respect to θ are

$$\frac{\partial q_A^D}{\partial \theta} = \frac{a(2k-1)}{3(k-2)} > 0$$

$$\frac{\partial q_A^S}{\partial \theta} = \frac{6ak}{9k-1} > 0$$

The difference between $\frac{\partial q_A^D}{\partial \theta}$ and $\frac{\partial q_A^S}{\partial \theta}$ is

$$\frac{\partial q_A^D}{\partial \theta} - \frac{\partial q_A^S}{\partial \theta} = \frac{a(25k+1)}{3(k-2)(9k-1)} > 0$$

The derivations of q_B^D, q_B^S with respect to θ are

$$\frac{\partial q_B^D}{\partial \theta} = -\frac{a(k+1)}{3(k-2)} < 0$$

$$\frac{\partial q_B^S}{\partial \theta} = -\frac{a(3k-1)}{9k-1} < 0$$

The difference between $|\frac{\partial q_B^D}{\partial \theta}|$ and $|\frac{\partial q_B^S}{\partial \theta}|$ is

$$|\frac{\partial q_B^D}{\partial \theta}| - |\frac{\partial q_B^S}{\partial \theta}| = \frac{a(29k-7)}{3(k-2)(9k-1)} > 0$$

The derivations of n_A^D, n_A^S with respect to θ are

$$\frac{\partial n_A^D}{\partial \theta} = \frac{a(2k-1)}{3k(k-2)} > 0$$

$$\frac{\partial n_A^S}{\partial \theta} = \frac{2a}{9k-1} > 0$$

The difference between $\frac{\partial n_A^D}{\partial \theta}$ and $\frac{\partial n_A^S}{\partial \theta}$ is

$$\frac{\partial n_A^D}{\partial \theta} - \frac{\partial n_A^S}{\partial \theta} = \frac{a(1+k+12k^2)}{3k(k-2)(9k-1)} > 0$$

The derivation of n_B^D with respect to θ is

$$\frac{\partial n_B^D}{\partial \theta} = -\frac{a(k+1)}{3k(k-2)} < 0$$

Proposition 3.

Proof: The difference between p_A^D and p_A^S is

$$p_A^D - p_A^S = \frac{a(2 - k + \theta + 25k\theta)}{3(k - 2)(9k - 1)}$$

When $\frac{k-2}{25k+1} < \theta < \frac{k-2}{k+1}$, we have $p_A^D > p_A^S$; otherwise, $p_A^D < p_A^S$.

The difference between p_B^D and p_B^S is

$$p_B^D - p_B^S = -\frac{a(-2 + k - 7\theta + 29k\theta)}{3(k - 2)(9k - 1)} < 0$$

Lemma 2.

Proof: The derivations of p_A^D, p_A^S with respect to θ are

$$\frac{\partial p_A^D}{\partial \theta} = \frac{a(2k - 1)}{3(k - 2)} > 0$$

$$\frac{\partial p_A^S}{\partial \theta} = \frac{6ak}{9k - 1} > 0$$

The difference between $\frac{\partial p_A^D}{\partial \theta}$ and $\frac{\partial p_A^S}{\partial \theta}$ is

$$\frac{\partial p_A^D}{\partial \theta} - \frac{\partial p_A^S}{\partial \theta} = \frac{a(25k + 1)}{3(k - 2)(9k - 1)} > 0$$

The derivations of p_B^D, p_B^S with respect to θ are

$$\frac{\partial p_B^D}{\partial \theta} = -\frac{a(k + 1)}{3(k - 2)} < 0$$

$$\frac{\partial p_B^S}{\partial \theta} = -\frac{a(3k - 1)}{9k - 1} < 0$$

The difference between $|\frac{\partial p_B^D}{\partial \theta}|$ and $\frac{\partial p_B^S}{\partial \theta}$ is

$$|\frac{\partial p_B^D}{\partial \theta}| - |\frac{\partial p_B^S}{\partial \theta}| = \frac{a(29k - 7)}{3(k - 2)(9k - 1)} > 0$$

The difference between n_B^D and n_A^S is

$$n_B^D - n_A^S = \frac{a(2 - 13k + 6k^2 + \theta + 4k\theta - 15k^2\theta)}{3k(k - 2)(9k - 1)}$$

Define $\text{expr4} = 2 - 13k + 6k^2 + \theta + 4k\theta - 15k^2\theta$. The sign of $n_B^D - n_A^S$ depends on expr4 . The derivation of expr4 with respect to θ is $\frac{\partial \text{expr4}}{\partial \theta} = 1 + 4k - 15k^2$. When $k > 2$, we have $\frac{\partial \text{expr4}}{\partial \theta} < 0$. Therefore expr4 is monotonically decreasing in $\theta \in \left(0, \frac{k-2}{k+1}\right)$. And the values at endpoints are

$$\text{expr4}|_{\theta=0} = 2 - 13k + 6k^2 > 0$$

$$\text{expr4}|_{\theta=\frac{k-2}{k+1}} = -\frac{9k(2 - 3k + k^2)}{1 + k} < 0$$

When $0 < \theta < \frac{6k^2-13k+2}{15k^2-4k-1}$, we have $n_B^D > n_A^S$; otherwise, $n_B^D < n_A^S$.

Proposition 4.

Proof: The difference between π_A^D and π_A^S is

$$\pi_A^D - \pi_A^S = \frac{4a^2 - 44a^2k + 36fk + 41a^2k^2 - 360fk^2 - 10a^2k^3 + 333fk^3 - 81fk^4 + 4a^2\theta - 50a^2k\theta - 4a^2k^2\theta + 14a^2k^3\theta + a^2\theta^2 - 14a^2k\theta^2 - 91a^2k^2\theta^2 + 68a^2k^3\theta^2}{9k(k - 2)^2(9k - 1)}$$

Define $\text{expr5} = 4a^2 - 44a^2k + 36fk + 41a^2k^2 - 360fk^2 - 10a^2k^3 + 333fk^3 - 81fk^4 + 4a^2\theta - 50a^2k\theta - 4a^2k^2\theta + 14a^2k^3\theta + a^2\theta^2 - 14a^2k\theta^2 - 91a^2k^2\theta^2 + 68a^2k^3\theta^2$. The sign of $\pi_A^D - \pi_A^S$ depends on expr5 . The above expression can be rewritten as $-(k - 2)^2(9fk(9k - 1) + a^2(10k - 1)) + 2a^2(2 - 25k - 2k^2 + 7k^3)\theta + a^2(1 - 14k - 91k^2 + 68k^3)\theta^2$.

When $k \in (2, +\infty)$, we have $2 - 25k - 2k^2 + 7k^3 = (k - 2)(-1 + 12k + 7k^2) > 0$ and $1 - 14k - 91k^2 + 68k^3 > 0$. expr5 is a quadratic function with respect to θ and a convex function of θ . Note that, the axis of symmetry of expr5 is on the left of line $\theta = 0$. expr5 is monotonically increasing in $\theta \in \left(0, \frac{k-2}{k+1}\right)$.

Solving $\text{expr5} = 0$ with respect to θ , we have $\theta = \frac{a^2(-2+25k+2k^2-7k^3)+3\sqrt{a^2(-2+k)^2k(-1+9k)(9a^2(-1+k)k+f(1-14k-91k^2+68k^3))}}{a^2(1-14k-91k^2+68k^3)}$ when $\theta > 0$. When $\theta = \frac{k-2}{k+1}$, we have

$$\text{expr5}|_{\theta=\frac{k-2}{k+1}} = -\frac{9k(k-2)^2(-8ka^2(k-1)+f(1+k)^2(9k-1))}{(k+1)^2}$$

Because $-8ka^2(k-1)+f(1+k)^2(9k-1) < ka^2\frac{(1+2\theta)^2(k+1)^2-8(k-1)(9k-1)}{9k-1} < ka^2\frac{29(k+1)^2-8(k-1)(9k-1)}{9k-1} = ka^2\frac{-63k^2+98k+1}{9k-1} < 0$, we have $\text{expr5}|_{\theta=\frac{k-2}{k+1}} > 0$ and

$$\frac{a^2(-2+25k+2k^2-7k^3)+3\sqrt{a^2(-2+k)^2k(-1+9k)(9a^2(-1+k)k+f(1-14k-91k^2+68k^3))}}{a^2(1-14k-91k^2+68k^3)} < \frac{k-2}{k+1}.$$

When $0 < \theta < \frac{a^2(-2+25k+2k^2-7k^3)+3\sqrt{a^2(-2+k)^2k(-1+9k)(9a^2(-1+k)k+f(1-14k-91k^2+68k^3))}}{a^2(1-14k-91k^2+68k^3)}$, $\text{expr5} < 0$, we have $\pi_A^D - \pi_A^S < 0$, if $f > f_2$, where $f_2 = \frac{a^2(1-14k-91k^2+68k^3)\theta^2+2a^2(2-25k-2k^2+7k^3)\theta-a^2(k-2)^2(10k-1)}{9k(k-2)^2(9k-1)}$. When $\frac{a^2(-2+25k+2k^2-7k^3)+3\sqrt{a^2(-2+k)^2k(-1+9k)(9a^2(-1+k)k+f(1-14k-91k^2+68k^3))}}{a^2(1-14k-91k^2+68k^3)} < \theta < \frac{k-2}{k+1}$, $\text{expr5} > 0$, we have $\pi_A^D - \pi_A^S > 0$ if $0 < f < f_2$.

$$\text{Define } \text{expr6} = \frac{a^2(1-14k-91k^2+68k^3)\theta^2+2a^2(2-25k-2k^2+7k^3)\theta-a^2(k-2)^2(10k-1)}{9k(k-2)^2(9k-1)} - \frac{ka^2(1+2\theta)^2}{(9k-1)^2} = \frac{a^2(-4+80k-473k^2+415k^3-99k^4-4\theta+86k\theta-590k^2\theta+94k^3\theta+90k^4\theta-\theta^2+23k\theta^2-179k^2\theta^2-743k^3\theta^2+576k^4\theta^2)}{9k(k-2)^2(9k-1)^2}.$$

Obviously, the sign of expr6 depends on $\text{expr7} = -4 + 80k - 473k^2 + 415k^3 - 99k^4 - 4\theta + 86k\theta - 590k^2\theta + 94k^3\theta + 90k^4\theta - \theta^2 + 23k\theta^2 - 179k^2\theta^2 - 743k^3\theta^2 + 576k^4\theta^2 = -(k-2)^2(1-19k+99k^2) + 2(k-2)(1-21k+137k^2+45k^3)\theta + (-1+23k-179k^2-743k^3+576k^4)\theta^2$. expr7 is a quadratic function with respect to θ and a convex function of θ . The signs of the coefficients are $1-21k+137k^2+45k^3 > 0$ and $-1+23k-179k^2-743k^3+576k^4 > 0$. Note that, the axis of symmetry of expr7 is on the left of line $\theta = 0$.

Solving $\text{expr7} = 0$ with respect to θ , we have $\theta_3 = \frac{2-43k+295k^2-47k^3-45k^4}{-1+23k-179k^2-743k^3+576k^4} + 27\sqrt{\frac{-4k^3+80k^4-473k^5+739k^6-423k^7+81k^8}{(-1+23k-179k^2-743k^3+576k^4)^2}}$ when $\theta_3 > 0$.

To satisfy $f > 0$, solving $4-44k+41k^2-10k^3+4\theta-50k\theta-4k^2\theta+14k^3\theta+\theta^2-14k\theta^2-91k^2\theta^2+68k^3\theta^2 = 0$ with respect to θ , we have $\theta_2 = \frac{-2+25k+2k^2-7k^3}{1-14k-91k^2+68k^3} + 9\sqrt{\frac{4k^2-44k^3+77k^4-46k^5+9k^6}{(1-14k-91k^2+68k^3)^2}}$ when $\theta_2 > 0$.

There are two cases for the range of f :

Case 1:

When $\theta_2 < \theta < \theta_3$, we have $\text{expr6} < 0$ if $0 < f < f_2$. Therefore, $\pi_A^D - \pi_A^S > 0$.

Case 2:

When $\theta_3 < \theta < \frac{k-2}{1+k}$, we have $\text{expr6} > 0$ if $0 < f < \frac{ka^2(1+2\theta)^2}{(9k-1)^2}$. Therefore, $\pi_A^D - \pi_A^S > 0$.

Similarly,

When $0 < \theta < \theta_2$, $0 < f < \frac{ka^2(1+2\theta)^2}{(9k-1)^2}$ or when $\theta_2 < \theta < \theta_3$, $f_2 < f < \frac{ka^2(1+2\theta)^2}{(9k-1)^2}$, we have $\pi_A^D - \pi_A^S < 0$.

In summary, when $\pi_A^D - \pi_A^S > 0$, there are two cases:

i) $\theta \in (\theta_2, \theta_3)$, $f \in (0, f_2)$;

ii) $\theta \in \left(\theta_3, \frac{k-2}{k+1}\right)$.

When $\pi_A^D - \pi_A^S < 0$, there are two cases:

iii) $\theta \in (0, \theta_2)$;

iv) $\theta \in (\theta_2, \theta_3)$, $f \in \left(f_2, \frac{ka^2(1+2\theta)^2}{(9k-1)^2}\right)$.

$$\text{Where } \theta_2 = \frac{-2+25k+2k^2-7k^3}{1-14k-91k^2+68k^3} + 9\sqrt{\frac{4k^2-44k^3+77k^4-46k^5+9k^6}{(1-14k-91k^2+68k^3)^2}}, \quad \theta_3 = \frac{2-43k+295k^2-47k^3-45k^4}{-1+23k-179k^2-743k^3+576k^4} + 27\sqrt{\frac{-4k^3+80k^4-473k^5+739k^6-423k^7+81k^8}{(-1+23k-179k^2-743k^3+576k^4)^2}}, \quad f_2 = \frac{a^2(1-14k-91k^2+68k^3)\theta^2+2a^2(2-25k-2k^2+7k^3)\theta-a^2(k-2)^2(10k-1)}{9k(k-2)^2(9k-1)}$$

Proposition 5.

Proof: The difference between π_B^D and π_B^S is

$$\pi_B^D - \pi_B^S = \frac{-4a^2 + 80a^2k + 36fk - 473a^2k^2 - 684fk^2 + 415a^2k^3 + 3573fk^3 - 99a^2k^4 - 3078fk^4 + 729fk^5 - 4a^2\theta + 74a^2k\theta - 572a^2k^2\theta + 952a^2k^3\theta - 342a^2k^4\theta - a^2\theta^2 - 19a^2k\theta^2 + 190a^2k^2\theta^2 - 647a^2k^3\theta^2 + 441a^2k^4\theta^2}{9(-2+k)^2k(-1+9k)^2}$$

Define $\text{expr8} = -4a^2 + 80a^2k + 36fk - 473a^2k^2 - 684fk^2 + 415a^2k^3 + 3573fk^3 - 99a^2k^4 - 3078fk^4 + 729fk^5 - 4a^2\theta + 74a^2k\theta - 572a^2k^2\theta + 952a^2k^3\theta - 342a^2k^4\theta - a^2\theta^2 - 19a^2k\theta^2 + 190a^2k^2\theta^2 - 647a^2k^3\theta^2 + 441a^2k^4\theta^2$. The sign of $\pi_B^D - \pi_B^S$ depends on expr8 . The above expression can be rewritten as $(k-2)^2(9f(9k-1)^2k + a^2(-1+19k-99k^2)) - 2a^2(2-37k+286k^2-476k^3+171k^4)\theta + a^2(-1-19k+190k^2-647k^3+441k^4)\theta^2$.

It is obviously that $9f(9k-1)^2k + a^2(-1+19k-99k^2) < 9k(9k-1)^2\frac{2ka^2(1+2\theta)^2}{(9k-1)^2} + a^2(-1+19k-99k^2) = 9k^2a^2(1+2\theta)^2 + a^2(-1+19k-99k^2) < 81k^2a^2 + a^2(-1+19k-99k^2) = a^2(-17k^2+19k-1) < 0$.

The signs of the coefficients are $9f(9k-1)^2k + a^2(-1+19k-99k^2) < 0$, $2-37k+286k^2-476k^3+171k^4 > 0$, $-1-19k+190k^2-647k^3+441k^4 > 0$ when $k \in (2, +\infty)$. expr8 is a quadratic function with respect to θ and a convex function of θ . Note that, the axis of symmetry of expr8 is on the right of line $\theta = 0$.

Solving $\text{expr8} = 0$ with respect to θ , we have $\theta = \frac{a^2(2-37k+286k^2-476k^3+171k^4)+3\sqrt{a^2k(2-19k+9k^2)^2(4a^2(1-5k)^2(-1+k)+f(1+19k-190k^2+647k^3-441k^4))}}{a^2(-1-19k+190k^2-647k^3+441k^4)}$ when $\theta > 0$.

When $\pi_B^D - \pi_B^S < 0$, we have $0 < f < f_3$, where $f_3 = \frac{a^2(k-2)^2(1-19k+99k^2)+2a^2(2-37k+286k^2-476k^3+171k^4)\theta+a^2(1+19k-190k^2+647k^3-441k^4)\theta^2}{9k(k-2)^2(9k-1)^2}$.

The difference between $\frac{a^2(k-2)^2(1-19k+99k^2)+2a^2(2-37k+286k^2-476k^3+171k^4)\theta+a^2(1+19k-190k^2+647k^3-441k^4)\theta^2}{9k(k-2)^2(9k-1)^2}$ and $\frac{ka^2(1+2\theta)^2}{(9k-1)^2}$ is

$$\begin{aligned} & \frac{a^2(k-2)^2(1-19k+99k^2)+2a^2(2-37k+286k^2-476k^3+171k^4)\theta+a^2(1+19k-190k^2+647k^3-441k^4)\theta^2}{9k(k-2)^2(9k-1)^2} - \frac{ka^2(1+2\theta)^2}{(9k-1)^2} \\ &= -\frac{a^2(4-44k+41k^2-10k^3+4\theta-38k\theta+86k^2\theta-34k^3\theta+\theta^2+28k\theta^2-82k^2\theta^2+53k^3\theta^2)}{9(-2+k)^2k(-1+9k)}. \end{aligned}$$

Define $\text{expr9} = -(4-44k+41k^2-10k^3+4\theta-38k\theta+86k^2\theta-34k^3\theta+\theta^2+28k\theta^2-82k^2\theta^2+53k^3\theta^2) = (k-2)^2(10k-1) + (-4+38k-86k^2+34k^3)\theta + (-1-28k+82k^2-53k^3)\theta^2$. When $k > 2$, the signs of the coefficients are $-4+38k-86k^2+34k^3 > 0$, $-1-28k+82k^2-53k^3 < 0$. expr9 is a quadratic function with respect to θ and a concave function of θ . Note that, the axis of symmetry of expr9 is on the right of line $\theta = 0$.

Solving $\text{expr9} = 0$ with respect to θ , we have $\theta_4 = \frac{-2+19k-43k^2+17k^3}{1+28k-82k^2+53k^3} + 3\sqrt{\frac{-16k+228k^2-740k^3+941k^4-495k^5+91k^6}{(1+28k-82k^2+53k^3)^2}}$ when $\theta_4 > 0$. When $\theta = \frac{k-2}{k+1}$, we have

$$\text{expr9}|_{\theta=\frac{k-2}{k+1}} = \frac{9k(k-2)^2(-4+13k-k^2)}{(1+k)^2}$$

When $2 < k < \frac{13+3\sqrt{17}}{2}$, we have $\text{expr9}|_{\theta=\frac{k-2}{k+1}} > 0$. In this condition, $0 < \theta < \frac{k-2}{k+1}$, $0 < f < \frac{ka^2(1+2\theta)^2}{(9k-1)^2}$, and $\pi_B^D - \pi_B^S < 0$.

When $k > \frac{13+3\sqrt{17}}{2}$, we have $\text{expr9}|_{\theta=\frac{k-2}{k+1}} < 0$. In this condition, when $0 < \theta < \theta_4$, we have $\text{expr9} > 0$ if $0 < f < \frac{ka^2(1+2\theta)^2}{(9k-1)^2}$, and $\pi_B^D - \pi_B^S < 0$.

When $k > \frac{13+3\sqrt{17}}{2}$, $\theta_4 < \theta < \frac{k-2}{k+1}$, we have $\text{expr9} < 0$ if $0 < f < f_3$, and $\pi_B^D - \pi_B^S < 0$.

When $\pi_B^D - \pi_B^S > 0$, $f > f_3$. If and only if $k > \frac{13+3\sqrt{17}}{2}$, $\theta_4 < \theta < \frac{k-2}{k+1}$, we have $\text{expr9} < 0$ if $f_3 < f < \frac{ka^2(1+2\theta)^2}{(9k-1)^2}$.

In summary, when $\pi_B^D - \pi_B^S > 0$,

$$\text{i) } k \in \left(\frac{13+3\sqrt{17}}{2}, +\infty\right), \theta \in \left(\theta_4, \frac{k-2}{k+1}\right), f \in \left(f_3, \frac{a^2(3k-3k\theta+\theta)^2}{(9k-1)^2}\right).$$

when $\pi_B^D - \pi_B^S < 0$, there are three cases:

$$\text{ii) } k \in \left(2, \frac{13+3\sqrt{17}}{2}\right), \theta \in \left(0, \frac{k-2}{k+1}\right);$$

$$\text{iii) } k \in \left(\frac{13+3\sqrt{17}}{2}, +\infty\right), \theta \in (0, \theta_4);$$

$$\text{iv) } k \in \left(\frac{13+3\sqrt{17}}{2}, +\infty\right), \theta \in \left(\theta_4, \frac{k-2}{k+1}\right), f \in (0, f_3).$$

$$\text{Where } \theta_4 = \frac{-2+19k-43k^2+17k^3}{1+28k-82k^2+53k^3} + 3\sqrt{\frac{-16k+228k^2-740k^3+941k^4-495k^5+91k^6}{(1+28k-82k^2+53k^3)^2}}, f_3 = \frac{a^2(k-2)^2(1-19k+99k^2)+2a^2(2-37k+286k^2-476k^3+171k^4)\theta+a^2(1+19k-190k^2+647k^3-441k^4)\theta^2}{9k(k-2)^2(9k-1)^2}.$$

Proposition 6.

Proof: The difference between EI^D and EF^S is:

$$EI^D - EF^S = -\frac{a(2(k+2k\theta)e_1 - (3k(5+\theta) - (2+\theta))e_2)}{3k(-1+9k)}$$

When $e_2 > \frac{2k(1+2\theta)e_1}{3k(5+\theta)-(2+\theta)}$, $EI^D > EF^S$; when $0 < e_2 < \frac{2k(1+2\theta)e_1}{3k(5+\theta)-(2+\theta)}$, $EI^D < EF^S$.

Extensions.

5.1 Impact of EVs substitutability

In Strategy DS, the number of charging stations are $n_A^{DS} = \frac{a(k(2-\gamma)(2(1+\theta)-\gamma)-(2+\theta))}{k(k(2-\gamma)^2-2)(2-\gamma)(2+\gamma)}$ and $n_B^{DS} = \frac{a(k(2-\gamma)(2-\gamma(1+\theta))-(2+\theta))}{k(k(2-\gamma)^2-2)(2-\gamma)(2+\gamma)}$; the quantity of EVs are $q_A^{DS} = \frac{a(k(2-\gamma)(2(1+\theta)-\gamma)-(2+\theta))}{(k(2-\gamma)^2-2)(2+\gamma)}$ and $q_B^{DS} = \frac{a(k(2-\gamma)(2-\gamma(1+\theta))-(2+\theta))}{(k(2-\gamma)^2-2)(2+\gamma)}$; the prices of EVs are $p_A^{DS} = \frac{a(k(2-\gamma)(2(1+\theta)-\gamma)-(2+\theta))}{(k(2-\gamma)^2-2)(2+\gamma)}$ and $p_B^{DS} = \frac{a(k(2-\gamma)(2-\gamma(1+\theta))-(2+\theta))}{(k(2-\gamma)^2-2)(2+\gamma)}$; the profits of manufacturers are $\pi_A^{DS} = \frac{a^2(k(2-\gamma)^2-1)(k(2-\gamma)(2(1+\theta)-\gamma)-(2+\theta))^2}{k(k(2-\gamma)^2-2)^2(2-\gamma)^2(2+\gamma)^2}$ and $\pi_B^{DS} = \frac{a^2(k(2-\gamma)^2-1)(k(2-\gamma)(2-\gamma(1+\theta))-(2+\theta))^2}{k(k(2-\gamma)^2-2)^2(2-\gamma)^2(2+\gamma)^2}$.

In Strategy SS, the number of charging stations is $n_A^{SS} = \frac{a(2(1+\theta)-\gamma)}{(2-\gamma)(k(2+\gamma)^2-1)}$; the quantity of EVs are $q_A^{SS} = \frac{ak(2+\gamma)(2(1+\theta)-\gamma)}{(2-\gamma)(k(2+\gamma)^2-1)}$ and $q_B^{SS} = \frac{ak(2+\gamma)(2-\gamma(1+\theta))+\theta}{(2-\gamma)(k(2+\gamma)^2-1)}$; the prices of EVs are $p_A^{SS} = \frac{ak(2+\gamma)(2(1+\theta)-\gamma)}{(2-\gamma)(k(2+\gamma)^2-1)}$ and $p_B^{SS} = \frac{ak(2+\gamma)(2-\gamma(1+\theta))+\theta}{(2-\gamma)(k(2+\gamma)^2-1)}$; the profits of manufacturers are $\pi_A^{SS} = \frac{a^2k(2(1+\theta)-\gamma)^2}{(2-\gamma)^2(k(2+\gamma)^2-1)} + f$ and $\pi_B^{SS} =$

$$\frac{a^2(k(2+\gamma)(2-\gamma(1+\theta))+\theta)^2}{(2-\gamma)^2(k(2+\gamma)^2-1)} - f.$$

5.2 The correlation between EV and charging station cross-sensitivity

In strategy D', the number of charging stations are $n_A^{D'} = \frac{a(2+\beta^2)(k(4-\beta^2)(2(1+\theta)-\beta)-(2+\beta^2)(1+\beta+\theta))}{4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6)}$ and $n_B^{D'} = \frac{a(2+\beta^2)(k(4-\beta^2)(2-\beta-\beta\theta)-(2+\beta^2)(1+\beta+\beta\theta))}{4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6)}$; the quantity of EVs are $q_A^{D'} = \frac{ak(4-\beta^2)(k(4-\beta^2)(2(1+\theta)-\beta)-(2+\beta^2)(1+\beta+\theta))}{4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6)}$ and $q_B^{D'} = \frac{ak(4-\beta^2)(k(4-\beta^2)(2-\beta-\beta\theta)-(2+\beta^2)(1+\beta+\beta\theta))}{4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6)}$; the prices of EVs are $p_A^{D'} = \frac{ak(4-\beta^2)(k(4-\beta^2)(2(1+\theta)-\beta)-(2+\beta^2)(1+\beta+\theta))}{4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6)}$ and $p_B^{D'} = \frac{ak(4-\beta^2)(k(4-\beta^2)(2-\beta-\beta\theta)-(2+\beta^2)(1+\beta+\beta\theta))}{4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6)}$; the profits of manufacturers are $\pi_A^{D'} = \frac{a^2k(k(4-\beta^2)^2-(2+\beta^2)^2)(k(4-\beta^2)(2(1+\theta)-\beta)-(2+\beta^2)(1+\beta+\theta))^2}{(4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6))^2}$ and $\pi_B^{D'} = \frac{a^2k(k(4-\beta^2)^2-(2+\beta^2)^2)(k(4-\beta^2)(2-\beta-\beta\theta)-(2+\beta^2)(1+\beta+\beta\theta))^2}{(4-3\beta^4-\beta^6+k^2(4-\beta^2)^3-k(32+24\beta^2-2\beta^6))^2}$.

In Strategy S', the number of charging stations is $n_A^S = \frac{a(1-\beta)(2(1+\theta)-\beta)}{(2-\beta)(k(2+\beta)^2-(1-\beta)^2)}$; the quantity of EVs are $q_A^S = \frac{ak(2+\beta)(2(1+\theta)-\beta)}{(2-\beta)(k(2+\beta)^2-(1-\beta)^2)}$ and $q_B^S = \frac{a((1-\beta)^2\theta+k(2+\beta)(2-\beta-\beta\theta))}{(2-\beta)(k(2+\beta)^2-(1-\beta)^2)}$; the prices of EVs are $p_A^S = \frac{ak(2+\beta)(2(1+\theta)-\beta)}{(2-\beta)(k(2+\beta)^2-(1-\beta)^2)}$ and $p_B^S = \frac{a((1-\beta)^2\theta+k(2+\beta)(2-\beta-\beta\theta))}{(2-\beta)(k(2+\beta)^2-(1-\beta)^2)}$; the profits of manufacturers are $\pi_A^S = \frac{a^2k(2(1+\theta)-\beta)^2}{(2-\beta)^2(k(2+\beta)^2-(1-\beta)^2)} + f$ and $\pi_B^S = \frac{a^2((1-\beta)^2\theta+k(2+\beta)(2-\beta-\beta\theta))^2}{(2-\beta)^2(k(2+\beta)^2-(1-\beta)^2)} - f$.

5.3 The platform encroachment

In Strategy DP, the decision sequence of manufacturer is as follows: the manufacturer first decides on the number of charging stations to build; then the manufacturer determines the number of EVs to produce

The equilibrium outputs in this scenario are: $n_M^{DP} = \frac{(a+cQ)\tau}{4k-\tau^2}$, $q_e^{DP} = \frac{2k(a+cQ)}{4k-\tau^2}$, $p_e^{DP} = \frac{2k(a+cQ)}{4k-\tau^2} - cQ$, $\pi_M^{DP} = \frac{k(a+cQ)^2}{4k-\tau^2}$. To ensure that the output is non-negative, we assume $4k - \tau^2 > 0$.

In Strategy PP, the decision sequence of manufacturer and charging operation platform is as follows: first, both manufacturer and the platform decide on the number of charging stations to build, then the manufacturer determines the number of EVs to produce.

The equilibrium outputs in this scenario are: $n_M^{PP} = \frac{(a+cQ)\tau}{4k-\tau^2} - \frac{cQ(1-\alpha)\tau}{4k}$, $n_P^{PP} = \frac{cQ(1-\alpha)\tau}{4k}$, $q_e^{PP} = \frac{1}{2} \left(a + cQ\alpha + \frac{(a+cQ)\tau^2}{4k-\tau^2} \right)$, $p_e^{PP} = \frac{2k(a+cQ)}{4k-\tau^2} - \frac{cQ(1-\alpha)}{2}$, $\pi_M^{PP} = \frac{(4k(a+cQ\alpha)+cQ(1-\alpha)\tau^2)}{16k(4k-\tau^2)}$, $\pi_P^{PP} = \frac{1}{16} cQ \left(8(1-\alpha) \left(a + cQ\alpha + \frac{(a+cQ)\tau^2}{4k-\tau^2} \right) - \frac{cQ(1-\alpha)^2\tau^2}{k} \right)$

Proposition 7.

Proof: The difference between n_M^{DP} and n_M^{PP} is:

$$n_M^{DP} - n_M^{PP} = \frac{cQ(1-\alpha)\tau}{4k} > 0$$

The difference between n_M^{DP} and $n_M^{PP} + n_P^{PP}$ is:

$$n_M^{DP} - (n_M^{PP} + n_P^{PP}) = 0$$

The difference between q_e^{DP} and q_e^{PP} is:

$$q_e^{DP} - q_e^{PP} = \frac{cQ(1-\alpha)1}{2} > 0$$

The difference between p_e^{DP} and p_e^{PP} is:

$$p_e^{DP} - p_e^{PP} = -\frac{cQ(1-\alpha)}{2} < 0$$

The difference between π_M^{DP} and π_M^{PP} is:

$$\pi_M^{DP} - \pi_M^{PP} = \frac{cQ(1-\alpha)(8ak + cQ(4k(1+\alpha) + (1-\alpha)\tau^2))}{16k} > 0$$

In Strategy DT, the sequence of decisions by the manufacturer and service provider is as follows: In the first stage, the manufacturer sets the commission for the charging stations, while the service provider determines the number of charging stations to build. In the second stage, the manufacturer decides on the number of EVs to produce.

The equilibrium outputs in this scenario are: $t = \frac{\tau(4ak-cQ(4k-\tau^2))}{16k-2\tau^2}$, $n_S^{DT} = \frac{(a+cQ)\tau}{8k-\tau^2}$, $q_e^{DT} = \frac{8ak+cQ\tau^2}{16k-2\tau^2}$, $p_e^{DT} = \frac{8ak+cQ\tau^2}{16k-2\tau^2}$, $\pi_M^{DT} = \frac{8a^2k+cQ(2a+cQ)\tau^2}{32k-4\tau^2}$, $\pi_S^{DT} = \frac{64ack^2Q+2k(a^2-6acQ+c^2Q^2)\tau^2+acQ\tau^4}{2(8k-\tau^2)^2}$. To ensure that the output is non-negative, we assume $0 < c < \frac{4ak}{Q(4k-\tau^2)}$.

Proposition 8.

Proof: The difference between n_M^{DP} and n_S^{DT} is:

$$n_M^{DP} - n_S^{DT} = \frac{4k(a+cQ)\tau}{4k(8k-3\tau^2)+\tau^4} > 0$$

The difference between q_e^{DP} and q_e^{DT} is:

$$q_e^{DP} - q_e^{DT} = \frac{cQ}{2} + \frac{2k(a+cQ)}{4k-\tau^2} - \frac{4k(a+cQ)}{8k-\tau^2} > 0$$

The difference between p_e^{DP} and p_e^{DT} is:

$$p_e^{DP} - p_e^{DT} = \frac{-32ck^2Q + 4k(a + 4cQ)\tau^2 - cQ\tau^4}{2(4k - \tau^2)(8k - \tau^2)}$$

When $k > \frac{a^2 + 4cQ\tau^2}{16cQ} + \frac{1}{16} \sqrt{\frac{a^2\tau^4 + 8acQ\tau^4 + 8c^2Q^2\tau^4}{c^2Q^2}}$, $p_e^{DP} < p_e^{DT}$; when $\frac{\tau^2}{4} < k < \frac{a^2 + 4cQ\tau^2}{16cQ} + \frac{1}{16} \sqrt{\frac{a^2\tau^4 + 8acQ\tau^4 + 8c^2Q^2\tau^4}{c^2Q^2}}$, $p_e^{DP} > p_e^{DT}$.

The difference between π_M^{DP} and π_M^{DT} is:

$$\pi_M^{DP} - \pi_M^{DT} = \frac{32ck^2Q(2a + cQ) + 4k(a^2 - 4acQ - 2c^2Q^2)\tau^2 + cQ(2a + cQ)\tau^4}{4(4k - \tau^2)(8k - \tau^2)}$$

$32ck^2Q(2a + cQ) + 4k(a^2 - 4acQ - 2c^2Q^2)\tau^2 + cQ(2a + cQ)\tau^4$ is a convex function with respect to k . Solving $\pi_M^{DP} - \pi_M^{DT} = 0$, we derive $k = \frac{(-a^2 + 4acQ + 2c^2Q^2)\tau^2 - \sqrt{(a^4 - 8a^3cQ - 20a^2c^2Q^2 - 16ac^3Q^3 - 4c^4Q^4)\tau^4}}{16cQ(2a + cQ)} < 0$ or $k = \frac{(-a^2 + 4acQ + 2c^2Q^2)\tau^2 + \sqrt{(a^4 - 8a^3cQ - 20a^2c^2Q^2 - 16ac^3Q^3 - 4c^4Q^4)\tau^4}}{16cQ(2a + cQ)} < 0$. Therefore, $32ck^2Q(2a + cQ) + 4k(a^2 - 4acQ - 2c^2Q^2)\tau^2 + cQ(2a + cQ)\tau^4$ increases in $k \in \left(\frac{\tau^2}{4}, +\infty\right)$. When $32ck^2Q(2a + cQ) + 4k(a^2 - 4acQ - 2c^2Q^2)\tau^2 + cQ(2a + cQ)\tau^4|_{\min} = cQ(2a + cQ)\tau^4 > 0$. Therefore, $\pi_M^{DP} - \pi_M^{DT} > 0$.

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Identifying key factors and interrelationships affecting large-scale agricultural biomass production: Insights from interpretive structural modeling

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ABSTRACT

Large-scale agricultural biomass production (LABP) has received much attention due to the growing global interest in renewable energy and the urgent need to achieve carbon neutrality. However, as its implementation is affected by the multitude of interrelated factors, analyzing these factors can help accelerate its scaling up. Although existing literature has classified the barriers to agricultural biomass energy, it tends to be limited to a unidimensional analyses and fails to comprehensively explore from a multi-dimensional analysis of various stakeholders. Thus, the primary objective of this research is to further identify the factors that influence LABP from a multi-stakeholder perspective, and to systematically elucidate the interrelationships between these factors. Through expert opinions and literature reviews, this paper identifies nineteen key factors influencing LABP and reveals the intricate relationship between these factors by the interpretive structural modeling method. Besides, the MICMAC analysis is applied to categorize the nineteen factors influencing LABP into three categories, i.e., autonomous factors, dependent factors and driver factors. This paper also explores the economic, social, and environmental benefits and offers policy insights and management recommendations based on the results, which show that non-technical factors hinder the development of LABP more prominently than technical factors. Legal and regulatory constraints and unstable governance environments are considered to be at the highest level, playing a fundamental role in promoting LABP development. Furthermore, this paper provides a solid theoretical framework and practical insights for policymakers, businesses, and academics to address these challenges and promote sustainable LABP.

1. Introduction

Agricultural biomass is regarded as the most abundant and widely used renewable energy source in the world [1], generating the fourth largest proportion of the global energy supply [2,3]. This concept is particularly critical at a time when the world is facing multiple challenges such as the energy crisis, climate change and environmental degradation. It is predicted that global energy consumption will expend significantly, with an expected rise of approximately 48 % from 2012 to 2040 [4]. However, current energy supply capacity is not sufficient to meet the needs of some developing countries, while demand is predicted to ascend sixfold over the course of this century [5]. To meet the growth in energy demand without harming environment and to ensure long-term sustainability, it is imperative to enhance the efficiency and scale of producing agricultural biomass [6].

By 2028, bioenergy is anticipated to remain the predominant source of renewable heat in global construction [7]. Increasing the substitution of fossil fuels with biomass will not only alleviate the greenhouse effect but also mitigate the repercussions of energy scarcity [8,9]. However, biomass must be used with care, as mismanagement of these resources could lead to increased environmental degradation rather than improved environmental quality [10]. Thus, finding efficient and reliable methods of large-scale agricultural biomass production (LABP) is always a challenge. Moreover, the cost of energy and materials generated by agricultural biomass production holds an important position in the circular economy [11]. How to achieve LABP has thus attracted widespread attention from a wide range of stakeholders in recent years, including producers, designers, policymakers, and scholars [12,13]. Large-scale implies a significant expansion of bioenergy production to levels comparable to those of major energy sources such as coal, oil and

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natural gas. Although biomass is a feasible energy source, further research is needed to fully understand the impact of multiple factors on LABP.

Several countries around the world have formulated relevant policies and regulations to realize the sustainable development of the agricultural biomass industry based on different resource conditions and environmental requirements. For example, the Ministry of National Energy and Environment, Government of India, has adopted an approach based on co-generation and biomass gasification for power generation to provide central financial assistance and fiscal incentives [14], the European Union and the United States have developed renewable fuel standards [15], and China has also introduced a number of policies to facilitate the swift advancement of biomass energy, covering the financing, construction and operation of biomass power generation projects, as well as a number of guiding policies [16,17]. Although these policies have been an important driving force for LABP, studies analyzing the factors influencing LABP are integrative due to the interdisciplinary nature of LABP, which requires expertise in different fields such as engineering science, agricultural science, management science and ecology. For instance, producers may need to have expertise in ecology and agricultural science to directly participate in planting crops. Meanwhile, applying knowledge of engineering sciences helps to optimize conversion technologies and processes of agricultural biomass. Furthermore, the research on LABP involves multiple stakeholders such as government agencies, consumers, enterprises, and scholars, which increases the complexity of the issue of LABP. To expand the scale of agricultural biomass production, it is urgent to identify potential influencing factors and their interrelationships, so that effective pathways can be found to address the current challenges. As a result, it is a valuable research topic to further investigate the influencing factors of LABP.

Current research is mainly devoted to biomass processing technology [18–20], biomass supply chains [21], and other barriers. The existing literature discusses agricultural biomass production from several single dimensions with numerous claims. For example, Wang and Wu [22] argued that a combination of policies, regulations and research is necessary to commercialize biofuels. Naveed et al. [23] highlighted the promising application of artificial neural networks in enhancing the efficiency of biofuel fermentation processes. Gani et al. [24] showed that collaboration with all stakeholders is the key to promote biofuels in the future. To date, however, there has been little discussion on in-depth analyses of the interrelationships between key factors influencing LABP from multiple dimensions.

The specific research questions to be addressed in this study are as follows: i) What are the key factors affecting LABP? ii) What are the complex interrelationships and hierarchies between these factors? And iii) What measures should be taken by stakeholders to address the problems encountered in LABP? To address research question one, this study identifies nineteen potential factors that can influence LABP through an extensive literature review and expert opinion. To address research question two, this paper identifies the interrelationships and hierarchical structure between factors using the interpretive structural modeling (ISM) methodology, which is widely used for factor analysis. Finally, this paper applies the matrixed impacts corises-multiplication appliance classement (MICMAC) methodology to categorize the identified factors. Besides, based on the research results, this paper not only provides a new perspective for understanding the complexity of LABP, but also provides a theoretical framework and important insights for relevant stakeholders including government, business and academia to understand LABP to answer research question three. In summary, this study aims to find effective pathways to address the current challenges of LABP and provide decision-making insights for relevant stakeholders by analyzing the factors affecting LABP, thus promoting the sustainable development of the agricultural biomass industry to meet the growth in global energy demand.

The structure of this study is organized as follows. Section 2 presented an overview of related research on agricultural biomass. Section

3 identifies the factors influencing LABP, determines the hierarchy between factors using the ISM method and the classification of factors using the MICMAC method. Section 4 offers a discussion of the main findings, comparative analysis, implementation benefits, policy implications, management insights and recommendations. Section 5 draws conclusions and limitations of this study, followed by a future research outlook.

2. Literature review

This section is a brief review of the work in relation to the paper, focusing on two primary aspects of research. The first looks at existing research on LABP, while the second delves into the utilization of ISM methodology.

2.1. Large-scale agricultural biomass production related studies

Agricultural biomass has attracted much attention for large-scale energy production to meet the growing global demand for energy and increasing environmental concerns. The current status of agricultural biomass for energy production, the challenges it faces and its potential contribution to cleaner production have been the subject of much research and analysis in the literature. A number of studies have shown that agricultural biomass has the potential to provide a sustainable and reliable source of energy. For instance, Liu and Huang [25] applied an autoregressive distributed lag model to analyze the interrelationships between fossil fuels, biomass energy, innovation, and green growth, and the results indicated that reducing dependence on fossil fuels would promote the cultivation of bioenergy. Akter et al. [26] applied mathematical, economic and engineering modeling techniques to explore the viability of using agricultural biomass as a potential solution to the energy crisis. Mana et al. [27] employed system advisor model to evaluate the energy and economic benefits of power generation from biomass and proposed to utilize the untapped potential of agricultural biomass waste as a means of attaining sustainable development and a steady power supply in rural areas. Miedema et al. [28] identified four major constraints from the supply side, including insufficient funding for demonstration plants, lack of technology policy, lagging market development and insecurity of biomass supply.

Significant progress has also been made in the field of agricultural biomass technology. Many studies have discussed advanced biomass energy technologies. For example, Paudel et al. [29] showed that pre-treatment is a key determinant of the sustainability of biofuel production by reviewing the basic principles and current status of several pre-treatment technologies for agricultural biomass using grain residues, vegetable waste, animal manure and forage. Based on this, Singh et al. [30] analyzed sustainable biomass conversion technologies and further emphasized the importance of pretreatment in the production of agricultural biomass. The study by Siddique et al. [31] covered different biomass thermochemical processes and explored the technical challenges of expanding the use of microwave technology for biomass processing.

Currently, some studies indicated that it is not technical problems but non-technical challenges that hinder the development of bioenergy [32]. McCormick and Kaberger [32] identified supply chain coordination, institutional capacity, expertise and economic conditions as major obstacles to bioenergy expansion. Mertens et al. [33] further found that the emerging bioeconomy's demand for large quantities of biomass exceeds the current value chain's supply capacity, and proposed seven specific measures that can be taken by participants to overcome the barriers. Bhatt et al. [34] introduced a novel mixed integer linear programming model to optimize the biomass supply chain by integrating fixed depots and portable depots for biomass pre-processing. Van Dijk et al. [35] showed that public acceptance of biomass energy depends on the type of biomass feedstock. Galik et al. [36] provided a direction for future research and policy considerations, highlighting the impact of

changing policies on agricultural biomass development. Rik Leemans [37] presented that the utilization of agricultural biomass as an energy source at scale is feasible, but needs be assessed in the context of many other environmental, social, and economic factors. According to the intuitive fuzzy cognitive map, Ma et al. [38] conducted several simulations and discussed how to promote biomass development by increasing public acceptance. The literature highlighted the importance of non-technical factors in LABP, but did not give an insight into how the key factors interacted each other and their combined impact.

These studies have provided a solid theoretical basis for further research on LABP. With so many stakeholders involved, an in-depth research on the influencing factors of LABP and their interrelationships is crucial for policy making and business practices. Moreover, this paper is close to Irfan et al. [39], but differs from Irfan et al. [39] in the research methodology and perspective. Irfan et al. [39] focused on identifying key barriers affecting biomass energy, whereas this paper is concerned with analyzing the interrelationships among various factors affecting LABP. More importantly, this paper identifies wider factors for LABP through expert opinion and literature. Unlike the above literature, this paper focuses on a comprehensive study of the complex relationships in LABP, thus paving the way for the formulation of better management practices within sustainable and green economic development. Table 1 summarizes representative studies that have discussed LABP.

2.2. Utilization of ISM methodology

ISM was firstly developed by Warfield in 1973 to identify the interplay between factors in intricate socio-economic system [40,41]. Due to its reliability in hierarchical structural modeling [42], the ISM method has been employed extensively in the field of barrier analysis. For example, Sarabi et al. [43] investigated 15 main barriers to nature-based solutions and then employed ISM and MICMAC analysis to form a six-level structural model and categorizing the barriers into four types. Feng et al. [44] explored 20 barriers to electric vehicle battery recycling and determined the hierarchical relationships between the barriers using the ISM methodology. Valmohammadi and Dashti [45] analyzed 13 obstacles and difficulties in the adoption of e-commerce through the ISM methodology and classified them into four major categories, including organizational, personal, environmental, and technological. Bagherian et al. [46] investigated the significant factors of energy sustainability from the digital dimension and determined strong interdependencies and causal relationships between these factors using

Table 1
Summary of representative studies on LABP.

Studies	Methodology	Categorization				
		Eco	Env	Tec	P&R	Soc
Liu and Huang [25]	ARDL	✓	✓			
Akter et al. [26]	Mathematical modeling and economic modeling	✓	✓	✓		
Mana et al. [27]	Financial modeling	✓		✓		
Miedema et al. [28]	MLP and TIS	✓		✓	✓	✓
McCormick and Kaberger [32]	Industry interactions, research workshops and case studies	✓		✓		
Mertens et al. [33]	Integrated analytical framework	✓				
Bhatt et al. [34]	MILP	✓				
Ma et al. [38]	IFCM					✓
This paper	ISM and MICMAC	✓	✓	✓	✓	✓

Note: Autoregressive Distributed Lag (ARDL), Multi-Level Perspective (MLP), Technological Innovation System (TIS), Mixed Integer Linear Programming (MILP), Intuitive Fuzzy Cognitive Map (IFCM). Eco, Env, Tec, P&R and Soc mean Economy, Environment, Technology, Policy and regulations, and Society, respectively.

MICMAC and ISM analysis. Jia et al. [47] and Majumdar and Sinha [48] studied the barriers in supply chain management and clarified the structural associations between these obstacles through the ISM approach.

Recently, literature on implementation barriers in the field of renewable energy has been published. For example, barriers to the implementation of solar power generation [49,50], and barriers to the adoption of solar energy in thermal power plants [51]. Avinash et al. [52] investigated the barriers to large-scale biodiesel production, identifying 11 key barriers through expert interviews, and finally identified the top-level barriers to biodiesel production from yellow grease using the ISM and MICMAC methodologies. Agarwal et al. [53] carried out a structured review of the nineteen factors that influence solar renewable energy products, and then used the ISM methodology to determine the hierarchical structure of each of these factors. Chen et al. [54] investigated the barriers to building integrated photovoltaics in Singapore and applied the MIMAC methodology to categorize the barriers identified into eight autonomous, five dependent and six driven groups according to the power and dependence of the drivers.

A large body of literature demonstrates that the combination of ISM and MICMAC provides a visual representation of the hierarchical structure and relationships between variables [55]. Overall, the ISM methodology contributes to a better understanding of the barriers to project delivery and helps the industry as a whole to assess the relative importance of these barriers. However, research on the interplay and hierarchical structure of factors affecting the implementation of LABP is still lacking to date, even if the widespread application of structured analysis methodologies such as ISM and MICMA in numerous fields. As a result, ISM and MICMAC methodologies are used to identify and screen the hierarchy of the factors influencing LABP herein.

2.3. Research gaps

Through reviewing the existing literature comprehensively, the following research gaps have been identified.

First, most existing LABP research focused on: i) the technical challenges of LABP; ii) environmental benefits of LABP; and iii) the economic and social impacts of LABP. These literatures are particularly important for further research on LABP due to their significant contributions. However, a systematic analysis of the factors influencing LABP from the perspective of different stakeholders is an important research topic that has been little discussed in the literature. To this end, this paper explores the influencing factors to LABP from a multi-stakeholder perspective to contribute to the scaling up of biomass production.

Second, although Harris et al. [56] assessed the commercialization potential of different process pathways from a technical and economic point of view, Azevedo et al. [57] discussed 13 constraints of biomass production from economic, social, and environmental dimension, there is limited literature on this aspect, and these studies do not comprehensively cover all the influencing factors of LABP. Thus, there is a need for further research into the factors that influence LABP and to analyze the interactions between factors. This paper analyzes the interrelationships between the factors affecting LABP through ISM and MICMAC methods, aiming to provide a basis for formulating targeted solutions and filling the research gap.

3. Methodology and results

This section will identify factors that influence LABP and to analyze the hierarchical relationships among these factors by the ISM and MICMAC methods.

3.1. Identifying influencing factors to LABP

Agricultural biomass production requires knowledge from multiple disciplines, including biotechnology, environmental science, policy and

regulation, and economic and social impacts. Interdisciplinary professional knowledge is crucial for a comprehensive assessment and resolution of the issues. Therefore, selecting various experts from multiple domains to take part in the assessment is essential. First, different experts have different expertise and perspectives in different areas, which can provide different perspectives and insights, reducing bias from a single area, which also helps to ensure that the assessment process is objective and fair, and that all aspects of agricultural biomass production are fully understood. Second, experts from different fields may inspire new ideas and solutions during the discussion and assessment process, thus driving innovation and development in agricultural biomass production. Finally, experts from a variety of backgrounds and experiences help to systematically identify and understand the interrelationships and impacts of different influencing factors. These experts also provide professional advice to ensure the assessment accuracy. In summary, the participation of experts from multiple fields can improve the practicality and credibility of the ISM and make it closer to practical application scenarios. To provide a more comprehensive and systematic view of the factors influencing LABP, three interdisciplinary academic experts whose areas of expertise span agricultural science, environmental science and engineering science, two suppliers from different agricultural biomass companies, two experts from different renewable energy companies, one expert from a government department, and one expert from an environmental organization were invited to form the team. These experts represented a variety of industries and perspectives to establish a team to assess the factors affecting agricultural biomass production. Table 2 presents information about the experts.

Based on discussions within the assessment team and a review of existing literature, this paper identifies key factors that significantly affect LABP as shown in Fig. 1. The detailed descriptions of these key influencing factors are provided below.

3.1.1. Fluctuating market prices (F1)

In assessing the potential for LABP, the impact of market price fluctuations must be considered [21]. These fluctuations are typically driven by a combination of factors, including carbon prices, raw material costs, land costs, and international market supply and demand conditions. Frequent changes in market prices for biomass raw material such as straw, maize and other agricultural products make it difficult to predict and control biomass production costs. Meanwhile, the biofuel market and feedstock demand are significantly affected by energy price fluctuations [58]. Fluctuations in market prices therefore create the risk of unstable incomes for producers and weaken their confidence, which may hinder the implementation of large-scale production.

3.1.2. Insufficient capital investment (F2)

Agricultural biomass production requires high capital investment for technology development, equipment purchase, marketing, etc. Without adequate financial support, producers may not be able to adopt efficient

production methods or introduce advanced technologies. In addition, the lack of financial resources can lead to limitations in the scale of production, making it difficult to realize economies of scale, which weakens the market competitiveness of the agricultural biomass industry. The lack of capital not only restricts technological research and development and industrial upgrading, but also affects the marketing and industrialization of biomass products. Consequently, insufficient capital investment is a key factor restricting the large-scale production of agricultural biomass energy [56].

3.1.3. Low return on investment (F3)

Low return on investment (ROI) poses a serious threat to biomass projects [39]. ROI is a core indicator for measuring investment effectiveness. However, the biomass industry currently faces the challenge of economies of scale, where smaller production scales lead to higher unit costs. The issue of ROI has become a factor that restricts the industry to move towards a circular economy. If the agricultural biomass industry's ROI lags behind other industries or the market average, it will be difficult to attract new capital and retain existing investment. In the agricultural biomass industry, low ROI may stem from high production costs, immature technology, market risks, and policy uncertainties. These issues have a negative impact on the industry's capital mobility and growth potential.

3.1.4. Lack of financial subsidies (F4)

Financial subsidies affect the various costs associated with the use of biomass, which will in turn affect stakeholders in the biomass supply chain [59]. First, the vulnerability of agricultural biomass production to natural disasters, coupled with the lack of effective subsidization mechanisms, makes producers highly vulnerable to major economic losses in the face of disasters. Second, the lack of subsidy results in high production costs, making biomass products less competitive and increasing business risks for the entire industry. As a result, it is difficult to achieve economies of scale and environmental protection without sound financial subsidies and incentives [60].

3.1.5. Low market transparency (F5)

Lack of market transparency hinders the implementation of LABP. The market for agricultural biomass is still in its infancy, with poor circulation of information on supply and demand, resulting in a lack of standardization and transparency in the pricing mechanism, which makes agricultural biomass producers may not be able to accurately predict the selling price of their products, thereby affecting the control of revenue and costs. Moreover, due to insufficient information, investors may have difficulty assessing the feasibility, profitability, and market prospects of projects, which may lead investors to be cautious towards agricultural biomass production, limiting the expansion of biomass production scale. More importantly, some market participants may exploit information advantages to manipulate the market, causing prices to deviate from the true value and providing room for speculative activities. Thus, increasing the accessibility of market information is crucial for achieving a fair, efficient and competitive market [61].

3.1.6. Conflicts in land use (F6)

As urbanization and industrialization accelerate, conflicts over the allocation of land resources among agricultural biomass production, urban expansion, and ecological conservation have intensified, limiting the supply potential of biomass resources [62]. Competition for land resources directly limits the area of agricultural biomass crops, which in turn limits the scale and development of production. In addition, ecosystem damage, such as increased soil erosion and loss of biodiversity, can result from land development to meet the demand for LABP, and may further exacerbate tensions in land use, which is contrary to the goal of sustainable agricultural biomass production.

Table 2
Information about the experts.

Interviewee	Affiliation	Expertise
Academic expert 1	University	Agricultural science
Academic expert 2	University	Environmental science
Academic expert 3	University	Engineering science
Industry expert 1	Agri-biomass company A	Agricultural biomass product supply
Industry expert 2	Agri-biomass company B	Agricultural biomass product supply
Industry expert 3	Renewable energy company A	Biomass energy conversion
Industry expert 4	Renewable energy company B	Biomass energy conversion
Government expert	Ministry of agriculture and rural affairs	Agricultural biomass policy
Environmental expert	Environmental protection organization	Sustainable agricultural practices

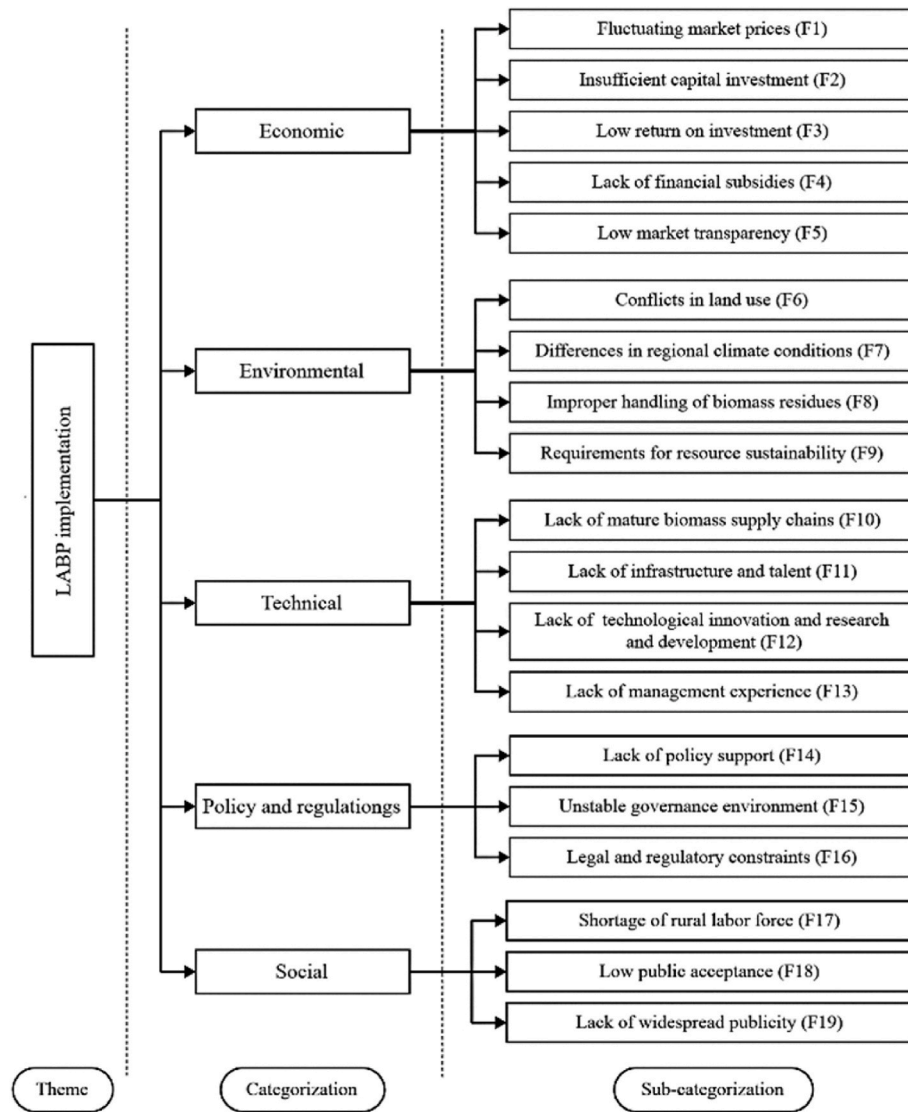


Fig. 1. Key factors affecting LABP.

3.1.7. Differences in regional climate conditions (F7)

Climatic conditions vary from region to region, which may affect the suitability and benefits of LABP. The diversity of climate conditions leads to variability in feedstock quality. Frequent extreme weather events increase the uncertainty of feedstock supply and affect the yield and growth cycle of biomass crops, limiting the continuity and predictability of production. Moreover, the seasonal characteristics of agricultural biomass production require producers to adopt flexible planting and harvesting strategies.

3.1.8. Improper handling of biomass residues (F8)

Utilizing all available biomass residues is a very important issue [63]. From an environmental point of view, inappropriate handling of biomass residues can lead to soil and water pollution. While in terms of resource recycling, the reconversion of these residues achieves value recovery of agricultural biomass waste and improves the efficiency of resource use. Therefore, the comprehensive utilization of biomass residues is an attractive option for promoting the economic development in rural areas [64].

3.1.9. Requirements for resource sustainability (F9)

Resource sustainability requirements help to promote a balance between economic and social benefits. On the one hand, producers must

pay attention to the long-term availability of resources and ecological balance in LABP. Recently, the international community has recognized this situation and committed to developing and implementing a series of sustainability standards and indicators for biomass products [65]. Additionally, carbon emissions can be further reduced by replacing fossil fuels with agricultural biomass, optimizing the energy structure and promoting sustainable development [66].

3.1.10. Lack of mature biomass supply chains (F10)

Poorly functioning biomass supply chains not only make it difficult for companies to operate consistently, but can also affect the growth of the biomass industry. On the one hand, poor management of bottlenecks in the supply chain (e.g. transportation, processing, etc.) will directly affect overall production efficiency and increase operating costs. More importantly, an immature supply chain makes it difficult for companies to quickly adapt production to changes in market demand.

3.1.11. Lack of infrastructure and talent (F11)

The insufficiency of infrastructure and talent severely restricts the scaling up of agricultural biomass production [57]. Lack of infrastructure limits the efficient collection, storage, and transportation of biomass feedstocks, which reduces production efficiency and increases overall costs [67]. Meanwhile, the shortage of talent should not be

overlooked. Because the workforce lacks specialized skills and knowledge, it is difficult to ensure quality and safety in the production process. Therefore, strengthening the development of infrastructure and the training of human resources has become the key to promoting the large-scale implementation and industrial upgrading of agricultural biomass production.

3.1.12. Lack of technological innovation and research and development (F12)

Technological innovation and research and development (R&D) in agricultural biomass production is facing certain challenges [68]. The lack of advanced production and conversion technologies limits the expansion of production scale and the improvement of efficiency, which has a direct impact on the cost-effectiveness of the industry. Meanwhile, the serious lack of investment in R&D erodes the capacity for independent innovation, resulting in a deficiency of core technology missing and an exacerbation of the technological bottleneck. Although the industry is exploring improved technology and innovative approaches, the lack of technology maturity continues to be an important barrier to the development of LABP [69].

3.1.13. Lack of management experience (F13)

As agricultural biomass production reaches a commercial scale, the demand for management becomes increasingly important [70]. Regarding production organization and operational efficiency, lack of managerial experience can lead to misallocation of resources and difficulty in controlling costs, reducing overall production efficiency. Moreover, lack of management experience makes it challenging to balance short-term benefits with long-term environmental goals, compromising the sustainability of projects. Therefore, accumulating and applying effective management experience contributes to the development of agricultural biomass production towards scale, efficiency, and sustainable.

3.1.14. Lack of policy support (F14)

Some countries or regions have recently introduced policies to promote and develop renewable energy, such as tax incentives and special funding. However, there is also a need to maintain consistency in policy implementation and to consider the risks and dilemmas that environmental changes pose for policy implementation in order to advance LABP [71].

3.1.15. Unstable governance environment (F15)

The instability in the governance environment slows down the process of scaling up agricultural biomass production [72]. Changes in policy may affect agricultural biomass production. Furthermore, an unstable governance environment may result in inconsistent enforcement of regulations, affecting the standardization and regulation of biomass production and increasing the complexity and cost of compliance for agricultural biomass enterprises. Efforts to establish a stable governance environment are crucial for the development of agricultural biomass production.

3.1.16. Legal and regulatory constraints (F16)

Some policies and regulations are not applicable to the entire chain from agricultural biomass to its products [73]. Stringent laws and regulations may restrict quality standards and market sales of biomass products, making market access more difficult. Meanwhile, complex legal procedures and administrative approvals can lead to delays in production programmes and loss of market opportunities. Furthermore, land use regulations may restrict the planting or production activities of biomass producers in specific areas, affecting feedstock supply and production layout [15]. Therefore, legal and regulatory constraints will continue to be a barrier to LABP until economies of scale in LABP are realized.

3.1.17. Shortage of rural labor force (F17)

Biomass development is a labour-intensive activity in rural areas. The process of urbanization and increasing levels of education has resulted in large numbers of rural workers migrating to urban areas in search of more job opportunities and a higher standard of living. This trend has weakened the human resource base for agricultural biomass production. Such a change in labour structure limits the scale of agricultural biomass feedstock production and poses a challenge to the sustainability of the agricultural biomass industry.

3.1.18. Low public acceptance (F18)

Increasing public acceptance of agricultural biomass can propel the market towards large-scale production [74]. On the one hand, low consumer awareness of biomass products can lead to low market demand, which directly limits the market penetration of products and the profitability of companies. On the other hand, low social acceptance leads to increased risk assessment and difficulty in financing agricultural biomass production projects by investors and financial institutions, affecting the financial liquidity and expansion capacity of the industry. This challenge calls for intensified public education and outreach to improve public awareness and acceptance of agricultural biomass production [35].

3.1.19. Lack of widespread publicity (F19)

There is a need to publicize the value of agricultural biomass utilization to attract more attention from rural residents and to establish a social consensus [75]. There is currently insufficient public awareness of agricultural biomass, which needs to be promoted and educated. This may be because biomass energy still has a small market share compared to traditional fuels and has not been widely publicized. Furthermore, ineffective publicity may result from the fact that the target population is relatively small and dispersed.

3.2. Theoretical framework

ISM method is a hierarchical model used to analyze the interrelationships of factors in complex systems. It decomposes a complex system into multiple levels to visualize the structure and interactions of the factors. MICMAC analysis helps in categorizing factors based on their driving power and dependence, allowing for a better understanding of the system's dynamics. To realize the research goals, a hybrid research method combining ISM and MICMAC is used herein.

Following the identification of key factors affecting LABP through a systematic review of the literature and expert opinion, ISM was used to construct a structured self-interaction matrix (SSIM) and to develop a hierarchical diagram revealing the causal relationships among factors influencing agricultural biomass production [76]. Finally, the MICMAC method categorizes the factors by assessing their driving force and dependency. This clarifies the influences and interdependencies between the factors and provides a basis for those involved to propose further targeted recommendations. The framework structure of the theoretic adopted herein is shown in Fig. 2.

Step 1 Based on a review of the literature and the opinions of experts, this paper identifies the key factors to implementing LABP, as described in Section 3.1.

Step 2 After several rounds of discussion by experts, this paper identifies the relationships between the factors and constructs the SSIM, which employs four symbols to present the connection between factor i and factor j . The symbols have the following meanings: 1) V indicates that factor j is influenced by factor i ; 2) A indicates that factor i is influenced by factor j ; 3) X indicates the interaction between factor i and factor j ; 4) O means no effect.

Step 3 On the basis of step 2, the symbols of the SSIM are represented by the numbers 0 and 1 to establish the adjacency matrix. The specific rules for numerical assignment are as follows: 1) If cell

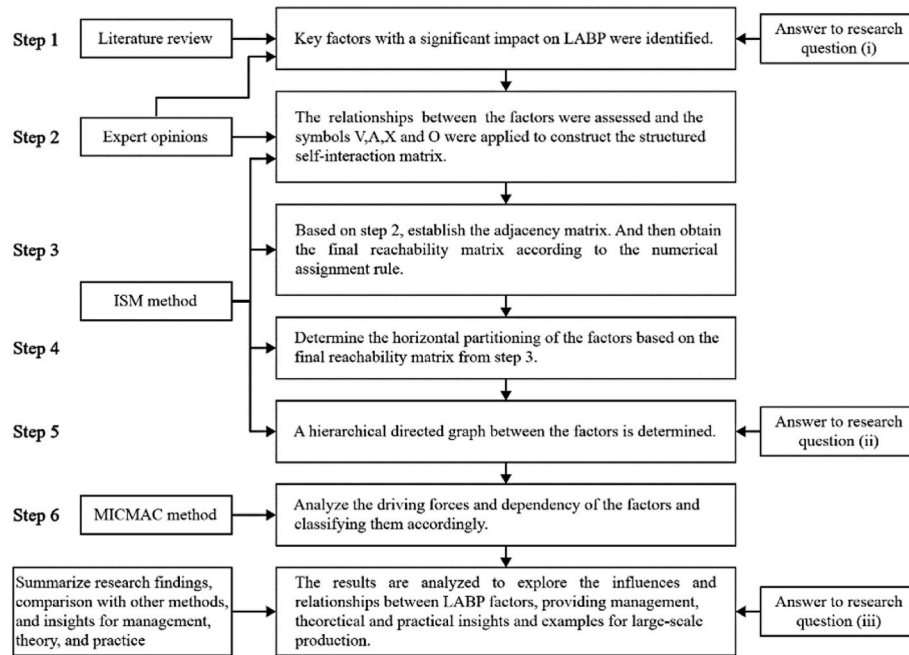


Fig. 2. Theoretical framework adopted in this paper.

(i, j) in the SSIM is represented by the symbol V, assign cell (i, j) as 1 and cell (j, i) as 0; 2) If cell (i, j) in the SSIM is represented by the letter A, assign cell (i, j) as 0 and cell (j, i) as 1; 3) If cell (i, j) in the SSIM is denoted by the letter X, both cell (i, j) and cell (j, i) are assigned the value 1; 4) If cell (i, j) in the SSIM is denoted by the letter O, both cell (i, j) and cell (j, i) are assigned the value 0. Following these rules, the final reachability matrix is obtained. This matrix reflects the reachability between elements, i.e., the direct or indirect influence of one element on another.

- Step 4 Horizontal partitioning of LABP factors. By calculating the intersection of the reachable set and antecedent set of each element, this paper determines the hierarchical structure of the factors and divides the final reachability matrix in Step 3 into different levels. In ISM, if the reachable sets and antecedent sets of a factor are the same, then the element is considered to be a level. After determining the highest level, it can be excluded from the reachability matrix. The hierarchical structure of the system is gradually revealed through the iterative elimination of factors.
- Step 5 Determination of the hierarchical directed graph between the factors. After determining the hierarchy of the factors, this paper draws a directed connection diagram to represent the hierarchy of the model more visually.
- Step 6 Application of the MICMAC method. After completing the ISM analysis, this paper applies the MICMAC method to further analyze the drivers and dependencies of the influencing factors of LABP. By classifying the factors into categories with different levels of influence and dependency, the understanding of the dynamic relationships in the system is deepened. Section 3.4 provides a detailed explanation of the classification criteria.

3.3. Step of the ISM methodology

This section describes the calculation process for hierarchical analysis using the ISM method. It identifies the interdependencies between different factors on the LABP and draws a directed diagram to show the overall system structure.

3.3.1. Structured self-interaction matrix (SSIM)

SSIM considers the contextual relationships of each variable, where any two factors may interact and be directed towards each other. Therefore, this paper invited nine domain experts to assess the connections between factors based on the introduction in Step 2, and employed the symbols V, A, X and O for the construction of the adjacency matrix, i.e. SSIM, as shown in Table 3. At the beginning, the assessment team holds a meeting aimed at establishing a common research goal, ensuring that all team members move in the same direction. In the ensuing roundtable discussion, experts fully exchange views and debates, share their professional insights with each other, propose innovative suggestions, and engage in an open discussion on the various opinions. Ultimately, the expert team determined the final assessment results by the voting mechanism of the minority principle.

3.3.2. Reachability matrix

The reachability matrix describes whether there is a connection path from one factor to another. Based on Table 3, the initial input adjacency matrix A is established according to the assignment rules provided in Step 3, as given in Table 4. Let I be a unit matrix of the same order as A. The final reachability matrix M can be generated by performing Boolean operations to the initial adjacency matrix A in Table 4 after it has been added to the unit matrix I, i.e., $(A + I)^{k-1} \neq (A + I)^k = (A + I)^{k+1} = M$, as illustrated in Table 5. Also, driving power (DRP) and dependence power (DEP) of each factor are calculated in Table 5. The sum of each row for factors is DRP, while the sum of each column is DEP.

3.3.3. Horizontal partitioning of factors

Following step 4, the final level partitioning of factors influencing LABP is shown in Table 6.

3.3.4. Hierarchical directed graph

Having identified the hierarchy of the nineteen representative factors influencing LABP, the hierarchical relationship of the factors in the overall system can be represented by a directed graph, as shown in Fig. 3. The influencing factors of LABP are divided into six levels, and there are interrelationships between the levels. Fluctuating market prices (F1), insufficient capital investment (F2), low return on investment (F3), conflicts in land use (F6), requirements for resource sustainability

Table 3
Structured self-interaction matrixfor LABP factors.

	F19	F18	F17	F16	F15	F14	F13	F12	F11	F10	F9	F8	F7	F6	F5	F4	F3	F2
F1	O	O	O	O	A	A	O	O	O	O	O	O	A	A	A	A	V	V
F2	A	A	O	O	A	O	O	O	O	X	O	O	O	O	A	O	A	
F3	O	O	O	O	A	O	A	A	A	A	O	A	O	O	O	O		
F4	O	O	V	O	O	A	V	V	V	O	O	O	O	V	O			
F5	O	O	O	O	A	A	O	O	O	O	O	O	O	O				
F6	O	A	A	A	O	A	A	O	O	O	X	O	A					
F7	O	O	O	O	O	O	O	O	O	O	O	O						
F8	O	O	O	O	O	A	A	A	A	V	V							
F9	O	A	O	A	O	A	O	O	O	A								
F10	O	O	O	O	O	O	A	A	A									
F11	O	A	O	O	O	O	O	O										
F12	O	O	O	O	O	O	O											
F13	O	O	O	O	O	O												
F14	O	V	V	A	O													
F15	V	O	O	O														
F16	O	O	O															
F17	A	A																
F18	A																	

Table 4
Initial adjacency matrixfor LABP factors.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
F1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
F3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	1	0	0
F5	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F7	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F8	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
F9	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
F10	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F11	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
F12	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
F13	0	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0
F14	1	0	0	1	1	1	0	0	1	0	0	0	0	0	0	1	1	0	0
F15	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
F16	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0
F17	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
F18	0	1	0	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0
F19	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0

Table 5
Final reachability matrix for LABP factors.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	DRP
F1	1	1	1	0	0	1*	0	0	1*	1*	0	0	0	0	0	0	0	0	0	6
F2	1*	1	1*	0	0	1*	0	0	1*	1	0	0	0	0	0	0	0	0	0	6
F3	1*	1	1	0	0	1*	0	0	1*	1*	0	0	0	0	0	0	0	0	0	6
F4	1	1*	1*	1	0	1	0	1*	1*	1*	1	1	1	0	0	0	1	0	0	12
F5	1	1	1*	0	1	1*	0	0	1*	1*	0	0	0	0	0	0	0	0	0	7
F6	1	1*	1*	0	0	1	0	0	1	1*	0	0	0	0	0	0	0	0	0	6
F7	1	1*	1*	0	0	1	1	0	1*	1*	0	0	0	0	0	0	0	0	0	7
F8	1*	1*	1	0	0	1*	0	1	1	1	0	0	0	0	0	0	0	0	0	7
F9	1*	1*	1*	0	0	1	0	0	1	1*	0	0	0	0	0	0	0	0	0	6
F10	1*	1	1	0	0	1*	0	0	1	1	0	0	0	0	0	0	0	0	0	6
F11	1*	1*	1	0	0	1*	0	1	1*	1	1	0	0	0	0	0	0	0	0	8
F12	1*	1*	1	0	0	1*	0	1	1*	1	0	1	0	0	0	0	0	0	0	8
F13	1*	1*	1	0	0	1	0	1	1*	1	0	0	1	0	0	0	0	0	0	8
F14	1	1*	1*	1	1	1	0	1*	1	1*	1*	1*	1*	1	0	0	1	1	0	15
F15	1	1	1	0	1	1*	0	1*	1*	1*	1*	0	0	0	1	0	1*	1*	1	13
F16	1*	1*	1*	1*	1*	1	0	1*	1	1*	1*	1*	1	0	1	1*	1*	0	0	16
F17	1*	1*	1*	0	0	1	0	0	1*	1*	0	0	0	0	0	0	1	0	0	7
F18	1*	1	1*	0	0	1	0	1*	1	1*	1	0	0	0	0	0	1	1	0	10
F19	1*	1	1*	0	0	1*	0	1*	1*	1*	1*	0	0	0	0	0	1	1	1	11
DEP	19	19	19	3	4	19	1	10	19	19	7	4	4	2	1	1	7	5	2	

Note: *represents the transitive links.

Table 6
Hierarchical classification of LABP factors.

Levels	Factors to LABP
First level	Fluctuating market prices (F1) Insufficient capital investment (F2) Low return on investment (F3) Conflicts in land use (F6) Requirements for resource sustainability (F9) Lack of mature biomass supply chains (F10)
Second level	Low market transparency (F5) Differences in regional climate conditions (F7) Improper handling of biomass residues (F8) Shortage of rural labor force (F17)
Third level	Lack of infrastructure and talent (F11) Lack of technological innovation and research and development (F12) Lack of management experience (F13)
Fourth level	Lack of financial subsidies (F4)
Fifth level	Low public acceptance (F18)
Sixth level	Lack of policy support (F14) Lack of widespread publicity (F19) Unstable governance environment (F15) Legal and regulatory constraints (F16)

(F9), and lack of mature biomass supply chains (F10) are located at the top level which are the surface level factors affecting LABP. In hierarchical graph, the top level is usually seen as representing the system's final goal, with the levels below serving as the causes of the previous level. It can be found that the bottom level contains two factors, which are unstable governance environment (F15), and legal and regulatory constraints (F16).

3.4. Classification of factors using MICMAC method

The nineteen influencing factors were classified based on the DEP and DRP values of the factors in Table 5, as illustrated in Fig. 4. All factors can be divided into four groups according to MICMAC. The first quadrant is the autonomous factors, which indicate that the factor's drive and dependency are relatively low. The second quadrant is the dependent factors, which are factors with low drive and high dependency. The linkage factors, which are comparatively high in drive and dependency, are in the third quadrant, and the driving factors in the fourth quadrant indicate that the factors are high in drive and low in dependency. The categorization results in Fig. 4 provide stakeholders with a scientific decision-support tool that enables them to formulate more rational and effective measures against these factors, thereby achieving more accurate and efficient management.

4. Discussion

This section discusses the analysis of results, comparative analysis, assessment of benefits, policy insights, management insights, and recommendations and future perspective.

4.1. Analysis of results

As shown in Fig. 3 and Table 6, factor F15 (unstable governance environment) and factor F16 (legal and regulatory constraints), which are located at the bottom of the hierarchy, constitute macro-factors for LABP implementation. For example, frequent changes in leadership or policy direction in relevant sectors can weaken investor and business confidence in LABP, and restrictions in laws and regulations can increase compliance costs and operational risks for businesses, limiting industry innovation and flexibility. Factor F15 has a direct impact on factor F19 (lack of widespread publicity), because the relevant departments may focus more on dealing with urgent social issues in a turbulent or unstable governance environment, thereby neglecting public promotion and education activities. Furthermore, factor F18 (low public acceptance) is affected. Factor F16 also has an impact on factor F14 (lack of policy support). Strict laws and regulations may limit the formulation and implementation of government policy on LABP, and the lack of effective policy support may reduce incentives for LABP. Thus, to achieve sustainable development of LABP, governments and relevant organizations need to offer more policy support and public education at the macro-level.

Factor F1 (fluctuating market prices) is located at the top level of the LABP influencing factors, which strongly confirms the importance of market stability for the agricultural biomass industry. Factor F2 (insufficient capital investment) may stem from low market transparency (F5) and lack of policy support (F14), which needs to be further improved by integrating the interactions of multiple dimensions such as market, policy, and technology. In addition, factors F6 (conflicts in land use) and F9 (requirements for resource sustainability) pose fundamental challenges to the physical basis and environmental sustainability of agricultural biomass production. Land use conflicts, which have a direct impact on supply, may limit the area of land available for biomass energy crops. Meanwhile, resource sustainability requirements emphasize the need to consider environmental protection and long-term resource availability in production. These factors indirectly affect deeper-level factors such as factors F12 (lack of technological innovation and research and development) and F13 (lack of management experience) by influencing factors F17 (shortage of rural labor force) and F8

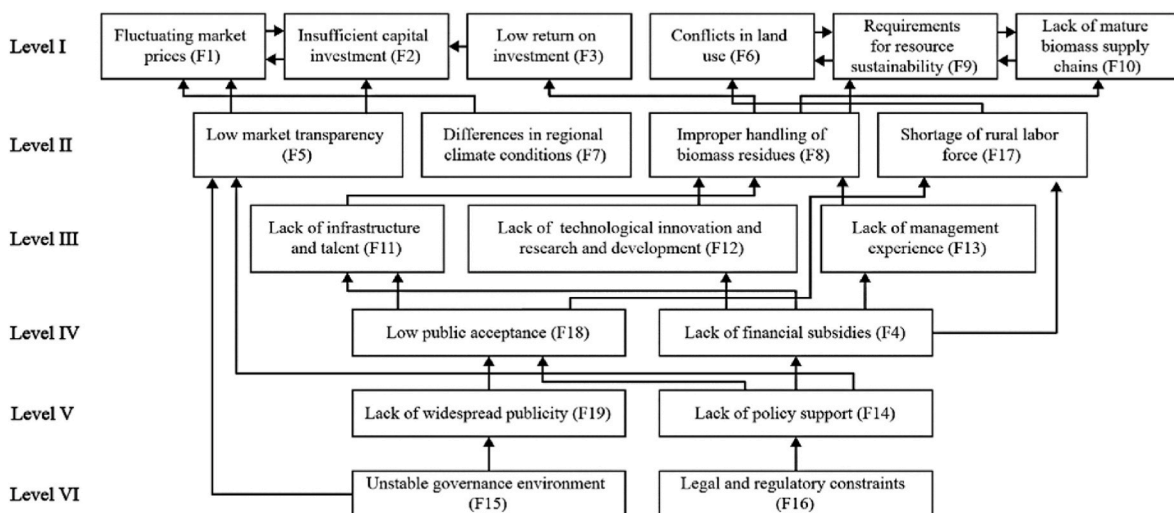


Fig. 3. Hierarchical directed graph of LABP factors.

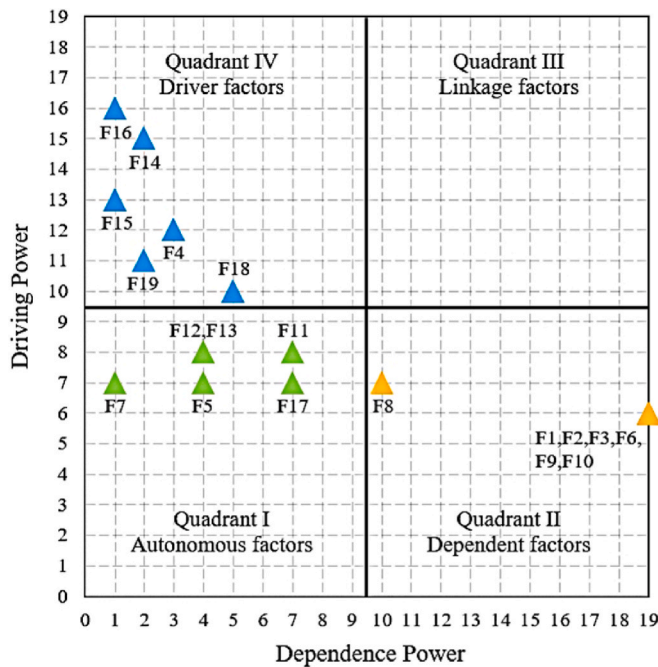


Fig. 4. MICMAC analysis for LABP factors.

(improper handling of biomass residues), and raise higher demands on the industry to adopt more environmentally friendly and resource efficient production methods. The complex interplay indicates that LABP requires a multidimensional and systematic approach to address the challenges.

The factors are grouped into different quadrants on the basis of the drivers and dependencies as shown in Fig. 4, revealing their dynamic roles and interactions within the system. The first quadrant contains the factors with lower drivers and lower dependencies. These factors may not influence the other factors as much as the drivers and linkage factors, but they do require attention. In the context of the LABP, these factors are autonomous, although part of the intermediate structure, which includes factors F5 (low market transparency), F7 (differences in regional climatic conditions), F11 (lack of infrastructure and talent), F12, F13 and F17. Although their direct impact on the system is limited, their presence may indicate potential structural problems within the system that require long-term and fundamental reforms to address. The second quadrant includes those factors with lower drivers but higher dependencies, such as F1, F2, F3, F6, F8, F9 and F10 (lack of mature biomass supply chains). While these factors have limited impact on the system's operation and transformative capacity, they depend heavily on the state and changes of other factors within the system. This may include areas that require improvement or resolution of other factors in order to move forward. The fourth quadrant of Fig. 4 contains factors F4 (lack of financial subsidies), F14, F15, F16, F18 and F19, which are considered key factors for LABP because of the strong driving power that allows them to effectively influence other factors without being overly dependent on the rest of the system. Thus, the factors require particular attention from all those involved.

4.2. Comparative analysis

This paper provides a comprehensive analytical approach to identifying the factors influencing LABP and prioritising the allocation of resources. There is little literature that thoroughly examines the barriers to LABP from a multi-stakeholder perspective, although the method described herein has been used in other disciplines. For example, Adams et al. [77] identified eleven potential barriers to the development of UK bioenergy projects from the perspective of feedstock suppliers, where

the uncertainty of grants or financial support is similar to the lack of financial subsidies (F4) factor discussed in this paper. According to their findings, which are consistent with those of this paper, poor or unclear ROI is a major barrier to the development of bioenergy feedstocks. Besides, they identified other barriers with similarities to the factors covered in this paper, such as requirements for differences in regional climate conditions (F7); resource sustainability (F9); and lack of policy support (F14). Building on the concept of sustainability in biomass-related countries, Azevedo et al. [57] pointed out that the main factors restricting biomass from becoming a major energy source include land and crop use for biomass production possibly reducing other agricultural product availability, which relates to the conflicts in land use (F6) factor herein. This further suggests that there may be some common challenges to biomass project development in different areas that need to be analyzed in depth from a multidimensional perspective.

Feng and Ma [78] studied the influencing factors of service innovation in manufacturing firms using the fuzzy DEMATEL (Decision-making Trial and Evaluation Laboratory) method based on the service ecosystem perspective. Table 7 is summarized to make the comparative analysis clearer. Wang et al. [79] presented an improved WINGS-ISM method to deal with the key factors in group decision-making for collaborative emergency management. Guo et al. [80] identified the impact pathways of emerging information technologies in alleviating supply chain vulnerabilities by utilizing a novel DEMATEL-ISM approach on the basis of grounded theory. Bagherian et al. [46] employed the ISM-MICMAC and DEMATEL methodologies to reveal ten dimensions of digital sustainability in energy.

ISM has been selected as the favored and efficient approach to investigate the interplay among elements in complex systems when compared to alternative approaches like DEMATEL, Analytic hierarchy process and social network analysis [81]. This is due to the following important features of the ISM method 1) ISM not only provides insight into the relationships between different elements, but also shows the causal hierarchy and structure of the system factors using visually appealing hierarchical topology diagrams. 2) ISM has an interpretive function. It relies on the subjective judgements of expert teams or groups to establish the relationships between factors. 3) The objective of using ISM is to order and orient the complex relationships between system elements, which help to identify key factors. 4) The ISM methodology can adapt to dynamic system changes. And it reflects the system evolution by analyzing structural changes over time or under different conditions. Furthermore, researchers can use MICMAC analysis to extend the knowledge gained from visual inspection of impact structures, providing a comprehensive assessment and analysis. The combined use of ISM and MICMAC allows for an in-depth analysis of the interactions and dependencies between factors [82]. Therefore, this paper adopts the ISM-MICMAC methods to analyze the interplay between factors affecting LABP, providing a comprehensive analysis and decision support for various dimensions, including economic, social, environmental, and policy.

Table 7
Comparative analysis of the literature.

Studies	Methodology	Applications
Feng and Ma [78]	DEMATEL	Service innovation in manufacturing firms
Wang et al. [79]	WINGS-ISM	Collaborative emergency management
Guo et al. [80]	DEMATEL-ISM	Supply chain vulnerabilities
Bagherian et al. [46]	ISM-MICMAC and DEMATEL	Digital sustainability in energy
This paper	ISM and MICMAC	Large-scale agricultural biomass production

4.3. Benefits of implementing LABP

This section analyses in detail the benefits of the LABP in three dimensions: economic, social and environmental, with the aim of assessing the potential contribution of the LABP to advancing the energy transition and achieving sustainable development goals.

4.3.1. Economic benefit

As the scale of agricultural biomass industry expands, the unit cost of biomass power generation gradually decreases and its economic benefits become more apparent [83]. The development of the LABP will create more employment opportunities in rural areas, particularly in the collection, processing and transport of biomass. This not only helps to raise the income level in rural areas, but also encourages farmers to actively participate in agricultural biomass production, which directly promotes local economic development and reduces the urban-rural economic gap. In addition, biomass projects tend to attract external investment and promote capital flow, further driving regional economic prosperity. According to statistics, biomass power generation in India attracts more than \$130 million of investment annually [84]. More importantly, agricultural biomass production and utilization serve as a model for a circular economy [11]. From the perspective of resource utilization, agricultural biomass production converts crop straws and residues, which were originally considered waste or low-value resources, into value-added biomass products such as biodiesel and biogas [85]. Furthermore, LABP also drives the development of related industry chains, such as agriculture, manufacturing, and services, thus promoting the diversification of the rural economic structure and enhancing the endogenous growth dynamics of the rural economy. The diversification of income sources helps to ensure stable returns for producers, investors, etc., especially when affected by factor F1.

4.3.2. Social benefits

The implementation of LABP production has demonstrated multiple positive social impacts. Firstly, the rise of biomass industry brings about the related upstream and downstream enterprises development, and then stimulates the prosperity of the job market [86]. Secondly, agricultural biomass production helps to make rural communities more cohesive. The implementation of LABP requires stakeholders to participate collectively in decision making, management and monitoring, which promotes links and cooperation within the community and builds a harmonious social relationship. Increased social awareness and public participation is also an important aspect of the social benefits of agricultural biomass production [87]. As knowledge of agricultural biomass becomes more widespread and the benefits of its use become clearer, the public is beginning to recognize the value of agricultural biomass, which has led to an increased public demand for agricultural biomass products, thereby effectively promoting infrastructure construction in rural areas [88]. Besides, the production and consumption of bioenergy encourages environmental behaviour and lifestyle changes among the public, contributing to a positive social atmosphere and laying a solid foundation for building a green and low-carbon society. On the other hand, agricultural biomass energy provides a sustainable alternative energy source for rural areas without a reliable source of power source [89], which also reduces health and safety risks during the collection and use of traditional fuels and improves public's quality of life.

4.3.3. Environmental benefits

Agricultural waste such as crop residues and animal manure are often burned or discarded in traditional treatment methods, which not only wastes resources but also may produce secondary pollution [90, 91]. Agricultural biomass production achieves the harmlessness and reduction of waste through the resourceful use of waste, effectively reducing the environmental pollution caused by agricultural activities. Secondly, utilizing agricultural biomass energy helps lessen reliance on fossil fuels [92]. Biomass produces fewer pollutants during combustion

or conversion and emits much lower amounts of harmful gases such as sulfur dioxide and nitrogen oxides compared to fossil fuels. Biodiesel can replace conventional diesel fuel and help decarbonize the transport sector [93], and emission reduction effect is crucial for achieving the carbon neutrality goals, providing a practical solution for global warming [94]. Moreover, LABP contributes to improving soil quality and promotes a virtuous cycle in agricultural ecosystems. Residues from agricultural biomass production (e.g., biomass ash), which are rich in minerals and trace elements, can be added to soil as soil amendments for plant growth and soil fertility [95]. By comprehensively considering and optimizing the production of agricultural biomass, its environmental benefits can be maximized and contribute to sustainable development goals.

4.4. Policy implications

The key to policy analysis to promote LABP is to establish a comprehensive, coordinated and sustainable policy framework. At the government level, policymakers should first integrate LABP into long-term planning for national energy and the green, low-carbon transformation of agriculture. Industry experts, business representatives and other parties should be brought together to formulate clear policy objectives, staged tasks and development paths for the agricultural biomass industry, and policy impact assessments should be carried out on a regular basis to ensure the coherence and stability of the policy environment. In response to the lack of policy support (F14) and legal and regulatory constraints (F16), policymakers can provide clear regulatory guidance and ongoing financial incentives. For example, policymakers can 1) establish dedicated funds to support R&D and construction of biomass projects; 2) offer tax reductions, loan interest subsidies, and other preferential policies for agricultural biomass enterprises; 3) and encourage financial institutions to increase their credit support for agricultural biomass projects. These measures are crucial to reducing the cost of agricultural biomass production and enhancing its economic appeal, especially if the initial investment is large. On this basis, policies should further optimize the allocation and utilization of agricultural biomass resources. The policies may be achieved through land transfer and scaled operations to promote intensive and large-scale production of agricultural biomass resources. Secondly, the lack of mature biomass supply chains (F10) directly affects the stability and efficiency of LABP. Therefore, policymakers need to increase the construction of infrastructure, encourage technological innovation and R&D investment. By supporting cooperation between enterprises and academic institutions, priority should be given to overcoming key technological bottlenecks and accelerating the industrial application of technological achievements. Improving the market mechanism is also an important aspect of policy formulation. Government departments should strengthen market monitoring and early warning, establish a sound market access standard and regulatory system for agricultural biomass products, and formulate a reasonable price control mechanism to improve market predictability and prevent market monopoly and undesirable competition. Moreover, policies should be flexible, providing differentiated support according to the actual situation of enterprises, and gradually shifting from direct subsidies to market incentive mechanisms, such as quota systems and green certificate trading. Finally, policymakers should fully consider the environmental and social impacts of LABP, strengthen the concept of green development and awareness of responsible management, and achieve a win-win situation that balances environmental protection with economic benefits.

4.5. Management and practice insights

Given that LABP is still in the early stages of scaling up, exploration in management is essential. As LABP involves multiple stakeholders, including governments, industry, farmers, consumers and

environmental organizations, an integrated management framework is needed to meet the needs and expectations of all stakeholders. The following provides some management measures from different perspectives, such as industry and academia, for reference.

From the perspective of the industry, the implementation of LABP requires the establishment of a cooperative mechanism involving multiple parties. Firstly, managers should develop a clear strategic plan to ensure effective allocation of resources, including funding, technology, and human resources. Meanwhile, communication with policymakers should be maintained to ensure project compliance with regulatory requirements and to obtain policy support. In response to factors F2 and F5, it is recommended to increase market predictability through diversified financing channels and the establishment of information-sharing platforms and thereby increase investment from both public and private sectors. In terms of consumer awareness, develop a comprehensive publicity program using various channels such as community seminars, school education campaigns and media cooperation. Managers should also develop a risk management plan to regularly monitor and evaluate the progress of the LABP and adjust strategies in a timely manner to address potential risks. Stable supply and quality control of biomass feedstock can be ensured by strengthening cooperation with raw material suppliers, processing enterprises and end-users, such as contract farming and order farming, and the industry should strive to cultivate a number of leading enterprises and industrial parks with demonstration and leadership roles, creating a positive situation for the coordinated development of upstream and downstream industrial chains.

Academics, on the other hand, should take on the role of providing theoretical support and guidance. Efforts should be devoted to interdisciplinary basic and applied research, conducting in-depth analysis of the economic, technical, environmental and social challenges facing the LABP industry. The combination of theoretical knowledge with actual agricultural biomass production will also provide a scientific basis and solutions for the industry. Second, the academic community should establish close cooperation with enterprises to jointly promote the transformation and application of technological achievements and cultivate biomass industry talents with professional knowledge and practical skills. In addition, academics can introduce advanced technologies and management experiences by participating in relevant international forums, thus ensuring the scientific and forward-looking nature of industry policies and practices.

Overall, the organic integration of policy and management activities will provide a solid foundation for the implementation of the LABP and promote the sustainable development of the industry, while ensuring that economic, social and environmental benefits are maximized.

4.6. Recommendations and future perspective

As an important force in the global energy transition, LABP has great potential for expansion. Its application in developing countries can provide a strong guarantee for local energy supply, reduce dependence on traditional fossil energy and help the world to address climate change and environmental issues. It creates new economic growth points for rural areas, continuously promotes the upgrading of rural industrial structure, and becomes the key to promoting sustainable development.

In the process of promoting LABP in developing countries, improving and adjusting the identified influencing factors requires an integrated approach. First, developing countries should formulate a forward-looking policy framework to provide a stable policy environment for the agricultural biomass industry. Meanwhile, a sound regulatory system should be established to avoid legal and regulatory constraints becoming a stumbling block to development. Secondly, in view of the relative disadvantages of developing countries in terms of capital and technology, we should actively introduce advanced agricultural biomass production technology and equipment, and then digest, absorb and re-innovate them with the characteristics of local resources. On this basis, explore business models that suit local economic conditions,

develop large-scale and decentralized biomass energy projects, and reduce reliance on high investment and complex technologies.

Looking into the future, interdisciplinary research will provide more comprehensive and solid theoretical support for LABP. Technological innovation will continue to lead the industry forward, with breakthroughs expected in biomass pre-treatment technology, conversion efficiency improvement and cost reduction. Optimizing the biomass supply chain under resource constraints and identifying context-specific biomass production models suitable for local markets are important directions for research. The construction and improvement of the carbon trading market and renewable energy quota system will inject a strong impetus for the market-based and large-scale development of LABP. Besides, in future research, conducting a full life cycle assessment will help to comprehensively identify the potential impacts of the agricultural biomass industry and provide a strong basis for sustainable development strategies.

5. Conclusions

A total of nineteen key factors affecting LABP implementation from a stakeholder perspective are identified herein. A solid basis for subsequent in-depth analysis is provided by the identification of these factors. Using the ISM method, an interpretive structural model is constructed herein in which these factors are categorized into six levels. The model reveals the complex interdependencies and hierarchical structures among the various factors involved in LABP and clarifies the underlying causes and key factors affecting the implementation of LABP. Furthermore, the MICMAC analysis method is used to categorize the nineteen influential factors of LABP into three groups: autonomous factors, dependent factors, and driver factors, which provides a scientific basis for resource allocation and strategy development. More importantly, this paper offers targeted strategic guidance and concrete management recommendations for stakeholders, such as policy makers, businesses and scholars, especially in terms of policy formulation, market expansion and sustainable development, to overcome the obstacles in the process of LABP implementation. As well as promoting resource recycling and diversification of the rural economy, this study makes a positive contribution to the sustainable development of the agricultural biomass industry. There is still a significant gap between the management of LABP and the requirements of sustainable development, although considerable progress has been made in this subject.

Although this paper has achieved some results in the analysis of factors affecting LABP, there are still some limitations. First, this paper mainly relies on literature review and expert consultation to obtain study data, which may introduce subjectivity and bias in the identified key factors, and lead, to some extent, to the shortcomings of the lack of linking factors in the research findings. Second, although the ISM-MICMAC methods are good at identifying interdependencies between factors, the methods are inherently qualitative and cannot quantitatively measure the intensity of influence between factors, which may limit the ability to prioritise factors based on relative influence weights. Future research should collect more empirical data through methods such as field surveys or big data analysis, and explore alternative methods to quantify the relationships between factors. Additionally, as the global energy landscape continues to evolve, the factors to LABP will also change dynamically. This paper mainly focuses on the current factors affecting LABP and gives insufficient consideration of new factors and challenges that may emerge in the future. Consequently, future research should strengthen the tracking and analysis of dynamic factors. Third, although this paper is comprehensive and focuses on multi-stakeholder perspectives, it may not be able to delve into the specific operational challenges faced by individual stakeholders. Finally, the generalisability of the findings is limited by the research environment. While this paper provides rich insights, it may not be able to dynamically reflect the LABP in different environments. Further research could develop context-specific models to validate and refine the research

results.

CRedit authorship contribution statement

Wenjing Liu: Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Jianghong Feng:** Writing – review & editing, Validation, Resources, Methodology, Funding acquisition, Conceptualization.

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Data availability

Data will be made available on request.

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A meta-auction for on-demand transportation procurement in industry 5.0

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ABSTRACT

The Cyber-Physical Internet (CPI) is a cutting-edge concept that brings together physical systems and cyber technologies to enable seamless interaction between the physical and virtual worlds. This innovative approach is revolutionizing the transportation industry by paving the way for a new era of logistics and transport networks. Introducing CPI into the procurement of transport services is leading to a re-evaluation of fundamental issues such as routing, mode choice and real-time pricing. This paper provides an in-depth discussion on the application of transport services procurement auctions in a CPI environment, with the aim of establishing a novel CPI-based trading platform for transport services using CPI technology, and calls the methodology proposed in this paper a *meta-auction*. The transport route allocation quandary is simplified into an auction model, where carriers truthfully submit unit route costs, and the winning carrier and pricing are determined using the single-unit Vickrey-Clark-Groves (VCG) method. To address scenarios with multiple carriers per network segment node, this paper proposes the multi-unit VCG auction method. Furthermore, the weighted affine VCG auction method is introduced, considering the weight of each network segment route. All three mechanisms are generalized VCG auctions, ensuring incentive compatibility, budget balance, allocation efficiency, and individual rationality. Case studies validate the effectiveness of the proposed methods, offering managerial insights based on key findings that are valuable for industry professionals and researchers in the CPI domain. This study highlights the transformative potential of CPI to revolutionize auctions for the procurement of transport services and underlines the benefits of combining physical and cyber technologies in auction design.

1. Introduction

The transport industry is facing a major transformation due to the increasing globalization of the economy and the rapid

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development of internet technology (Tijan et al., 2021). Inefficiencies and high costs, as well as poor information flow and severe information asymmetry, plague the traditional logistics and transport model (Xu and He, 2022). The lack of transparency of key information such as the distance of goods transported, cargo tracking, transport time, etc. brings inconvenience and uncertainty to enterprises and consumers (Dutta et al., 2020; Oliveira et al., 2015). Furthermore, the traditional bidding method has disadvantages such as being cumbersome, time-consuming and inefficient. To improve the efficiency and cost management of logistics and shipping operations, many countries have begun to integrate Internet technologies into the delivery of shipping services (Mu and Antwi-Afari, 2024). This includes leveraging logistics big data analysis (Wang et al., 2016), automated loading and unloading equipment, and intelligent route planning to boost efficiency, minimize costs, enhance safety, and drive sustainable development within the industry.

Internet-based auctions have gradually emerged and become widespread in recent years (Feng et al., 2024; Li et al., 2023; Xu et al., 2023). Transport service procurement auctions are a way of matching and trading between shippers and logistics service providers via an internet platform (Karaenke et al., 2019; Sahinyazan et al., 2021). Shippers can post their transport requirements and logistics service providers can bid for the best price and conditions for the transport contract via the transport service auction platform (Guo et al., 2022). This auction-based transport service model can improve the transparency and efficiency of the logistics and transport market compared to the traditional transport market (Chen et al., 2005; Garrido, 2007).

However, there are some challenges associated with traditional transport services procurement auctions. First, the costs to auctioneers (shippers) of determining the best supplier in an auction may increase due to the complexity and diversity of transport services (Wan and Beil, 2009). Different transport demands may require different types of suppliers, which may be located in different geographical locations, and the auction process can be challenging to ensure that the best supplier is found for each demand (Agatz et al., 2024). Second, traditional auction models may limit supplier participation and competition. Auctions are typically based on competitive bidding, and price is not the only factor in selecting a supplier (Van Duin et al., 2007). Other factors like quality of service, reliability and transit time are equally important, but are sometimes overlooked in traditional competitive bidding. Furthermore, the traditional auction model can be overly reliant on bids, neglecting the overall effectiveness of the supply chain. When it comes to procuring transport services, the efficiency and co-ordination of the entire supply chain is of great importance (Kanda and Deshmukh, 2008), but competitive auctions can lead to fragmentation and incoherence in the supply chain as suppliers focus primarily on winning the auction. This may adversely affect the effectiveness and cost-effectiveness of the entire supply chain. Finally, there can be a lack of flexibility and personalization in traditional auction models. Each company's transport demands are unique and the traditional auction model may not be able to provide personalized solutions and meet the company's specific demands. To overcome these challenges, it may be necessary to consider more flexible approaches that incorporate advanced technology tools to provide intelligent solutions.

The term 'Physical Internet' was first mentioned in *The Economist* in 2006 (Economist, 2006), and after more than a decade of development, the physical internet has gradually evolved towards cyber-physical internet (CPI) (Wu et al., 2024). For example, Koubãa and Andersson (2009) provided a realistic scenario of the CPI concept and discussed the associated design guidelines. Subsequently, Huang (2022) built on the original foundation by proposing a new CPI concept to modernise and revolutionise global logistics, i.e. CPI focuses more on the spatial and temporal analysis of logistics (Zhao et al., 2024). Yin et al. (2024) proposed a CPI-based supply chain management platform for off-site construction and designed incentives and information sharing mechanisms at the core level. CPI refers to the integration of the physical world with the cyber world through advanced technologies such as internet of things and cyber-physical systems (Tan et al., 2023). It aims to create a networked environment where physical objects, machines and systems are connected to each other and can interact with the digital world in real time. With the help of CPI, physical objects can be equipped with sensors, actuators and communication capabilities in order to collect and exchange data. This data can then be processed, analyzed and used to make informed decisions and take action. It enables more efficient and intelligent systems by seamlessly integrating physical devices, digital services and human-computer interaction. Industry 5.0 highlights human-centricity, sustainability and resilience (Leng et al., 2022), while Industry 4.0 is a concept that emphasizes smart manufacturing (Tao et al., 2019; Zhong et al., 2017bs). CPI can help realize the personalized and customized production emphasized in Industry 5.0 by providing a platform for remote collaboration in Industry 5.0. In addition, the large amount of data generated by CPI can be used by Industry 5.0 to optimize production processes and efficiency. In a sense, therefore, the CPI is part of Industry 5.0. The CPI can be used in a wide range of industries, such as smart cities, health care, transport, manufacturing and the energy industry. It promises to enable new levels of connectivity and interconnectivity, increase automation, optimize resource allocation and improve decision making. In the field of transport services, the application of CPI technology can achieve real-time monitoring and intelligent scheduling of vehicles, goods, people and other information, improve transport efficiency, reduce costs and maximize the satisfaction of users' individual demands.

Consider a logistic network where shippers entrust goods to carriers for seamless transportation from the origin to the final destination. Within this network, the CPI plays a crucial role in streamlining the transport process, enabling shippers to access synchronized logistics services on demand. By way of illustration, envision a cross-border transport scenario where cargos have to be moved from a warehouse to a customer. In the warehouse, cargos are methodically loaded onto trucks in segmented sections. These trucks then journey via highways or roads to the next logistics hub. At this hub, the cargos are meticulously packed into containers and then transported by ship, rail, or air to a designated port, station, or airport. Subsequently, the cargos are transported by truck to the logistics center, where they are unpacked and ultimately delivered to the awaiting customer. Drawing parallels with the internet infrastructure, within the CPI framework, segments can be likened to trucks or ships, communication links mirror motorways and roads, and packets resemble containers. Much like truck follow designated routes within the global logistics network; packets navigate specific paths within the CPI system.

However, there have been relatively few studies of transport services auctions on the basis of the CPI. The construction of theoretical models and the design of algorithms are the main focus of existing research on transport service auctions (Hammami et al., 2021; Lau and Li, 2021; Lyu et al., 2023), and there is still limited research on the problems and challenges of CPI-based transport

service auctions in practical applications. In CPI-based on-demand transportation service auctions, suitable bidding strategies need to be designed so that logistics service providers can gain a competitive advantage while maintaining good transport service quality. Moreover, another important research issue is how to evaluate the effectiveness of transport auctions and how to track and optimize the results of the auctions. CPI-based on-demand transport service auctions also face the challenge of dynamic changes and diversity in transport demand. As the economy develops and the market changes, cargo owners' transport needs may change, including increasing or decreasing transport volume and urgency of transport time. It is therefore necessary to adjust the auction rules and the bidding strategies in accordance with the actual needs of the cargo owners, so that the auction can adapt to the changes in demand. The privacy and transaction security of cargo owners and logistics service providers must also be considered in the Internet environment. Therefore, the interests of all participants need to be safeguarded through the establishment of a credible auction platform for transport services and a fair and equitable auction mechanism.

CPI is able to monitor logistics-related data in real time, including vehicle location, transport status, transport routes, etc., which allows for more accurate planning and scheduling and improves the efficiency of logistics transport. With CPI, logistics companies can achieve complete tracking of goods, including information on origin, transit and arrival, enabling real-time monitoring and management and improving logistics security. Moreover, CPI can collect and analyze a large amount of logistics data, including vehicle operation data, cargo information, etc., and can provide more accurate logistics services and optimize the transport network and supply chain management through data analysis and forecasting. Thus, this paper is motivated by the ability of CPI in logistics applications to improve efficiency, reduce costs and provide better customer service, while optimizing logistics management through data analysis and forecasting. Particularly, this paper aims to focus on the following research questions:

- 1) How can the characteristics of the CPI be used to rationalize the design of transport procurement auction mechanisms?
- 2) How can a CPI-based auction system for the procurement of transport services be designed to provide a secure and efficient transaction facility for the relevant stakeholders?
- 3) What is the optimal bidding strategy for the CPI-based on-demand transport procurement?

The aim of this study is to build a new CPI-based on-demand transport service trading platform using CPI technology, integrating supply and demand information, and designing a novel auction mechanism to realize transport service transparency and efficiency. The proposed method is called *meta*-auction throughout this paper. We simplify the transport route allocation problem to an auction model, where carriers only need to truthfully submit the unit route cost, and then the winning carrier and pricing are determined by the proposed single-unit Vickrey-Clarke-Groves (SU-VCG) method. Considering that each segment node has multiple carriers, this paper proposes the multi-unit VCG (MU-VCG) auction method. Finally, weighted affine VCG (WA-VCG) auction is proposed by considering the weight of each segment route. These three mechanisms are generalized VCG auctions, all of which achieve incentive compatibility, budget balance and individual rationality.

This paper aims to investigate the problem of transport procurement auctions through a new transaction model to maximize social welfare in the transport market. The contribution made by this study can be highlighted in the following three ways. i) This paper proposes a CPI-based auction mechanism for procuring on-demand transport services by combining CPI and transport route auctions. The VCG pricing mechanism proposed in this paper is different from the traditional auction mechanism in that the VCG pricing herein integrates real data and estimated data, and the auction is conducted in real time. Therefore, this paper attempts to construct transport service procurement and trading mechanism under the CPI environment, which is expected to provide a brand-new solution idea for the logistics pricing and allocation mechanism under the CPI environment. ii) The second contribution of this paper lies in the innovation of the research questions. Although the literature has explored the procurement of transport services, it has not further explored the issue of real-time auctions for the procurement of transport services in the context of the CPI and the coupling of the mechanisms proposed in this paper with the research questions, these mechanisms are able to effectively address the research questions posed. As a result, by combining innovative research questions with effective mechanisms, this paper not only enriches the theoretical framework of the relevant field, but also provides new perspectives and methods for subsequent research. iii) This paper proves theoretically that the three mechanisms belong to generalized VCG auctions, and demonstrates the validity of the proposed methodology through case studies and numerical experimental results, and provides managerial insights based on the main conclusions, which are useful for managers and those engaged in related CPI research. More importantly, although the mechanism proposed in this paper is a fundamental model, it has important insights for dynamic auction design, which provides an important theoretical foundation for understanding complex auction behaviour and valuable guidance for practical applications.

The rest of the study has the following structure. [Section 2](#) provides a review of the relevant literature on transport service procurement auction and the CPI. The framework of the developed CPI-based on-demand transportation procurement auction system is presented in [Section 3](#). [Section 4](#) introduces an overview of the problem and a simple example. [Section 5](#) outlines an auction model and two novel models for transport route auctions herein. [Section 6](#) validates the effectiveness of the methodology proposed in this paper via a case study and further summarizes the advantages of the developed system and methodology for transport service procurement auctions. Finally, the conclusions of the research and possible directions for future research are presented in [Section 7](#).

2. Literature review

In this section, a review of the relevant literature will be carried out from two main streams: transport services procurement auction and the CPI.

2.1. Transportation service procurement auction

Auctions as an effective method of resource allocation and pricing have been widely used and researched in the field of transport service procurement. Literature on transport auctions currently falls into three broad categories: (i) double auction, where buyers and sellers in the transport services procurement market engage in bilateral bidding and market clearing (Xu and Huang, 2015); (ii) continuous auctions, where demand for transport services arrives randomly in the auction system of the transport procurement market, followed by timely auctions and market clearing (Agrali et al., 2008; Xu et al., 2015; Xu and Huang, 2013); and (iii) combined auctions, where buyers can bid for a group of transport services in the transport procurement market (Chang, 2009; Remli and Rekik, 2013; Sheffi, 2004; Song and Regan, 2005). For instance, Sheffi (2004) considered service levels to be as important as other non-price factors in transport procurement auctions. Consequently, the consideration of other factors in transport service auctions became the focus of subsequent research. Contributing to the study of today's market with uncertain demand for transport services, Garrido (2007) studied the problem of double auction for transport procurement with elastic demand and showed that the proposed mechanism is effective in saving transport costs. Huang and Xu (2013) constructed a double auction model for transport procurement services and designed three efficient trading mechanisms to achieve optimal allocation. Xu and Huang (2013) designed an improved double auction trading mechanism for solving stochastic or supply-demand asymmetric transport service procurement problems. Lafkihi et al. (2019) carried out a comprehensive review of freight transport service procurement, including auctions to procure transport services, and interested readers may wish to read the paper. Sun et al. (2019) investigated the problem of auctions for multi-modal transport procurement, considered transaction costs in an auction model, and evaluated the performance of the proposed mechanism through a series of numerical experiments.

However, logistics supply chains are inevitably subject to disruptions and failures in a rapidly changing market environment (Aghajani et al., 2023; Schmitt et al., 2017; Yang and Yang, 2010). For example, during the COVID-19 pandemic, closing factories, blockading cities, grounding aircraft, blockading ports, and border closures led to a shortage of logistical resources and sharply increased the cost of shipping and air travel; meanwhile, restrictions on social distances dramatically increased the demand for logistical services in communities (Zhang et al., 2021). There is an urgent need to examine the risks of disrupting and dismantling transport services. For instance, Qian et al. (2020) constructed a two-stage model for determining the winner to deal with the risk of disruption, and solved the model using a scenario-based approximation method. Qian et al. (2021) further investigated the issue of sustainability and responsiveness under the risk of disruption in transport procurement auctions. Yin et al. (2021) also investigated the problem of procuring transport services with both volume discounts and disruption risk by developing a stochastic non-linear model to determine the winner in an auction. Another key issue in transport procurement is to allocate transport services to the best carrier in the shortest possible time to maximize overall social welfare (Badiie et al., 2023). These studies theoretically analyze the impact of disruption risk on the system in transport service auctions, but do not examine how modern technology can be used to reduce the negative impact of disruption risk. It is worth noting that the literature on on-demand transport services has received considerable attention in recent years (Egan and Jakob, 2016; Gao et al., 2023; Wu et al., 2023; Zhen et al., 2023a). For example, Zhen et al. (2023b) constructed a mathematical optimization model for an on-demand bus transport service platform considering constraints such as time window, bus type, and walking limit, and the experimental results confirmed the effectiveness of the model. Zhen et al. (2019) constructed a nonlinear optimization model for solving the fleet and transport demand realization problem, and real case data verified the effectiveness of the model and algorithm.

Furthermore, VCG auctions, which are relevant to this paper, have been studied extensively in recent years. Xu and Huang (2014) constructed a one-sided VCG auction for determining the winning carrier, considering the model as solving a cost-optimal problem. Guo et al. (2022) considered the problem of procuring transport services with transaction costs and designed VCG auctions with multi-unit trade reduction. Further, Zhang et al. (2019) studied the problem of multi-unit, multi-attribute transport procurement auctions and designed an efficient trading mechanism to minimize costs. Moreover, studies have also investigated the issue of transport procurement auctions with volume discounts (Liang et al., 2020). While the traditional SU-VCG auction mechanism is for transactions of a single good or service where the bidder pays the second highest bid, the SU-VCG auction mechanism proposed in this paper has only one carrier bidding for each transport route. By the same token, the traditional MU-VCG auction mechanism for multiple auctions of the same good or service allows a participant to bid for more than one unit, whereas the MU-VCG mechanism proposed in this paper has multiple carriers bidding on each transport line. Moreover, the transaction mechanism proposed in this paper differs from the traditional VCG mechanism in terms of calculating the amount of money received by the carriers.

With regard to auctions for the procurement of transport services, most of the existing research focuses on the design of auction mechanisms and models for determining winners; however, there is little literature dedicated to CPI-based on-demand auctions for the transport services procurement. While CPI cannot eliminate or avoid disruptions and interruptions from global supply chains, it can empower improvisation. Furthermore, the transparency and traceability provided by CPI can be used to eliminate or significantly reduce variability and uncertainty in logistical systems, thus enabling a shift from stochastic to adaptive decision-making. The major difference with the above literature is that we study transport service procurement auctions under CPI in this paper. As the CPI is data-driven and each link uses a large amount of real-time data, our study focuses more on the mechanism design and pricing strategy of the operators within each link. It is unclear how resource allocation and transaction prices are determined in an environment of CPI to ensure incentive compatibility and budget balance.

2.2. The related work of CPI

Recently, physical internet, which aims to achieve friendly economic-social-environmental sustainable logistics development, has

received a lot of attention from industry and academia (Pan et al., 2017; Sallez et al., 2016; Tran-Dang et al., 2020). Pan et al. (Pan et al., 2015) have defined new issues related to inventory management in the physical internet environment and have provided new insights into the impact of the physical internet on traditional inventory management strategies. Zhong et al. (2017a) have extended physical internet to the manufacturing industry, using a range of intelligent technologies to create an intelligent shop floor environment that helps management make decisions. Meyer et al. (2019) proposed a four-layer framework model by incorporating blockchain into the physical internet, introducing the configuration of blockchain and the network structure of the physical internet. Ambra et al. (2019) investigated the relationship between the concepts of physical internet and synchronous modes mentioned in the

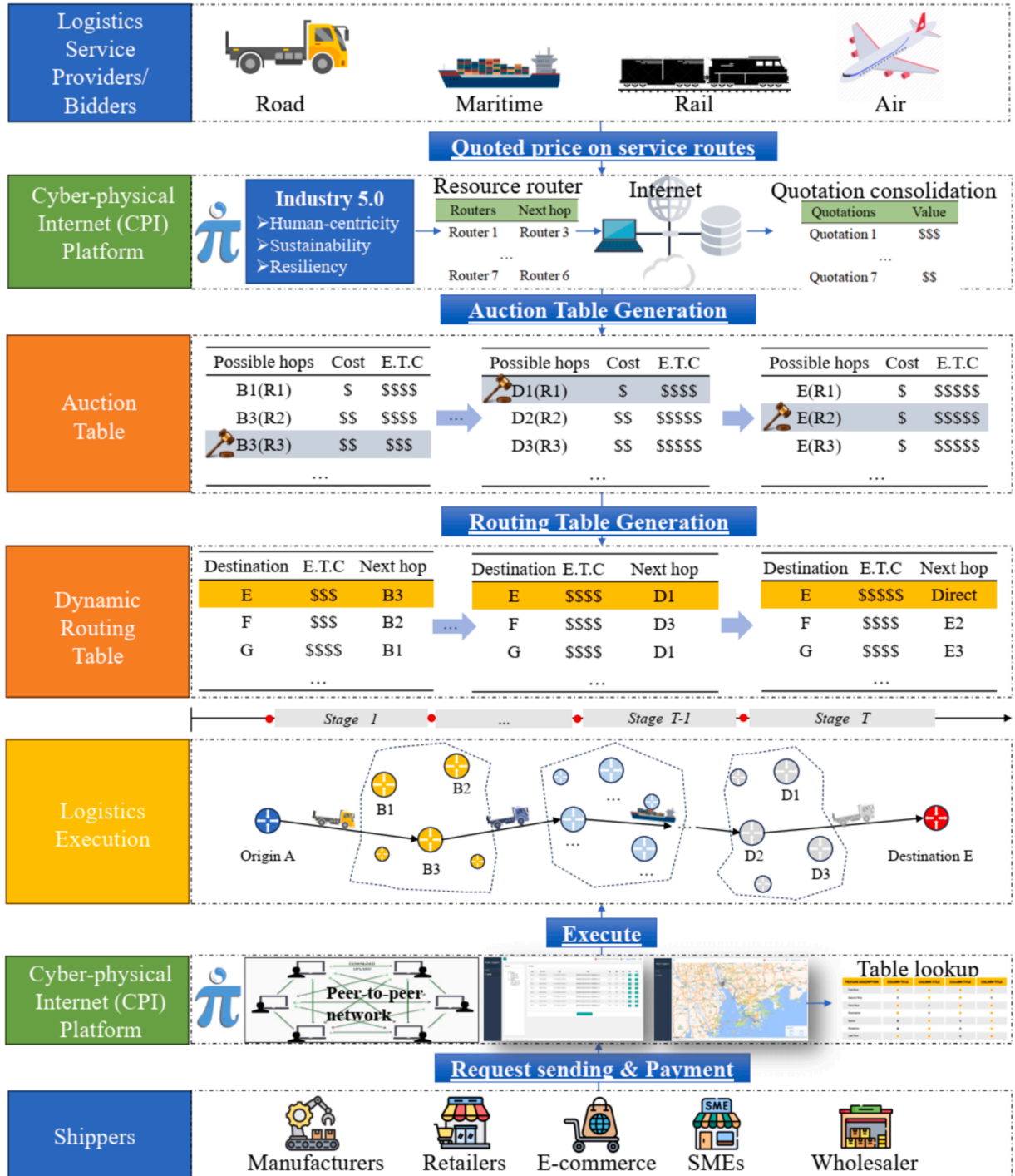


Fig. 1. Overview of CPI-based transport service procurement and execution.

literature and the results showed that there is no obvious relationship between the two concepts. Pan et al. (2021) considered the physical internet as an innovative new paradigm for logistics and analyzed the important role of digital interoperability in logistics. Essghaier et al. (2023) studied the vehicle scheduling problem under the physical internet structure and constructed a multi-objective optimization model, this study took into account the special characteristics of physical internet and proposed a novel solution idea for the model. There is also some literature on constructing mathematical optimization models to optimize supply chain networks in a physical internet environment, e.g., inventory decisions (Yang et al., 2017), logistics system (Fazili et al., 2017), and cross-docking optimization (Chargui et al., 2022).

Another CPI-related literature is cyber-physical systems, and several related applications of cyber-physical systems have been reported in recent years (Bordel et al., 2018; Pivoto et al., 2021). Kong et al. (2021) designed an improved transaction mechanism to maximize social welfare by providing automated real-time auctions on on-demand logistics platforms through cyber-physical systems. Abusuliman (2023) argued that cyber-physical systems can secure the supply chain to some extent, and have used machine learning to build security to detect cyber-physical systems. As cyber-physical systems are integrated systems that combine computers, networks and physical components to monitor and control physical processes, they are used in a wide range of applications such as transportation (Lin et al., 2023), manufacturing and industrial automation (Peng et al., 2022), smart grids (Olivares-Rojas et al., 2022), and agriculture (Afrin et al., 2022). These studies lay the foundation of a theoretical framework for the further implementation and application of cyber-physical systems.

Undoubtedly, the above literature has made important contributions to the development of the physical internet and cyber-physical systems. These literatures are mainly concerned with the physical properties of material flows, even though they deal with the Internet of Things (IoT), digital twins and information-physical systems. Very little consideration is given to digitization and the lack of digital infrastructure severely limits the scope for innovation and breakthroughs in physical internet. To the best of our knowledge, there has not yet been any literature reported on CPI-based on-demand transport services procurement auctions.

3. CPI-based transport service procurement auction framework

In the realm of the internet, routers serve as network devices crucial for transferring data packets between distinct networks. Their function involves scrutinizing the destination address of each packet and routing it to the appropriate destination accordingly. In the context of CPI, routers can be likened to transportation hubs in the physical world, overseeing and managing the flow of data packets. The routing table, a pivotal data structure housed within routers, plays a vital role in determining the optimal path for packets. Containing intricate details about network topology, available pathways, and distances between network nodes, the routing table serves as a guiding map for routers. Upon the arrival of a packet at a router, the router references the routing table to ascertain the designated interface through which the packet should be forwarded to reach its intended destination. In essence, routers serve as linchpins in steering packet flow within the CPI, while routing tables empower routers to make informed decisions, ensuring swift and secure delivery of packets to their destinations. While in the digital internet, the geographically dispersed routers guarantee the connectivity of the Internet by looking up the routing table to decide the next hop for data transmission. Inspired by the digital internet and physical internet, CPI aims to maximize the social welfare by providing scientifically segmented transport services with reasonable price. The routing table in the digital internet is dynamically updated through Routing Information Protocol (RIP). Routers running the distance-vector protocol send all or a portion of their routing tables in routing-update messages to their neighbours. The logistics routing table in the CPI is generated and updated through a series of auction mechanisms to enable the transport to reach higher granular and seamless level. In the CPI-based on-demand transportation services procurement, it is essential to clarify two key concepts within the CPI framework: routers and routing tables.

Fig. 1 hierarchically depicts the details of CPI-based transport services procurement and execution. Shippers include a variety of roles, such as manufacturers, retailers and wholesalers. All have a potential need for transport services. The transport requests based on distinct requirements are sent by the shippers to the CPI platform. The CPI platform also provides access to logistics service providers, who submit their price bids for various routes via the resource router. Each transport hub has a resource router that is capable of sensing and communicating with other intelligent devices. The resources router can monitor the departure and arrival times of the vehicle through IoT technologies such as GPS and Bluetooth Low Energy to enhance the authenticity of the bidding process. The resource router communicates with the CPI platform which consolidates the quotations and generates the auction table. The auction table confirms the most appropriate route operated by the logistics provider by checking the estimated total cost (E.T.C). The detailed mechanism is introduced and proved in the later sections. The destination of the winning bid serves as the next hop in the dynamic routing table. The dynamic routing table, encompassing the destination, E.T.C., and next hop, exists in each transport hub for reference. The shipment that arrives in one transport hub conducts the dynamic routing table lookup activity to determine the next transport hub and corresponding logistics service provider. The payment from the shipper to the logistics service provider is also settled through the CPI platform.

4. Problem description and an example

This section reviews the problem of CPI-based on-demand transportation services procurement auction, then illustrates the proposed methodology by means of a simple example.

4.1. Problem description

Consider a transport network with a shipper and several carriers. The shipper has a batch of goods that needs to be transported from origin to destination. There may be multiple modes of transport (e.g., rail, sea, and road) or multiple transport routes between origin and destination. Traditional transport services are often provided directly by a freight forwarder, who transports the shipper's goods from origin to destination along pre-determined routes. In practice, factors like raw material shortages, natural disasters and unforeseeable events that lead to port shutdowns, political changes and rising fuel costs can disrupt a logistics chain. Suffering transport delays from external uncertainties lead to unavoidable losses for shippers. One potential way to reduce transport uncertainty is to use technological tools like IoT and big data to share information and monitor transport links in real time, identifying potential problems in advance and taking appropriate action to prevent disruptions. Specifically, this paper considers such a realistic scenario in the context of the CPI. CPI is an advanced networked system concept that links the physical and virtual worlds, integrating sensors, actuators and intelligent devices with the power of the internet.

We provide Fig. 2 to facilitate a better description of the problem. A shipper has a shipment that needs to be transported from node A to node E. In traditional transport services the shipper negotiates the price directly with the carrier and then transports the shipment directly. Yet, in the CPI environment the transport service is divided into T stages from the origin A to the destination E, which include stage 1, stage 2, stage i , and stage T . There are $T+1$ segments in Fig. 2. It is worth noting that the number of nodes within each segment is not the same. For example, segment 0 denotes the origin and its number of nodes is 1, segment i includes multiple nodes, and segment $T+1$ denotes the destination and its number of nodes is also 1. In a CPI-based on-demand transportation procurement auction, all the nodes excluding the origin A and the destination E are referred to as bidders (indeed, these nodes are called routers in the CPI environment). Each bidder in stage t can only transport goods from segment $t-1$ to segment t . Our CPI-based on-demand transportation procurement auction runs as follows. A real-time auction can be conducted from origin A to locations in segment 1, where origin A is the auctioneer, and B1, B2, B3, B4, and B5 in segment 1 are bidders, and once one of these nodes (B3) wins, it becomes the auctioneer in the next stage. Also note that in CPI-based on-demand transportation procurement auction, the last stage does not require an auction, and the price to be paid is calculated directly by the system based on the routing table. The routing table is given by the real-time data within the system. It is worth mentioning that the bidders in each stage (e.g. B1, B2, B3, B4 and B5) are virtual. In practice, each carrier only bids for transport routes A-B1, A-B2, A-B3, A-B4, and A-B5.

The CPI-based on-demand transportation procurement auction can effectively reduce uncertainties in the transport process and improve transport efficiency. For example, if the traditional transport routes are interrupted due to natural disasters or other factors, the carriers may need to pay more costs to ensure the transport services. Our proposed method has advantages in resolving uncertainties. Here are several key advantages of using CPI-based auctions in reducing transport uncertainty: i) Real-time data integration. CPI enables the seamless integration of real-time data from various sources, including traffic conditions, weather, and demand patterns. This data-driven approach allows for more accurate forecasting and dynamic adjustments in transport services, reducing uncertainty related to delays and availability. ii) Enhanced transparency. The use of CPI in auctions provides a transparent framework for pricing and service availability. Stakeholders can access real-time information about costs and service levels, which builds trust and reduces uncertainty for consumers when making transport decisions. iii) Adaptive pricing mechanisms. CPI-based auctions can implement dynamic pricing strategies that adjust in response to real-time market conditions. This flexibility helps stabilize prices during peak demand periods, reducing the unpredictability often associated with traditional pricing models. iv) Risk mitigation. By distributing risks among various stakeholders through a collaborative approach, CPI-based auctions can stabilize service offerings. Transport providers can share insights and data, leading to more robust contingency plans and reduced uncertainty in service delivery. v) Interoperability and scalability. The cyber-physical framework allows for the integration of various transport modes and services, promoting interoperability. This scalability means that as demand grows or shifts, the system can adapt without significant

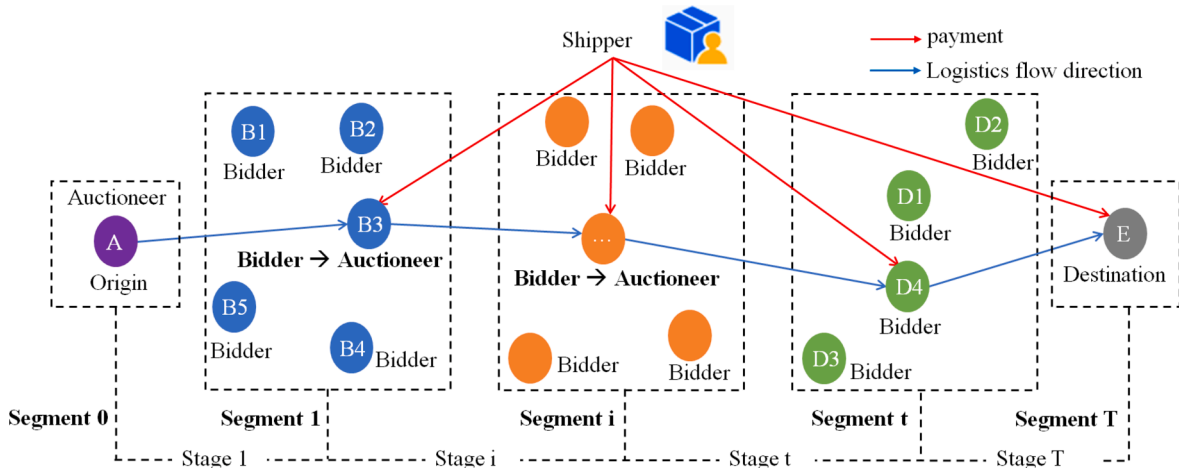


Fig. 2. Schematic of a CPI-based auction for transport services procurement.

disruptions, further reducing uncertainty.

4.2. A simple example

Consider a transport network consisting of origin A (segment 0), segment 1 (B1 and B2), segment 2 (C1 and C2) and destination D (segment 3). The four segments are divided into three stages comprising stage 1, stage 2 and stage 3. The distance-location relationship is shown in Fig. 3. There is a unit demand for transport services from origin A to destination D. The transport services from origin A to segment 1 and segment 1 to segment 2 are realized through real-time auction, while the route cost from segment 2 to destination D is given by the routing table in the CPI system.

Segment routes, real-time and estimated route costs are given in Table 1. We will use real-time truthful auctions to solve the optimal allocation and pricing problem. In the CPI-based on-demand transportation procurement auction of stage t , the overall cost includes two parts: (i) the real-time transport cost in stage t , and (ii) the real-time transport cost from the node of stage t to destination given by the routing table. For example, the total cost in stage 1 is given by one of the following two expressions

$$c_{A-B1-D} = v_{A-B1}d_{A-B1} + s_{B1-D} \quad (1)$$

$$c_{A-B2-D} = v_{A-B2}d_{A-B2} + s_{B2-D} \quad (2)$$

where $s_{B1-D} = 25.4$ and $s_{B2-D} = 26.5$ are determined by the cost routing table in the CPI system. Thus, c_{A-B1-D} and c_{A-B2-D} are given by

$$c_{A-B1-D} = v_{A-B1}d_{A-B1} + s_{B1-D} = 3 \times 3 + 25.4 = 34.4 \quad (3)$$

$$c_{A-B2-D} = v_{A-B2}d_{A-B2} + s_{B2-D} = 2.5 \times 5 + 26.5 = 39 \quad (4)$$

The bidder associated with the smallest value between c_{A-B1-D} and c_{A-B2-D} is selected as the winner, i.e., $\min\{c_{A-B1-D}, c_{A-B2-D}\} = 34.4$. Thus, in the first-stage auction, bidder B1 becomes the winner. According to the VCG-like payment rule, the price (p_{B1}) that the shipper pays to the bidder B1 is given by

$$p_{B1} = v_{A-B1}d_{A-B1} + (c_{A-B2-D} - c_{A-B1-D}) = 9 + (39 - 34.4) = 13.6 \quad (5)$$

where $(c_{A-B2-D} - c_{A-B1-D})$ represents bidder B1's marginal contribution to the system, or equivalently his profit.

Next, the route A-B2 is eliminated and node B1 becomes the auctioneer. In the second stage, the route costs $c_{B1-C1-D}$ and $c_{B1-C2-D}$ can be obtained as

$$c_{B1-C1-D} = v_{B1-C1}d_{B1-C1} + s_{C1-D} = 2.1 \times 7 + 10 = 24.7 \quad (6)$$

$$c_{B1-C2-D} = v_{B1-C2}d_{B1-C2} + s_{C2-D} = 2 \times 8 + 12 = 28 \quad (7)$$

Likewise, the route B1-C2 is eliminated and node C1 becomes the winner, and the price (p_{C1}) is

$$p_{C1} = v_{B1-C1}d_{B1-C1} + (c_{B1-C2-D} - c_{B1-C1-D}) = 2.1 \times 7 + (28 - 24.7) = 18 \quad (8)$$

In the last stage, the route can be determined directly. The shipper needs to pay the carrier (say D) a price of $p_D = (1 + \lambda)s_{C1-D}$, where $s_{C1-D} = 10$ denotes the cost in the routing table and λ denotes the profitability of the route. In this example, it is assumed that λ takes the value of 20 %. Then, the total amount paid by the shipper is $p_{B1} + p_{C1} + p_D = 13.6 + 18 + 12 = 43.6$, and the optimal route is $A \rightarrow B1 \rightarrow C1 \rightarrow D$.

In this example, the route costs and winning segment routes are given in Fig. 4. The red line in Fig. 4 represents the final transport route and the numbers on the lines represent the route costs. For example, in the first stage, nodes B1 and B2 bid (and tells the truth), while the costs of route B1-D and B2-D are estimated by the CPI system. Due to overall cost minimization, node B1 wins. Then, node

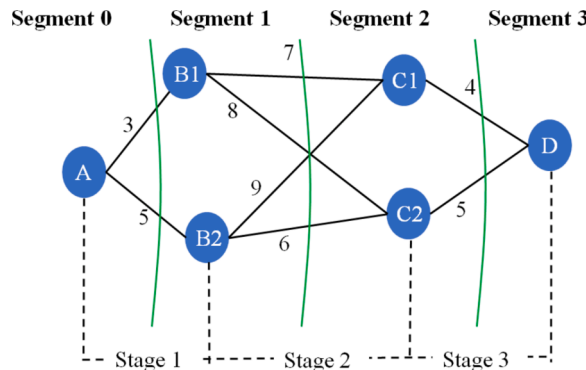


Fig. 3. Location distance schematic.

Table 1

Segment routes, real-time and total route costs.

Stage	Segment route	Real-time cost per unit distance (v) in stage i	Distance (d)	Segment route	Total cost (s) from a node in stage t to destination
Stage 1	A $\rightarrow$ B1	3	3	B1 $\rightarrow$ D	25.4
	A $\rightarrow$ B2	2.5	5	B2 $\rightarrow$ D	26.5
Stage 2	B1 $\rightarrow$ C1	2.1	7	C1 $\rightarrow$ D	10
	B1 $\rightarrow$ C2	2	8	C2 $\rightarrow$ D	12
Stage 3	—	—	4	C1 $\rightarrow$ D	10
	—	—	5	C2 $\rightarrow$ D	12

B2 and the routes associated with B2 are removed.

5. Auction mechanisms

This section describes three auction mechanisms, SU-VCG, MU-VCG and WA-VCG, for on-demand transportation procurement in a CPI environment. Recalling the previous problem description and example, assume that there are T segments other than the origin with m_t number of nodes (routers) in segment t ($t = 1, 2, \dots, T$). The symbols are described as shown in Table 2.

5.1. Single-unit VCG auction

This section provides a detailed description of the model construction, mechanism design, properties of SU-VCG auction.

5.1.1. Model

Consider an on-demand transportation service procurement network consisting of a shipper, multiple carriers and a third-party auction platform, and each carrier wants to qualify for transport services. Here, it is assumed that the shipper's transport demand is one unit, and auctions are used to achieve optimal transport within the first t stages, while in the $(t+1)th$ stage it is given directly by the system based on the routing table. Each carrier's unit transport cost valuation is its private information. In this paper, we design a novel mechanism to ensure that each carrier bids truthfully. The platform collects information about the carriers (bids) and performs transport allocation. Since there are multiple stages of transport service auctions involved, it is only possible to move to the next stage of the auction after the previous stage has been completed. In the winner-determination model, the platform minimizes costs through CPI-based on-demand auctions. Each carrier submits a set of bids. Here, we need to make it clear that if we want to determine the

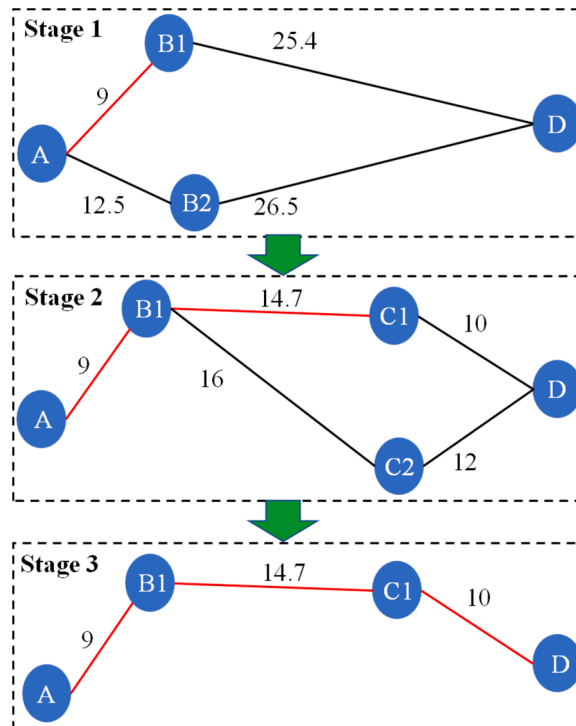


Fig. 4. Schematic of the operation of stage real-time auction.

Table 2
Symbolic parameters in the SU-VCG auction.

Parameters	Description
t	Index of stages, $t = 1, 2, \dots, T$, in this paper, we assume that stage t and segment t are of the same sign.
m_t	Set of the number of nodes (routers) in segment t , $t \in T$.
M	Set of the number of nodes in the remaining segments other than the destination segment, $M = \{m_1, m_t, \dots, m_T\}$, $m_0 = 1, m_T = 1$, $m_t > 1$.
j, k	Index of nodes (routers) in the segment t , $j, k \in M$.
$v_{jk}(t)$	Denotes the unit distance reservation value from node j in segment $t-1$ to node k in segment t , $j, k \in M$.
$\tilde{v}_{jk}(t)$	Denotes the bid price per unit distance from node j in segment $t-1$ to node k in segment t , $j, k \in M$.
$d_{jk}(t)$	Denotes the distance from node j in segment $t-1$ to node k in segment t .
$s_k(t)$	Denotes the route cost from node k in segment t to the destination, $k \in m_t$.
$x_{jk}(t)$	0–1 variable, $x_{jk}(t) = 1$ means that the route from node j in segment $t-1$ to node k in segment t is selected, otherwise, $x_{jk}(t) = 0$, $j, k \in M$.
$x_k(t)$	0–1 variable, $x_k(t) = 1$ means that the route from node k in segment t to the destination in stage t is selected, otherwise, $x_k(t) = 0$.

winning segmentation route for stage t by the following model, it implies that the winning node has already been determined in stage $t-1$. Thus, the cost minimization $W(t, M)$ model for stage t is given as follows:

$$P1 : W(t, M) = \min \left\{ \sum_{k \in M} \tilde{v}_{jk}(t) x_{jk}(t) d_{jk}(t) + s_k(t) x_k(t) \right\} \quad (9)$$

$$\text{s.t. } \sum_{k \in M} x_{jk}(t) = 1 \quad (10)$$

$$x_{jk}(t), x_k(t) \in \{0, 1\}, k \in m_t \quad (11)$$

The objective function (9) represents the minimum cost of segment $t-1$ to the destination in stage t . In model **P1**, we assume that node j in segment $t-1$ is the winner of the previous stage $t-1$. It is worth mentioning that due to the specificity of the problem, segment t and stage t are numerically equal in this paper. For example, if we require the winning node in stage 3, i.e., $t = 3$, $k \in m_3$. Thus, if not otherwise specified, segment and stage (t) can be considered the same in the formulas throughout this paper. Constraint (10) denotes that only one route can be chosen from node j in segment $t-1$ to node k in segment t in stage t .

5.1.2. Mechanism

We now describe the process of the proposed SU-VCG auction. The platform collects the distance information of the routes for stage t , and then all nodes $j(j \in \{m_1, m_t, \dots, m_T\})$ (carriers) in segment $t(t = 1, 2, \dots, T)$ submit their unit transport costs for the routes $\tilde{v}_{jk}(t)$. The platform computes the minimized transport costs based on the model **P1** to determine winner, and an efficient mechanism is designed to ensure that the transport routes obtained by the model **P1** are a set of efficient allocations and that the shippers are required to pay the following payments to the winning carriers.

In the first stage, if node $j(j \in m_1)$ in segment 1 wins, then the price $p_{1j}(1)$ that the shipper needs to pay the carrier from the origin 0 to node $j(j \in m_1)$ in segment 1 in stage 1 is

$$p_{1j}(1) = \tilde{v}_{1j}(1) \times d_{1j}(1) + [W(1, M \setminus \{j\}) - W(1, M)], j \in m_1 \quad (12)$$

where $W(1, M \setminus \{j\})$ denotes the function value of the model **P1** if node j in segment 1 in stage 1 is eliminated. Thus, $W(1, M \setminus \{j\}) - W(1, M)$ denotes the benefit that node j in segment 1 brings to the system, i.e., it denotes the cost incentive compensation that the carrier of node j should receive.

Once the winner is identified in the first stage of the auction, then the shipper's shipment will be transported from the origin 0 to node j in segment 1, and the other nodes in segment 1 will be removed, so node j in segment 1 will become the auctioneer and all the nodes in segment 2 (carriers) will become the bidders. If node $k(k \in m_2)$ in segment 2 becomes the winner, then the amount $p_{jk}(2)$ to be paid by the shipper to node k (carrier) in segment 2 in the second stage is

$$p_{jk}(2) = \tilde{v}_{jk}(2) d_{jk}(2) + [W(2, M \setminus \{k\}) - W(2, M)], k \in m_2 \quad (13)$$

where $W(2, M \setminus \{k\})$ denotes the function value of the model **P1** if node k in segment 2 in stage 2 is eliminated. Thus, $W(2, M \setminus \{k\}) - W(2, M)$ denotes the benefit that node k in segment 2 in stage 2 brings to the system, i.e., it denotes the cost incentive compensation that the carrier of node k should receive.

Assume that node j in segment $t-1$ in stage $t-1$ wins, then the other nodes in segment $t-1$ are removed, at which node j in segment $t-1$ in stage t becomes auctioneer and all nodes in segment t become bidders, and if node k in segment t in stage t wins, then the price that the shipper needs to pay to node k (carrier) in segment t in stage t is

$$p_{jk}(t) = \tilde{v}_{jk}(t) d_{jk}(t) + [W(t, M \setminus \{k\}) - W(t, M)], k \in m_t, t = 1, 2, \dots, T \quad (14)$$

Obviously, the total amount to be paid by the shipper to the carrier consists of the first t stages of the auction and the amount to be paid in the $t+1$ stage, so that the total amount p is

$$p = \sum_{j \in m_{t-1}} \sum_{k \in m_t} \sum_{t \in T} p_{jk}(t) + s_k(t+1)(1+\lambda), t = 1, 2, \dots, T \quad (15)$$

where $s_k(t+1)$ denotes the route cost from node k in segment t directly to the destination. It is worth noting that the reason why shippers choose the CPI-based SU-VCG auction method proposed in this paper for optimal transport is due to the advantages of the proposed method in resolving uncertainty and costs. Indeed, in the transportation of freight, the reservation value set by the shipper is usually the maximum shipping cost they are willing to pay. This reservation value helps shippers control their budgets and ensures that the cost of transport is not more than they can afford. This practice is common in the logistics and transport industry and helps to make cost management more efficient. Shippers can set this reservation value based on market conditions, distance travelled, type of shipment, etc. so that they have a clear upper limit when it comes to auctions. This will avoid financial losses due to excessive costs. Let TC denote the reservation value of the shipper's payment. If $p \leq TC$, then the transaction succeeds, otherwise, the transaction fails. Thus, the CPI-based SU-VCG auction process is presented as follows:

- Step 1.** Collect distances d_{jk} from node j in segment 0 (origin) to node k in segment 1.
- Step 2.** Collect carrier bids $\tilde{v}_{jk}(t)$ from node j in segment 0 (origin) to node k in segment 1 in the stage 1.
- Step 3.** Collect the route cost s_k between node k in segment 1 in stage 1 to the destination.
- Step 4.** Determine the transport routes and winning nodes in stage 1 according to model P1.
- Step 5.** Calculate the price $p_{jk}(t)$ that the shipper needs to pay to node k (carrier) in segment 1 in stage 1 by using Eq. (14).
- Step 6.** Repeat steps 1–5 to find the winning node and the price paid by the shipper for the remaining stages in turn.
- Step 7.** Calculate the total amount p that the shipper needs to pay to the all carriers by using Eq. (15).
- Step 8.** Compare the size of values p and TC . If $p \leq TC$, trade, otherwise, the auction fails.

5.1.3. Properties

Proposition 1. In CPI-based SU-VCG auction, truthful bidding is the carrier's dominant strategy in any stage t .

Proof.. Suppose that all carriers truthfully submit their bids. If carrier k in stage t submits his/her true valuation $\tilde{v}_{jk}(t)$, s/he is supposed to receive payment $p_{jk}(t) = \tilde{v}_{jk}(t)d_{jk}(t) + [W(t, M\{k\}) - W(t, M)]$. This means that his/her net payoff will be $W(t, M\{k\}) - W(t, M)$. If s/he bids $\tilde{v}'_{jk}(t) \neq \tilde{v}_{jk}(t)$, then s/he will receive payment $p'_{jk}(t) = \tilde{v}'_{jk}(t)d_{jk}(t) + [W(t, M\{k\}) - W(t, M)]$, where k represents the node assigned to the carrier in that case, and

$$W(t, M) = \tilde{v}_{jk}(t)d_{jk}(t) + s_k(t) + \sum_{i \in M \setminus \{k\}} \left(\tilde{v}_{ji}(t)d_{ji}(t)x'_{ji}(t) + s_i(t)x'_i(t) \right) \quad (16)$$

$W(t, M)$ is the result welfare. Here, $x'_{ji}(t)$ and $x'_i(t)$ denote the optimal solution to $W(t, M)$. Is carrier k in stage t better off by submitting this bid? Suppose s/he does. Then, we must have

$$p'_{jk}(t) > p_{jk}(t) = \tilde{v}_{jk}(t)d_{jk}(t) + [W(t, M\{k\}) - W(t, M)] \quad (17)$$

Substituting for $p'_{jk}(t)$ yields

$$W(t, M) > \tilde{v}_{jk}(t)d_{jk}(t) + s_k(t) + \sum_{i \in M \setminus \{k\}} \left(\tilde{v}_{ji}(t)d_{ji}(t)x'_{ji}(t) + s_i(t)x'_i(t) \right) \quad (18)$$

Obviously, this contradicts the fact that $W(t, M)$ represents an efficient allocation. Finally, the same argument can easily be made for any carries in M . Thus, the proposed CPI-based SU-VCG auction mechanism is incentive compatible.

If a carrier becomes a winner by misrepresenting the bid price, s/he may face a scenario of negative net profit. In this paper, we use a simple example to illustrate a scenario where a carrier does not bid truthfully and may have a negative net profit. Table 3 gives the nodes and the routing tables of the corresponding nodes for any of the stages. For example, node B2 will not be the winner if s/he bids truthfully. Since node B1 has the smallest route cost, i.e., $\min\{4 \times 3 + 12, 4.5 \times 2.8 + 12.6, 3.5 \times 4 + 14\} = 24$. If the carrier at node B2 changes the reservation price of 4.5 to 4 to bid in order to be a winner, then B2 will be the winner because $\min\{4 \times 3 + 12, 4 \times 2.8 + 12.6, 3.5 \times 4 + 14\} = 23.8$. However, the carrier's true cost is $4.5 \times 2.8 = 12.6$, and the payment that the carrier at node B2 will receive is $4 \times 2.8 + (24 - 23.8) = 11.4$. Obviously, the carrier receives a net profit of $11.4 - 12.6 = -1.2$. Such result shows that carrier k in stage t does not receive a better payment than the true bid.

Taking the above analyses into account, the carrier does not get better results by misrepresenting the bid value, so as a rational

Table 3

A simple example of a misrepresented bid illustrates.

Stage	Segment route	Reservation costs/ Bidding	Distance	Segment route	Route cost from node j in segment t in stage t to the destination
Stage t	A → B1	4/4	3	B1 → D	12
	A → B2	4.5/4	2.8	B2 → D	12.6
	A → B3	3.5/3.5	4	B3 → D	13

bidder; truthful bidding is the optimal strategy for all carriers. Thus, the proposed CPI-based SU-VCG auction mechanism is incentive compatible.

Assumption 1. The CPI system selects the carrier with the earliest bid as the winner if there are simultaneously $f(f < m_t)$ nodes of segment t in stage t such that the optimal function values $W(t, M)$ are equal. Then the platform eliminates the nodes $f(f < m_t)$ whose optimal value is $W(t, M)$ and recalculates the optimal value after proposing the nodes $f(f < m_t)$. Furthermore, it is assumed in this paper that all nodes in segment t at stage t cannot simultaneously satisfy model P1.

Assumption 2.. For any winning carrier, as long as the payment received is greater than the bid submitted, then the carrier will participate in the bidding. Indeed, this assumption is realistic, because as long as the carrier can be a winner, s/he will always realize a positive return. Under this premise, most carriers tend to participate in the platform.

Proposition 2. The proposed CPI-based SU-VCG mechanism is individually rational provided that assumptions 1 and 2 hold.

Proof.. In the SU-VCG mechanism proposed in this paper, the carrier maximizes his/her utility by bidding truthfully. Assume that node k (carrier) in segment t wins in stage t , then his/her expected payment is $p_{jk}(t) = \tilde{v}_{jk}(t)d_{jk}(t) + [W(t, M \setminus \{k\}) - W(t, M)]$. $\tilde{v}_{jk}(t)d_{jk}(t)$ is the route cost of carrier k (carrier) in segment t , while $W(t, M \setminus \{k\}) - W(t, M)$ is the net profit that carrier k (carrier) in segment t earns in stage t . Apparently, $W(t, M \setminus \{k\}) - W(t, M) \geq 0$ holds. Indeed, if $W(t, M \setminus \{k\}) - W(t, M) = 0$ holds, there is no incentive for the winning carrier, as s/he receives zero net profit. Since assumption 1 holds, scenario $W(t, M \setminus \{k\}) - W(t, M) = 0$ is not possible. Thus, there is always a positive return for the winning carrier. Then, under the condition that assumption 2 holds, the carrier k chooses to participate in the auction, which implies that the CPI-based on-demand transportation procurement auction mechanism proposed herein is individually rational.

Proposition 3. The proposed CPI-based SU-VCG mechanism is budget balance.

Proof. In the proposed CPI-based SU-VCG auction, only the winning carrier receives the payment. If $p \leq TC$ is satisfied, then the auctioneer will pay a payment of $p_{jk}(t)$ to the winning carrier at node k in segment t in stage t . Conversely, if $p > TC$ holds, then the transaction fails. It is clear that if the transaction succeeds, then it means that the system receives a payment from the shipper equal to the payment to the carriers. Thus, the proposed CPI-based SU-VCG mechanism is budget balance.

5.2. Multi-unit VCG auction

In the proposed SU-VCG auction, it is assumed that only one carrier exists at node j within any segment other than origin and destination to provide transport services, i.e., in the auction, it is necessary to determine the winner in each stage. In the next model presentation, we assume that there are multiple carriers providing transport services at node j within any segment other than origin and destination, i.e., there are multiple carriers participating in the auction for the same route, which is referred to as the MU-VCG auction in this paper.

5.2.1. Model

Without loss of generality, we assume that $v_{jkr}(t)$ Denotes the unit distance reservation value of carrier r from node j in segment $t-1$ to node k in segment t in stage t , $x_{jkr}(t) = 1$ means that the carrier r from node j in segment $t-1$ to node k in segment t in stage t is selected, otherwise, $x_{jkr}(t) = 0$. q_t^k denotes the set of the number of carriers at node k in segment t , and Q denotes the set of the number of carriers at node in the remaining segments other than the destination segment, $q_t^k \in Q$. Thus, the MU-VCG model constructed in this paper is as follows:

$$P2 : W(t, Q) = \min \left\{ \sum_{k' \in Q} \tilde{v}_{jkr}(t) x_{jkr}(t) d_{jkr}(t) + s_{kr}(t) x_{kr}(t) \right\} \quad (19)$$

$$\text{s.t. } \sum_{k' \in Q} x_{jkr}(t) = 1 \quad (20)$$

$$x_{jkr}(t), x_{kr}(t) \in \{0, 1\} \quad (21)$$

Eq. (19) denotes the minimum cost of segment $t-1$ to the destination in stage t . We assume that node j in segment $t-1$ is the winner of the previous stage $t-1$ in model P2. Constraint (20) denotes that only one carrier from node j to node k in stage t can be qualified for

Table 4
Example of using SU-VCG trade mechanism in MU-VCG auction.

Stage	Segment route	Carriers (r)	Reservation costs/ Bidding	Distance (d)	Segment route	Total cost from a node in stage t to destination
Stage t	A $\rightarrow$ B1	1	2.5/2.5	3	B1 $\rightarrow$ D	25.4
		2	3.5/3.5			
		3	3/2.4			
	A $\rightarrow$ B2	1	2.5/2.5	5	B2 $\rightarrow$ D	26.5
		2	2.4/2.4			

transport.

Observation 1: If the SU-VCG mechanism continues to be used in the MU-VCG mechanism, truthful bidding will no longer be the optimal strategy for carriers.

We use a simple example to illustrate **Observation 1**, and the data information is shown in Table 4. Suppose that in stage t there are carriers 1, 2, and 3 in node B1 and carriers 1 and 2 in node B2 participating in the bidding, and that carrier 3 in node B1 bids untruthfully while the other participants bid truthfully. If the SU-VCG mechanism is followed, then carrier 3 in node B1 will win and receive a payment of $p_{B1(3)} = 2.4 \times 3 + (38.5 - 32.6) = 13.1$ and utility 5.9. Therefore, the use of the SU-VCG mechanism in the MU-VCG auction clearly fails to achieve incentive compatibility.

5.2.2. An example

Definition 1. In MU-VCG auctions, second price auctions can be used to achieve incentive compatibility, individual rationality, and budget balance. In stage t , the winning carrier is obtained by model P2, however, the winning carrier is eliminated, the optimal value is obtained again by model P2, and the difference between the optimal values obtained by model P2 twice is the amount to be paid by the carrier.

We use a simple numerical example to illustrate the proposed MU-VCG method. Again using Fig. 3 as an example, assume that nodes B1, B2, C1, and C2 have 3, 2, 3, and 2 carriers participating in the bidding process, respectively, and their bidding price information is shown in Table 5.

In the first stage, the minimum value of the total route cost for all carriers bidding in nodes B1 and B2, respectively, is calculated as follows:

$$\text{minc}_{A-B1-D} = \begin{cases} v_{A-B1(1)}d_{A-B1} + s_{B1-D} = 2.5 \times 3 + 25.4 = 32.9 \\ v_{A-B1(2)}d_{A-B1} + s_{B1-D} = 3.5 \times 3 + 25.4 = 35.9 \\ v_{A-B1(3)}d_{A-B1} + s_{B1-D} = 3 \times 3 + 25.4 = 34.4 \end{cases} = 32.9 \quad (22)$$

$$\text{minc}_{A-B2-D} = \begin{cases} v_{A-B2(1)}d_{A-B1} + s_{B1-D} = 2.5 \times 5 + 26.5 = 39 \\ v_{A-B2(2)}d_{A-B1} + s_{B1-D} = 2.4 \times 5 + 26.5 = 38.5 \end{cases} = 38.5 \quad (23)$$

From the minimization of the total route cost of all it can be determined which carrier in a node wins, i.e. $\min\{c_{A-B1-D}, c_{A-B2-D}\} = \min(32.9, 38.5) = 32.9$, which indicates that the carrier 1 in node B1 wins. Therefore, according to the VCG-like payment rule, the price ($p_{B1(1)}$) that the shipper pays to the carrier 1 is given by

$$p_{B1(1)} = v_{A-B1(1)}d_{A-B1} + (\text{minc}_{A-B-D(\setminus 1)} - \text{minc}_{A-B-D}) = 2.5 \times 3 + (34.4 - 32.9) = 9 \quad (24)$$

where $\text{minc}_{A-B-D(\setminus 1)}$ denotes the minimum value of model P2 after excluding carrier 1 in node B1. Next, the route $A-B2$ is eliminated and node B1 becomes the auctioneer, and carrier 1 in node B1 will be responsible for the transport of the segmented route $A-B1$, the. In stage 2, the route costs $c_{B1-C1-D}$ and $c_{B1-C2-D}$ can be obtained as

$$\text{minc}_{B1-C1-D} = \begin{cases} v_{B1-C1(1)}d_{B1-C1} + s_{B1-D} = 2.1 \times 7 + 10 = 24.7 \\ v_{B1-C1(2)}d_{B1-C1} + s_{B1-D} = 2.3 \times 7 + 10 = 26.1 \\ v_{B1-C1(3)}d_{B1-C1} + s_{B1-D} = 2 \times 7 + 10 = 24 \end{cases} = 24 \quad (25)$$

$$\text{minc}_{B1-C2-D} = \begin{cases} v_{B1-C2(1)}d_{B1-C2} + s_{B2-D} = 2 \times 8 + 12 = 28 \\ v_{B1-C2(2)}d_{B1-C2} + s_{B2-D} = 1.9 \times 8 + 12 = 27.2 \end{cases} = 27.2 \quad (26)$$

Likewise, the route $B1-C2$ is eliminated and the carrier 3 in node C1 becomes the winner, and the price ($p_{C1(3)}$) is

$$p_{C1(3)} = v_{B1-C1(3)}d_{B1-C1} + (\text{minc}_{B1-C-D(\setminus 3)} - \text{minc}_{B1-C-D}) = 2 \times 7 + (24.7 - 24) = 14.7 \quad (27)$$

The price of the last stage is similar to the SU-VCG mechanism. Thus, the optimal transport route in this example is

Table 5
MU-VCG mechanism example information.

Stage	Segment route	Carriers (r)	Real-time cost per unit distance (v) in stage t	Distance (d)	Segment route	Total cost from a node in stage t to destination
Stage 1	A → B1	1	2.5	3	B1 → D	25.4
		2	3.5			
		3	3			
	A → B2	1	2.5	5	B2 → D	26.5
		2	2.4			
		3	2.3			
Stage 2	B1 → C1	1	2.1	7	C1 → D	10
		2	2.3			
		3	2			
	B1 → C2	1	2	8	C2 → D	12
		2	1.9			
		3	1.9			
Stage 3	—	—	—	4	C1 → D	10
		—	—	5	C2 → D	12

$A \rightarrow B1(1) \rightarrow C1(3) \rightarrow D$, where $B1(1)$ and $C1(3)$ denote the carrier 1 and carrier 3 in nodes $B1$ and $C1$, respectively.

5.2.3. Properties

Proposition 4. In CPI-based MU-VCG auction, truthful bidding is the carrier's dominant strategy in any stage t .

Proof. Suppose that all carriers truthfully submit their bids. If carrier r at node k in stage t submits his/her true valuation $\tilde{v}_{jk^r}(t)$, s/he is supposed to receive payment $p_{jk^r}(t) = \tilde{v}_{jk^r}(t)d_{jk^r}(t) + [W(t, Q \setminus \{k^r\}) - W(t, Q)]$. This means that his/her net payoff will be $W(t, Q \setminus \{k^r\}) - W(t, Q)$. If s/he bids $\tilde{v}_{jk^r}(t) \neq \tilde{v}_{jk^r}(t)$, then s/he will receive payment $p'_{jk^r}(t) = \tilde{v}_{jk^r}(t)d_{jk^r}(t) + [W(t, Q \setminus \{k^r\}) - W'(t, Q)]$, where k represents the node assigned to the carrier in that case, and

$$W'(t, Q) = \tilde{v}_{jk^r}(t)d_{jk^r}(t) + s_{k^r}(t) + \sum_{i^r \in Q \setminus \{k^r\}} \left(\tilde{v}_{ji^r}(t)d_{ji^r}(t)x'_{ji^r}(t) + s_{i^r}(t)x'_{i^r}(t) \right) \quad (28)$$

$W(t, Q)$ is the result welfare. Here, $x'_{ji^r}(t)$ and $x'_{i^r}(t)$ denote the optimal solution to $W'(t, Q)$. Is carrier r at node k in stage t better off by submitting this bid? Suppose s/he does. Then, we must have

$$p'_{jk^r}(t) > \tilde{v}_{jk^r}(t)d_{jk^r}(t) + [W(t, Q \setminus \{k^r\}) - W(t, Q)] \quad (29)$$

Substituting for $p'_{jk^r}(t)$ yields

$$W(t, Q) > \tilde{v}_{jk^r}(t)d_{jk^r}(t) + s_{k^r}(t) + \sum_{i^r \in Q \setminus \{k^r\}} \left(\tilde{v}_{ji^r}(t)d_{ji^r}(t)x'_{ji^r}(t) + s_{i^r}(t)x'_{i^r}(t) \right) \quad (30)$$

Obviously, this contradicts the fact that $W(t, Q)$ represents an efficient allocation. Finally, the same argument can easily be made for any carries in Q . Thus, the proposed CPI-based MU-VCG auction mechanism is incentive compatible.

Proposition 5. The proposed CPI-based MU-VCG mechanism is individually rational.

Proof.. In the MU-VCG mechanism, the carrier maximizes his/her utility by bidding truthfully. Assume that carrier r at node k in segment t wins in stage t , then his/her expected receive payment is $p_{jk^r}(t) = \tilde{v}_{jk^r}(t)d_{jk^r}(t) + [W(t, Q \setminus \{k^r\}) - W(t, Q)]$. $\tilde{v}_{jk^r}(t)d_{jk^r}(t)$ is the route cost of carrier r at node k in segment t , while $W(t, Q \setminus \{k^r\}) - W(t, Q)$ is the net profit that carrier r at node k in segment t earns in stage t . Apparently, $W(t, Q \setminus \{k^r\}) - W(t, Q) \geq 0$ holds. Thus, there is always a positive return for the winning carrier, which implies that the CPI-based on-demand transportation procurement auction mechanism proposed herein is individually rational.

5.3. Weighted affine VCG auction

In this section, a novel auction mechanism is proposed by considering the weighting problem of each transport route in a CPI environment.

5.3.1. Model

In practice, since there may be differences in the transport timescale of each route, each feasible route should be given a different weight (e.g., routes with short transport timescales are given a smaller weight, while those with longer transport timescales are given a larger weight), assuming that node k in segment t in stage t corresponds to a weight of $\lambda_k(t)$. In addition, it is assumed that each node k in stage t has an affine externality to the other nodes, which is defined as $\rho_k(t)$ in this paper. The benchmark model of the WA-VCG auction proposed in this paper is as follows:

$$\mathbf{P3} : \pi(t, \mathbf{M}) = \min \sum_{k \in \mathbf{M}} \lambda_k(t) \left[\tilde{v}_{jk}(t)x_{jk}(t)d_{jk}(t) + s_k(t)x_k(t) \right] + \rho_k(t) \quad (31)$$

s.t. (10) – (11)

$$\lambda_k(t) > 0, \rho_k(t) \in \mathbb{R}$$

Model **P3** gives the optimal route, assuming that the value of model **P3** is $\pi(t, \mathbf{M})$, while $\pi(t, \mathbf{M} \setminus \{k\})$ denotes the value after excluding node k from the model. If node k in segment t in stage t wins, then the payment $p_k(t)$ s/he should receive can be determined by the following equation

$$p_k(t) = \frac{1}{\lambda_k(t)} \left\{ \lambda_k(t)\tilde{v}_{jk}(t)d_{jk}(t) + \rho_k(t) - [\pi(t, \mathbf{M}) - \pi(t, \mathbf{M} \setminus \{k\})] \right\} \quad (32)$$

Eq. (32) can be simplified to $p_k(t) = \tilde{v}_{jk}(t)d_{jk}(t) + \frac{\rho_k(t) - [\pi(t, \mathbf{M}) - \pi(t, \mathbf{M} \setminus \{k\})]}{\lambda_k(t)}$, then the utility $u_k(t)$ of the carrier at node k in stage t is

$$u_k(t) = p_k(t) - \tilde{v}_{jk}(t)d_{jk}(t) = \frac{\rho_k(t) + \pi(t, \mathbf{M} \setminus \{k\}) - \pi(t, \mathbf{M})}{\lambda_k(t)} \quad (33)$$

5.3.2. An example

We apply a simple numerical example to illustrate the proposed WA-VCG mechanism. Assume that there is a determination of the optimal route from three nodes B1, B2, and B3 in stage t . The corresponding information is shown in Table 6. Substituting the data in Table 6 into model P3 yields the optimal value of $\pi(t, M) = \min(0.88 \times (2 \times 2 + 3) + 2, 1.1 \times (2 \times 2 + 2) + 3, 0.76 \times (2.5 \times 2 + 5) + 1) = 8.16$, and node B1 wins. Node B1 is eliminated and the optimal value obtained through model P3 is $\pi(t, M \setminus \{B1\}) = \min(1.1 \times (2 \times 2 + 2) + 3, 0.76 \times (2.5 \times 2 + 5) + 1) = 8.6$. Thus, the node B1 receives payment $p_{B1}(t) = 2 \times 2 + 3 + \frac{2+8.6-8.16}{0.88} = 9.77$, and the utility $u_{B1}(t)$ of the carrier at node k^i in stage t is $u_{B1}(t) = \frac{2+8.6-8.16}{0.88} = 2.77$.

5.3.3. Properties

Proposition 6. In the proposed WA-VCG mechanism, bidding truthfully in any stage t is the carrier's optimal strategy.

Proof. Suppose that all carriers truthfully submit their bids. If carrier k in stage t submits his/her true valuation $\tilde{v}_{jk}(t)$, s/he is supposed to pay $\tilde{p}_{jk}(t) = \tilde{v}_{jk}(t)d_{jk}(t) + \frac{\rho_k(t) + \pi(t, M \setminus \{k\}) - \pi(t, M)}{\lambda_k(t)}$. This means that the utility of node k is $\tilde{u}_k(t) = \rho_k(t) + \pi(t, M \setminus \{k\}) - \tilde{\pi}(t, M)\lambda_k(t)$, and

$$\tilde{\pi}(t, M) = \sum_{k \in M} \left\{ \lambda_k(t) \left[\tilde{v}_{jk}(t)d_{jk}(t)x_{jk}(t) + s_k(t)x_k(t) \right] + \rho_k(t) \right\} \quad (34)$$

is the result welfare. If s/he bids $\tilde{v}_{jk} \neq \tilde{v}_{jk}$, then s/he has to pay

$$\tilde{p}_{ji}(t) = \tilde{v}_{ji}(t)d_{ji}(t) + \frac{\rho_i(t) + \pi(t, M \setminus \{i\}) - \tilde{\pi}'(t, M)}{\lambda_i(t)} \quad (35)$$

where i represents the node assigned to the carrier in that case, and

$$\tilde{\pi}'(t, M) = \lambda_i(t) [\tilde{v}_{ji}(t)d_{ji}(t) + s_i(t)] + \rho_i(t) + \sum_{k \in M \setminus \{i\}} \left\{ \lambda_k(t) \left[\tilde{v}_{jk}(t)d_{jk}(t)x'_{jk}(t) + s_k(t)x'_k(t) \right] + \rho_k(t) \right\} \quad (36)$$

is the result welfare. Here, $x'_{jk}(t)$ and $x'_k(t)$ denote the optimal solution to $\tilde{\pi}'(t, M)$. Is carrier j better off by submitting this bid? Suppose s/he does. Then, we must have

$$\tilde{p}_{ji}(t) > \tilde{p}_{jk}(t) = \tilde{v}_{jk}(t)d_{jk}(t) + \frac{\rho_j(t) + \pi(t, M \setminus \{j\}) - \tilde{\pi}(t, M)}{\lambda_j(t)} \quad (37)$$

Substituting for $\tilde{p}_{ji}(t)$ yields

$$\tilde{\pi}(t, M) > \lambda_i(t) [\tilde{v}_{ji}(t)d_{ji}(t) + s_i(t)] + \rho_i(t) + \sum_{k \in M \setminus \{i\}} \left\{ \lambda_k(t) \left[\tilde{v}_{jk}(t)d_{jk}(t)x'_{jk}(t) + s_k(t)x'_k(t) \right] + \rho_k(t) \right\} \quad (38)$$

Obviously, this contradicts the fact that $\tilde{\pi}(t, M)$ represents an efficient allocation. Finally, the same argument can easily be made for any carries in M . Thus, the proposed CPI-based WA-VCG auction mechanism is incentive compatible. Therefore, Proposition 6 is proved.

Proposition 7. The proposed CPI-based WA-VCG mechanism is individually rational and budget balance.

Proof.. In the proposed WA-VCG mechanism, if the carrier at node k wins, then s/he should receive a payment of $p_k(t) = v_{jk}(t)d_{jk}(t) + \frac{\rho_k(t) + \pi(t, M \setminus \{k\}) - \pi(t, M)}{\lambda_k(t)}$, as well as a utility of $u_k(t) = \frac{\rho_k(t) + \pi(t, M \setminus \{k\}) - \pi(t, M)}{\lambda_k(t)}$. Obviously, $u_k(t) \geq 0$ holds, which shows that as long as the carrier bids truthfully and becomes the winner, then s/he will always receive non-negative utility. Therefore, the proposed WA-VCG mechanism is individually rational. Besides, only the winning carrier receives the payment $p_k(t)$. In the auction system, if the payment $p_k(t)$ is greater than the shipper's reservation, then the transaction will fail; conversely the transaction will succeed. The WA-VCG mechanism is then able to achieve budget balanced.

Corollary 1. If a note k in stage t wins and has a smaller weight, then the carrier on that route will receive a larger payment; conversely, it will receive a smaller payment.

Proof.. Assuming that node k in segment t in stage t wins, then the carrier receives a payment $p_k(t) = v_{jk}(t)d_{jk}(t) + \frac{\rho_k(t) + \pi(t, M \setminus \{k\}) - \pi(t, M)}{\lambda_k(t)}$. If $0 < \lambda_k^*(t) < \lambda_k(t)$ holds, then

Table 6

Illustration of a simple example of the WA-VCG mechanism.

Stage	Segment route	$\lambda_{k^i}(t)$	$\rho_{k^i}(t)$	$v_{j \rightarrow k^i}(t)$	$d_{j \rightarrow k^i}(t)$	Segment route	$s_{k^i}(t)$
Stage t	A $\rightarrow$ B1	0.88	2	2	2	B1 $\rightarrow$ D	3
	A $\rightarrow$ B2	1.1	3	2	2	B2 $\rightarrow$ D	2
	A $\rightarrow$ B3	0.76	1	2.5	2	B3 $\rightarrow$ D	5

$$p_k^*(t) - p_k(t) = \frac{\rho_k(t) - [\pi^*(t, \mathbf{M}) - \pi(t, \mathbf{M} \setminus \{k\})]}{\lambda_k^*(t)} - \frac{\rho_k(t) - [\pi(t, \mathbf{M}) - \pi(t, \mathbf{M} \setminus \{k\})]}{\lambda_k(t)} \quad (39)$$

Where

$$\pi^*(t, \mathbf{M}) = \lambda_k^*(t) [v_{jk}(t) d_{jk}(t) + s_k(t)] + \sum_{k \in \mathbf{M}} \rho_k(t) \quad (40)$$

$$\pi(t, \mathbf{M} \setminus \{k\}) = \lambda_l(t) [v_{jl}(t) d_{jl}(t) + s_l(t)] + \sum_{l \in \mathbf{M} \setminus \{k\}} \rho_l(t) \quad (41)$$

Eq. (39) can then be written as

$$p_k^*(t) - p_k(t) = \frac{\lambda_l(t) [v_{jl}(t) d_{jl}(t) + s_l(t)] [\lambda_k(t) - \lambda_k^*(t)]}{\lambda_k^*(t) \lambda_k(t)} > 0 \quad (42)$$

Eq. (42) shows that for the winning node k , the smaller its weight on the whole transport route, then the payment received by the carrier at that node will increase and the utility will become larger. Realistically, if a route has a stable transport timeframe with low uncertainty, then the weight of that route should be reduced. This is because the lower the weight, the easier it is for node k to win. Therefore, the carrier at node k should be given more incentives.

6. Case study

This section will further validate the effectiveness of the proposed method by using case studies to illustrate the advantages of the proposed method in dealing with multiple transport route options and reducing uncertainty.

6.1. Case description

Cross-border logistics transport includes a variety of modes such as international maritime transport, air freight, rail transport and road transport. If a shipper needs to transport a batch of cargos from a factory to a customer in another country, the process roughly consists of four stages: the first stage is from the factory to the logistics hub, which is usually the place where the cargos are loaded into the containers; the second stage is to transport the cargos from the logistics hub to the port, railway station or airport, etc. to change into the corresponding mode of transport; the third stage is to transport the cargos from the port, railway station or airport of the destination country to the logistics hub to be dismantled; and the fourth stage is to transport the cargos from the logistics center to the customer directly.

This paper uses a case study of a factory in Hefei, China that needs to deliver a shipment to a customer in Hamburg, Germany to illustrate the cross-border logistics transport process. The schematic of this transport is depicted in Fig. 5. Initially, the products are transported by trucks from the factory to various logistics hubs, where they are then loaded into containers. Subsequently, in the second stage, the goods are further transported from these logistics hubs to ports, railway stations, or airports. For instance, they may travel from the port of Shanghai to the port of Hamburg, Germany by sea, or from the Xinqiao international airport in Hefei to the

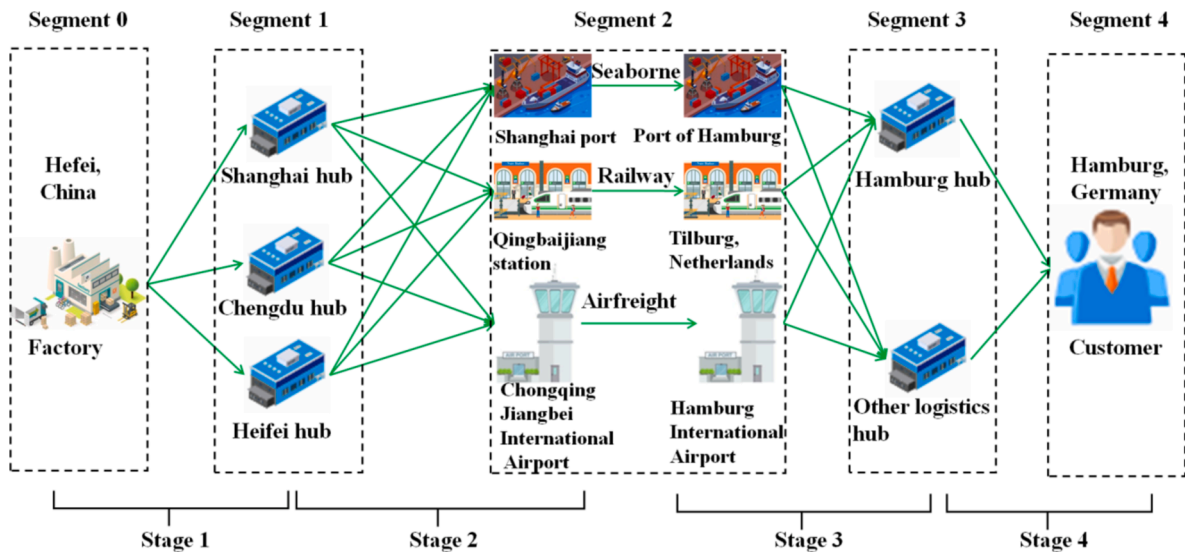


Fig. 5. Schematic diagram of multiple transport modes in cross-border logistics.

international airport of Hamburg, Germany by air, or via the China-Europe express to Tilburg in the Netherlands. In the third stage, the goods are conveyed from the ports, railway stations, or airports back to the logistics hubs for disassembly. In the last stage, the goods are delivered to the designated customers via trucks. Given that the mode of transport for stage 2—sea, air, or railway—can be predetermined, this segment will be analyzed as a single unit without factoring in the transport service auction.

6.2. Data collection and results

In this paper, the validation of the model is carried out with some of the real and hypothetical data collected. Some of the data in this paper are provided by a company engaged in cross-border logistics, and based on the information of the data provided by this company, this paper assumes that $t = 4$, $m_1 = 3$, $m_2 = 3$, $m_3 = 2$, $m_4 = 1$. In addition, the distance data are obtained based on the transport mode of the enterprise, for example, the trucking distance from the Hefei factory to the logistics centre in Shanghai is about 612 km, whereas the parameters $v_{jk}(t)$ and $s_k(t)$ are statistically counted and estimated from the historical data information of the enterprise. The distance data for each stage and the estimated cost from the corresponding node to the destination are shown in Table 7. Assume that the origins plant is denoted by A and the destinations are denoted by D. The unit transport costs in the auction are similarly estimated from the real-time data and given interval values, and the average value of unit transport costs in Table 7 is taken as the simulated value.

The numerical results obtained by substituting the data in Table 7 into model P1 are shown in Table 8. The optimal transport route is $A \rightarrow 1^1 \rightarrow 1^2 \rightarrow 2^3 \rightarrow D$, and the sum of the payments made by the shipper to the carrier is 6277.55, which does not include the transport costs in segmented 2.

6.3. Discussion

This section discusses the performance of the MU-VCG and WA-VCG mechanisms and the advantages of the proposed method.

6.3.1. Performance of the MU-VCG mechanism

In the MU-VCG mechanism, it is assumed that the number of carriers at each node is 10, 20, 30, 40 and 50 respectively and the bid values of the carriers follow a continuous uniform distribution and the data are shown in Table 7. In this paper, we analyze the effect of different number of carriers on the optimal value of model P2 and the payment received by the carriers, and the results are shown in Table 9. The results in the table show that as the number of carriers per node increases, the optimum of model P2 and the payments received by the carriers will decrease, which is consistent with the realistic scenario. This is because as the number of carriers increases and the number of winning carriers remains the same, competition increases and the difference in bid prices between carriers does not become too large, leading to the trend in Table 9. From a realistic perspective, the greater the number of carriers at each node, then the payment made by the shipper should theoretically be smaller, which is favourable to the shipper, however, as the number of carriers at each node increases, the smaller the payment received by the carrier, which may be unfavourable to the carrier. Therefore, platforms need to trade off the number of carriers to ensure that the interests of all parties are balanced.

6.3.2. Performance of the WA-VCG mechanism

In practice, cost is not the only factor in determining the choice of cross-border transport routes; transport timeliness is another key

Table 7
Basic data information.

Stage	Segment route	$v_{jk}(t)$	$d_{jk}(t)$	Segment route	$s_k(t)$	$\lambda_k(t)$
Stage 1	$A \rightarrow 1^1$	[3.8,4.2]	612	$1^1 \rightarrow D$	3145	1.21
	$A \rightarrow 2^1$	[1.5,2]	1437	$2^1 \rightarrow D$	3426	1.19
	$A \rightarrow 3^1$	[7,7.4]	125	$3^1 \rightarrow D$	5396	0.98
Stage 2	$1^1 \rightarrow 1^2$	[6,6.5]	121	$1^2 \rightarrow D$	1612	1.34
	$1^1 \rightarrow 2^2$	[0.4,0.8]	2178	$2^2 \rightarrow D$	1768	1.12
	$1^1 \rightarrow 3^2$	[0.6,0.8]	1727	$3^2 \rightarrow D$	2078	0.87
	$2^1 \rightarrow 1^2$	[0.6,0.8]	2243	$1^2 \rightarrow D$	1612	1.25
	$2^1 \rightarrow 2^2$	[5.7,6.3]	127	$2^2 \rightarrow D$	1768	1.34
	$2^1 \rightarrow 3^2$	[2.4,3]	352	$3^2 \rightarrow D$	2078	0.92
	$3^1 \rightarrow 1^2$	[2.4,2.8]	598	$1^2 \rightarrow D$	1612	1.04
	$3^1 \rightarrow 2^2$	[0.8,1]	1396	$2^2 \rightarrow D$	1768	1.15
	$3^1 \rightarrow 3^2$	[0.6,0.9]	1594	$3^2 \rightarrow D$	2078	0.92
Stage 3	$1^2 \rightarrow 1^3$	[6.2,7]	183	$1^3 \rightarrow D$	674	0.97
	$1^2 \rightarrow 2^3$	[6,6.6]	172	$2^3 \rightarrow D$	686	0.89
	$2^2 \rightarrow 1^3$	[3.2,3.4]	465	$1^3 \rightarrow D$	674	1.13
	$2^2 \rightarrow 2^3$	[2.8,3.2]	483	$2^3 \rightarrow D$	686	1.08
	$3^2 \rightarrow 1^3$	[12,14]	43	$1^3 \rightarrow D$	674	1.11
	$3^2 \rightarrow 2^3$	[11.6,12]	61	$2^3 \rightarrow D$	686	1.13
Stage 4	—	—	—	$1^3 \rightarrow D$	674	—
	—	—	—	$2^3 \rightarrow D$	686	—

Table 8
Results for model P1.

Stage	Winning segmented route	Value of model P1	Payments received by carrier
Stage 1	A→1 ¹	5593	2795.75
Stage 2	1 ¹ →1 ²	2368.25	1462.8
Stage 3	1 ² →2 ³	1769.6	1195.8
Stage 4	2 ³ →D	—	823.2

Table 9
Results for model P2.

Stage	10		20		30		40		50	
	VMP2	P	VMP2	P	VMP2	P	VMP2	P	VMP2	P
Stage 1	5666.44	3040.04	5617.48	2953.82	5599.12	2881.97	5556.28	2767.01	5525.68	2652.05
Stage 2	2386.4	1615.26	2380.35	1549.92	2376.72	1484.58	2369.46	1332.12	2354.94	1157.88
Stage 3	1807.44	1243.38	1797.12	1234.23	1791.96	1228.74	1776.48	1195.8	1757.56	1159.2
Stage 4	—	823.2	—	823.2	—	823.2	—	823.2	—	823.2

Note: VMP2 denotes the value of model P2, and P denotes payments received by carrier.

factor in the choice of transport routes. The proposed model P1 does not consider the timeliness of transport routes, which restricts the further extension and application of the model. The WA-VCG auction proposed herein introduces weight coefficients, which can effectively solve the timeliness delay problem due to uncertainty. For example, if some transport routes have a high risk of transport timeliness delays despite low transport costs, the weights of that transport route should be large. Taking the data in Table 6 as an example, the weight coefficient is obtained by the ratio of the average timeliness from node k to the destination to the expected timeliness of the shipper. Furthermore, the affine externality $\rho_k(t)$ of each node is assumed to obey a continuous uniform distribution on the interval $[-100, 100]$. The results obtained via the WA-VCG mechanism are shown in Table 10.

From Tables 8 and 9, it is easy to see that the shipper pays more to the carrier in the WA-VCG mechanism than in the SU-VCG mechanism. This is a realistic scenario because in cross-border logistics shippers tend to consider both transport cost and transport time, and generally transport cost is higher if transport time is fast. And the proposed WA-VCG mechanism takes both cost and timeliness into account. Although the shipper pays more cost in the WA-VCG mechanism, its transport time is relatively shorter.

Next, this paper verifies corollary 1 through numerical experiments. Taking stage 1 as an example, assume that the weights of node 3¹ are 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.98, respectively. Then the trend of payments received by the carrier at node 3¹ is shown in Fig. 6. It is obvious that for the winning carrier, the smaller the weight coefficient of its operation route, the larger the gain it receives.

6.3.3. Comparative analysis

The purpose of this section is to further highlight the advantages of the proposed methodology by comparative analysis. In a traditional single-unit sequential auction, one method is to determine the winner and payment based only on the unit bids of the bidders, i.e., the distance travelled is not taken into account in the auction, while the other method is to determine the winner and payment based on the unit bids and the distance travelled. Then according to the data in Table 7, the results of the traditional single-unit sequential auction can be obtained as shown in Table 11. Obviously, in the traditional single-unit sequential auction, which does not take into account the distance travelled, the shipper has to pay more. This is because only the unit transport bid price is considered in the model; for example, the shipper may choose rail, air or road transport, which has different unit prices and different distances. Although shippers pay relatively less than in the SU-VCG auctions proposed in this paper in traditional single-unit sequential auctions that take into account transport distances, they may not be able to adequately cope with uncertainties in the transport process, such as changes in weather, traffic delays, or fluctuations in demand. For this reason, while traditional single-unit sequential auctions may provide lower payment amounts in some cases, the SU-VCG auction mechanism may be more applicable and able to effectively deal with complex market environments in the face of uncertainties in the transport process.

6.3.4. Advantages of the proposed method

This paper integrates transport route auction and CPI into the system and proposes several novel trading mechanisms. To this end,

Table 10
Numerical results for model P3.

Stage	Winning segmented route	Value of model P3	Payments received by carrier
Stage 1	A→3 ¹	6244.08	1509.64
Stage 2	3 ¹ →3 ²	2900.62	1761.19
Stage 3	3 ² →1 ³	1354.63	757.13
Stage 4	1 ³ →D	—	823.2

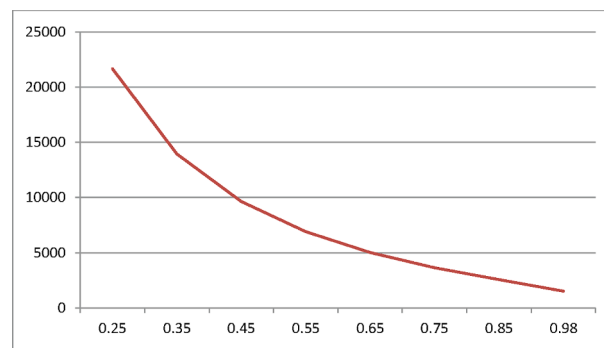


Fig. 6. Trends in payments received by carriers versus changes in weight factor.

Table 11

Results of comparative analyses with traditional single-unit sequential auction.

Method	Stage	Winning segmented route	Payments received by carrier
Traditional SU-VCG auction without considering transport distances	Stage 1	$A \rightarrow 2^1$	5748
	Stage 2	$2^1 \rightarrow 1^2$	5831.8
	Stage 3	$1^2 \rightarrow 2^3$	1135.2
	Stage 4	$2^3 \rightarrow D$	823.2
Traditional SU-VCG auction with considering transport distances	Stage 1	$A \rightarrow 3^1$	2448
	Stage 2	$3^1 \rightarrow 3^2$	1256.4
	Stage 3	$3^2 \rightarrow 1^3$	719.8
	Stage 4	$1^3 \rightarrow D$	808.8
SU-VCG auction proposed in this paper	Stage 1	$A \rightarrow 1^1$	2795.75
	Stage 2	$1^1 \rightarrow 1^2$	1462.8
	Stage 3	$1^2 \rightarrow 2^3$	1195.8
	Stage 4	$2^3 \rightarrow D$	823.2

the paper summarizes the advantages of the proposed methods as follows.

The WA-VCG method proposed in this paper can reduce the transport cost and improve the transport efficiency. Costs can be effectively reduced and transport capacity utilization increased by auctioning off transport route resources. Simultaneously, CPI can help find vehicles with idle capacity and schedule appropriately through resource sharing, reducing idle time. Furthermore, data sharing and intelligent scheduling functions provide real-time information about each hub, such as quantity, location, vehicle status, and more, for more accurate route planning and resource allocation.

Dynamic scheduling can be achieved. CPI can monitor changes in the transport process in real time, such as traffic congestion, changes in cargo volume, etc. By combining it with transport route auction methods, it can achieve dynamic scheduling, timely route adjustment and resource redistribution to cope with unexpected situations and ensure the smooth progress of transport.

Provide more choices for carriers and shippers. More choice can be offered to carriers and shippers by combining the route auction method with CPI. The transporters can choose the items to participate in the auction according to their own resources and capabilities; the cargo owners can choose the appropriate transporters and routes according to their actual needs, thus improving the flexibility and satisfaction of transport.

Reduce uncertainty and complexity. In the absence of a CPI environment, the uncertainty and complexity of traditional transport route decision models are very high and the solution are usually NP-hard and the size of the problem has to be controlled to obtain an optimal solution. However after combining CPI with transport route allocation auctions, cyber-physical visibility is established through real-time IoT, and data spatio-temporal traceability is derived from visibility, which together simplify the boundary conditions and greatly reduce uncertainty and complexity. The solution algorithm is greatly simplified for better results. While traditional single-unit sequential auctions may provide lower payment amounts in some cases, the SU-VCG auction mechanism proposed in this paper is able to effectively deal with complex market environments caused by uncertainty in the transport process.

6.4. Theoretical implications

While previous research has predominantly focused on auctions for the procurement of transport services, emphasizing auction mechanisms, pricing strategies, participant behaviour, and optimization algorithms, little attention has been paid to examining auction behaviour through the lens of transport route allocation. This paper breaks new ground by focusing on route allocation auctions and introducing three different trading mechanisms based on CPI auctions.

Traditional transport route optimization typically focuses on minimizing costs or selecting the shortest route as an objective function, which is then tackled by algorithmic solutions. However, a disadvantage of this approach is that once the optimal route has

been determined, the vehicle is restricted to following that specific route, which can lead to significant uncertainty in the transport operation if unexpected circumstances arise. Contrasting with this traditional approach, the SU-VCG mechanism in this study breaks down the transport route into segmented sections, allowing the platform to ascertain the optimal route based on truthful bidding by carriers for these segments. Theoretically, the SU-VCG mechanism has lower uncertainty than traditional route planning methods because it uses real-time auction strategies and continuous collection of route information to mitigate transport risks. Thus, the mechanism proposed in this paper represents an innovative solution to the transport service procurement problem and provides potential avenues for future research in auction-based transport route optimization.

More importantly, this paper considers the transport timeliness and uncertainty problem, and by introducing the weight parameter λ to portray the timeliness and uncertainty problem of each transport route, thus proposing a novel WA-VCG mechanism. For example, if the transport timeliness of a route is short and uncertain, the cost weighting factor of the bid is relatively small. This paper theoretically demonstrates that the proposed WA-VCG mechanism has the important properties of incentive compatibility, individual rationality and budget balance. Moreover, this paper also provides theoretical evidence that the smaller the cost weighting factor is, the larger the payment received by the transport operator. This important theory is in line with the real world scenario. For example, carriers are willing to pay more for routes that have a fast transport timeframe and where the transport is subject to uncertainty events. Therefore, the proposed WA-VCG mechanism demonstrates excellent performance in both theory and practice.

6.5. Managerial insights

This paper introduces a novel approach to logistics operations by leveraging network configuration protocols to establish routing tables and routing protocols. This fundamental reform aims to enhance the planning, scheduling, and execution of logistics operations. However, the development of routing tables and protocols necessitates the analysis of a vast amount of real-time data, given the instantaneous variability of spatial factors. While the pricing and allocation mechanisms between supply and demand are well developed and refined in the internet value chain, the market mechanism of CPI requires further exploration and understanding. This paper represents a valuable endeavor in auctioning transport routes within the framework of CPI. The proposed pricing and mechanism demonstrate the potential to achieve incentive compatibility and promote efficiency in transport route allocation. This research contributes to advancing our understanding of how CPI can optimize transport operations and highlights the importance of exploring new market mechanisms in the evolving landscape of the digital economy.

CPI relies heavily on real-time data across its segments, which requires robust data collection and sharing practices within each segment. However, the challenge arises when data providers struggle to cover the costs of collecting and uploading data, which can disrupt the balance in the CPI value chain and cause the whole process to break down. To address this issue, managers must establish a comprehensive incentive mechanism to ensure the real-time, accuracy, and authenticity of data in their specific solutions. Furthermore, the transparency and traceability that CPI provides can play an important role in reducing variability and uncertainty in transport systems. The use of routing tables and protocols within CPI, which have a high level of data intelligence, can facilitate a shift from stochastic to adaptive decision-making. This transformation enables a more informed and strategic approach to decision-making, enhancing the efficiency and effectiveness of operations within the CPI value chain.

CPI enables physical systems to converge seamlessly with digital networks, promoting efficient, real-time communication between equipment, machines and humans. The CPI-based transport auction mechanism proposed herein enables automation, monitoring and control of processes. Unlike traditional route optimization models, the proposed transaction mechanism offers a simpler approach that uses CPI to collect and share massive amounts of real-time data from sensors, devices and machines. Managers can analyze this data to extract valuable insights, make informed decisions, and enhance process optimization and resource allocation.

7. Conclusions

This paper investigates the problem of on-demand transport procurement in a CPI environment, where each node (router) of a segmented route acts as both a bidder and an auctioneer. Traditional transport service procurement mechanisms cannot be applied to the transport route allocation problem in a CPI environment. Thus, three mechanisms, namely SU-VCG, MU-VCG and WA-VCG mechanism, which are called *meta-auction*, are proposed for different CPI transport environments based on the well-known VCG. This paper theoretically proves that these three mechanisms have incentive compatibility, individual rationality and budget balance. This paper also considers the uncertainty of each segmented route, introduces the concept of weight coefficients, and proposes an auction method with route weights that complements the existing auction theory. The proposed trading mechanism can be applied to multi-stage transport route planning problems. Moreover, this paper carries out a case study to verify the effectiveness and scientific validity of the proposed method, and the results show that the smaller the route weights are in the WA-VCG mechanism, the greater the gains obtained by the carriers. This phenomenon suggests that the greater the gains for carriers in the market that are characterized by stable transport times and lower costs.

The importance of this work is summarized as follows. First, the paper addresses the problem of on-demand transport procurement in a CPI environment, and the methodology is particularly applicable to cross-border logistics problems with multiple transport segments. This is despite the fact that the pricing and allocation mechanisms between supply and demand in transport service procurement auction are well established, as evidenced in the previous literature. However, the existing pricing and transaction mechanisms in the logistics industry may no longer be able to satisfy the operating mechanism in the CPI model. This paper thus explores the transport route auction problem in the CPI environment, which will have a great impact on the logistics industry from both theoretical and practice. Second, the transaction mechanism proposed herein is especially tailored for the CPI environment. Incorporating the

proposed approach in the CPI environment and proposing a conceptual system framework with practicability makes the research in this paper more practically relevant. For example, CPI requires a large amount of real-time data to support it, which provides a favourable data base for the subsequent real-time cost of segmented routes. From the perspective of the platform manager, if the platform fails to create a set of appropriate incentives for data providers, it may not be able to ensure the timeliness, accuracy and authenticity of the data. In addition to ensuring that there are incentives for agents to participate in the auction, there should also be incentives for data providers not participating in the auction to ensure the sustainability of the system.

This paper concludes by highlighting three potential directions in which future research efforts could be directed. Firstly, this paper has only considered one-side VCG auction in the CPI environment, but it is possible to consider bilateral market issues in future research, which would allow for further additions to the transport route allocation problem in the CPI environment. Secondly, a variety of constraints can be added to the model in this paper to determine the winner determination set, such as the satisfaction constraint, where each bidding carrier is given a rating by the system and this rating is embedded in the objective function in a particular way, which will affect the winner determination set. This is also realistic as shippers usually need to select the right carrier from multiple perspectives. Finally, the weighted factors and the externalities for each route can be obtained in the future by means of empirical methods with a large data base. Although the research may be complex, the research content can further complement the foundation of logistics research in the CPI environment, thus further establishing that the transport route allocation network in the CPI environment has great potential for improving efficiency and reducing uncertainty in the logistics industry.

CRedit authorship contribution statement

Su Xiu Xu: Supervision, Software, Resources, Funding acquisition, Data curation, Conceptualization. **Zhiheng Zhao:** Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **George Q. Huang:** Methodology, Investigation, Formal analysis, Conceptualization. **Yifang Ding:** Methodology, Formal analysis. **Ming Li:** Visualization, Formal analysis. **Jianghong Feng:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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