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Circular economy to ensure production operational sustainability: A green-lean approach

Abstract: Satisfying the requirements associated with environmental concerns and resource efficiency in the manufacturing process has become necessary to realize effective production management. Specifically, manufacturers must identify novel working procedures or methodologies to enhance the resource efficiency and environmental friendliness of production processes. Green-lean production and a circular economy are promising schemes to achieve this goal. However, compared to green-lean management, the implementation of a circular economy in production operations remains relatively unclear. Several scholars have recommended the combination of the circular economy and green-lean concepts to bridge this gap, however, systematic methods remain to be developed. Considering this aspect, this study proposes a method that integrates green-lean solutions with the circular economy concept. The proposed method is applied in production operations through the principle of continuous improvement to enhance the environmental and resource performance aspects. The method includes three successive phases, which can not only help managers fully identify the opportunities for improvement but also provide managers with directions for improvement by introducing four strategy quadrants. The effectiveness and practicability of the proposed method are proven considering an industrial case of the assembly workshop of an automobile company. The proposed study can support enhance theoretical knowledge regarding the green-lean and circular economy concepts and demonstrates the implementation of a circular economy in the process of optimizing the production operation of manufacturing enterprises.

Keywords: Environmental improvement; Resource efficiency; Circular economy; Production operation; Green-lean

Nomenclature

CE	Circular Economy	BI	Before-Implementation
GL	Green and Lean	PI	Post-Implementation
CEEP	Circular Economy Embedded Production	MV	Mean Value
NVA	None Value Adding	SWC	Specific Water Consumption
BM	Business Model	SEC	Specific Electricity Consumption
CM	Circular Manufacturing	PWCPV	Production Waste Cost Per Vehicle
MFA	Material Flow Analysis	ITL	Interior Trim Line
I4.0	Industry 4.0	CL	Chassis Line
3Rs	Remanufacturing, Recycle, Reuse	FL	Finished Line
CEIR	Circular Economy Improvement Room	QIL	Quality Inspection Line
SPS	Structured Pragmatic Situational	MS	Material Saving
EVS	Environmental Value Stream	E/W	Energy/Water
WDP	Waste from Defective Products	PR	Pollution Reduction
SC	Supply Chain	RE	Resources Efficiency
SCM	Supply Chain Management	CR	Cost Reduction
MES	Manufacturing Execution System	QI	Quality Improvement
EMS	Energy Management System	D(T)	Delivery (time)
FTT	First Time Through	UD	Urgency Degree
IoT	Internet of Things	QC	Quality Control
GPM	Green Performance Map	JPH	Jobs Per Hour

1. Introduction

According to the Global Material Resources Outlook report (OECD, 2019), the limited resources on the planet have been rapidly consumed in recent years, and the consumption of primary materials is expected to double to 167 billion tons by 2060. Therefore, countries and enterprises are committed to finding appropriate solutions to avoid or reduce resource use and alleviate environmental problems (Tukker, 2015) and are hoping to gain a competitive advantage by solving these problems (Pagell & Gobeli, 2009). As a resource-consuming giant, the manufacturing industry should focus on resource issues in product design, production operation, and other related fields (Kurdve & Bellgran, 2021).

As a traditional management mindset, lean manufacturing emphasizes zero defects and zero losses (Agyabeng-Mensah et al., 2021; Jasti & Kodali, 2015). This lean principle is part of sustainable thinking (Henao et al., 2019). As an extension of lean production (G. Johansson & Sundin, 2014), green and lean (GL) management emphasizes the increase in environmental and economic efficiencies in the manufacturing process (Kurdve et al., 2014; Sagnak & Kazancoglu, 2016). Consequently, GL is emerging as a new way to increase the resource efficiency (RE) (Zokaei et al., 2017) in manufacturing operations while improving the environment (Abreu et al., 2017) as manufacturing evolves.

Moreover, the circular economy (CE) concept has been discussed with increasing enthusiasm in recent years (Donati et al., 2020). According to Kirchherr et al. (2017), CE, as a pathway to more sustainable solutions (N. Johansson & Henriksson, 2020), is a more promising paradigm for enhancing the RE and solving environmental problems. CE aims to reduce resource consumption by slowing, closing, and narrowing resource loops (Geissdoerfer et al., 2017). By using renewable energy and recycled materials, CE can help reduce life-cycle greenhouse gas (GHG) emissions and resource consumption (Esteva et al., 2020). Unfortunately, CE has been introduced mainly as a pathway for product life-cycle design and business model (BM) development (Mont, 2007), and the CE concept in the context of production operation has not received the same level of attention (Korhonen et al., 2018). Production refers to the continuous input of resources and output of products, which usually results in significant resource waste (Hicks & Dietmar, 2007; Ma et al., 2015). Production managers should thus extensively consider the CE concept to achieve resource and environmental goals (Kurdve & Bellgran, 2021).

Although the concept of GL manufacturing includes the sustainability aspect (Anass Cherrafi et al., 2021), the existing literature on GL manufacturing involves little evidence of CE-related concepts. Based on the latest GL empirical research, Caldera et al. (2018)

highlighted the need for integrating GL and the CE concept. In terms of several practical concepts, GL production and CE share similar goals. For example, common terminologies associated with the CE concept and efforts include the RE (Kristoffersen et al., 2020), eco-efficiency (Ma et al., 2015), waste reduction (Ren et al., 2017), and waste recycling (Bartolacci et al., 2018; Wu et al., 2014). Numerous examples prove that GL approaches typically focus on these characteristics as well (Zokaei et al., 2017). For instance, GL studies often involve the synchronization of concepts such as 6-sigma (A. Cherrafi et al., 2016), Green Production, and Supply Chain Management (SCM) (Duarte & Cruz-Machado, 2019; Lim & Jones, 2017). Kurdve and Bellgran (2021) suggested that combining GL and CE and applying the resulting approach to production operations is of significance for improving the resource and environmental performance of manufacturing systems, as such an approach can not only harness the potential of CE but also support operations in GL production systems.

In general, CE is considered a superior paradigm for achieving sustainability goals, but methods to implement CE in manufacturing operations remain to be established. Although researchers have recommended combining GL with CE to facilitate this implementation, no systematic approach for the same has been reported.

Thus, the study develops a circular economy embedded production (CEEP) method that aims to bridge the aforementioned gap. The main contributions are as follows: (1) The findings can help enhance the theoretical knowledge of CE and clarify the relationship between GL and CE. (2) The proposed CEEP method is an innovative way to apply the CE concept in production operations and provides a pathway for implementing CE in the production process of manufacturing companies, which has not been addressed in previous studies.

The remaining paper is organized as follows. Section 2 describes the relevant background and explains the relationship between CE and GL solutions. Section 3 describes the CEEP method. Section 4 describes the case study to further illustrate the proposed method. Section 5 presents the associated discussions, implications, and limitations. Finally, Section 6 presents the concluding remarks.

2. Theoretical background and framework

To clarify the aforementioned gaps, this section first presents an overview of applying the combination of CE and GL in production operations. Then, this study outlines a definition for CE in terms of production operations and the research status under this dimension (micro-level). Finally, a comprehensive analysis of the intersection between GL and CE concepts is presented through a Venn diagram.

2.1 Research review of GL combined with CE

By summarizing production principles, Ciliberto et al. (2021) concluded that the combination of CE and lean manufacturing can help alleviate the associated environment problems and recommended the expansion of the vision of lean management to promote the application of CE in the future. Gupta et al. (2021) developed a manufacturing sustainability assessment framework based on CE, cleaner production, and Industry 4.0 (I4.0) and indicated that manufacturing enterprises should adopt CE and cleaner production processes to ensure sustainable development. Through a systematic review of the resource recovery industry, Wang et al. (2019) identified lean manufacturing and reverse logistics as emerging research trends in the resource recovery industry, which require the attention of researchers. Based on the improvement of the workshop water cycle, Sartal et al. (2020) concluded that the combination of lean practice (5S) and CE can increase labour productivity and significantly reduce water use. Abreu et al. (2017) analysed all GL models and stated that the goal of these models was to reduce waste and environmental impact, thereby complementing the CE concept. Through a survey of Thai manufacturing companies, Piyathanavong et al. (2019) discussed the possibility of developing countries implementing various environmentally sustainable methods of operation and indicated that the implementation of GL and CE could increase the operational efficiency. In conclusion, the potential of combining CE-related concepts (e.g., CE, eco-efficiency, and industrial symbiosis) with GL-related concepts (e.g., green-lean, clean production, and lean manufacturing) for sustainable development has been widely recognized by researchers.

Shahbazi et al. (2019) introduced a GL tool (known as GPM) and demonstrated that this GL tool could increase the material efficiency and promote recycling in industrial cases. Thereafter, Kurdve and Bellgran (2021) reviewed the cases of GPM implementation and concluded that the combination of CE and GL in production operations could improve the production environment, while highlighting that the existing research regarding this aspect was limited. Caldera et al. (2019) suggested that SMEs can implement CE with GL strategies and proposed a strategy model; however, this study was based on interviews of decision-makers rather than empirical research. Romero and Rossi (2017) proposed circular lean product-service systems (CLPSSs) and confirmed the compatibility of CE and lean principles. Nascimento et al. (2019) discussed the combination of I4.0 emerging technologies and CE practices and proposed the circular smart production system (CSPS) management model. However, both CLPSSs and CSPS are primarily BMs instead of practical production operation models. Based on green, lean, CE and I4.0 concepts, Yadav et al. (2020) developed a framework for achieving sustainability. However, the target object was SCM rather than the whole production process. Overall, no systematic methodology or framework to realize this combination has been reported.

The literature review shows that although the combination of CE-related concepts and GL is promising for achieving sustainable development in manufacturing, there exists a research gap in terms of the methods to apply the combination of CE and GL in production operations. Consequently, more conceptual and practical research is needed in this field.

2.2 Definition and implementation scales

Although GL is an emerging field (Fu et al., 2017), scholars have reached a consensus on the meaning of GL. GL management is based on lean principles and introduces environmental management aspects (Szymanska-Bralkowska & Malinowska, 2018). GL is a new approach to realize sustainable operations that combines green and lean production principles (Leong et al., 2019), focusing on avoiding unnecessary use of resources, reducing emissions, and improving the environment (Dües et al., 2013).

Many different definitions of CE exist, and different fields have different interpretations of CE (Korhonen et al., 2018). However, to integrate CE with production management, we must identify specific meanings relevant to the manufacturing domain. In general, according to Moraga et al. (2019), mainstream researchers use two definitions to represent CE, which are based on *sensu stricto* and *sensu latu*. The *sensu stricto* definition emphasizes the distinction between CE and the linear economy from two characteristics of slowing and closing resource loops (Bocken et al., 2016). However, *sensu latu* regards CE as an economic model to maximize the ecosystem function and human well-being. This definition focuses more on the three pillars of the environment, economy, and society (Murray et al., 2017).

Notably, CE, as part of the production operations in its broadest scope, may involve energy and material circulation, prolongation of material and product life and minimization of use (Kurdve & Bellgran, 2021). By integrating CE thinking and using CE solutions, the manufacturing industry can transform its production operations to increase the RE (Kurdve & Bellgran, 2021). From an operations viewpoint, the definition of CE should focus on circulating materials, management of production waste, and energy conservation (Kirchherr et al., 2017). In this study, it is not necessary to identify which definition is appropriate for CE as the definitions are used only as a basis to establish the framework to understand and apply CE thinking.

Moreover, CE can be implemented at different scales (Li et al., 2010; Mhatre et al., 2021). The taxonomy from two reviews outlines three main scales: micro, associated with a single product, company, or organization; meso, pertaining to eco-industrial parks and industrial symbiosis; and macro, pertaining to a city, province, region, or nation (Ghisellini et al., 2016; Kirchherr et al., 2017). Most of the existing studies have focused on the latter two dimensions rather than on enterprises and organizations at the micro-level (Ma et al., 2015). The few micro-level studies almost exclusively discussed the development of new CE business models (Lewandowski, 2016) and highlighted the obstacles and incentives in introducing CE (Aranda-Usón et al., 2020); the focus of these studies was not on implementing the CE concept in the manufacturing processes of enterprises (Gusmerotti et al., 2019). Because enterprises are expected to have a large amount of wasted resources in their processes, such as non-recyclable waste and non-recyclable by-products, it is necessary to recognize that the enterprise is the main stakeholder in CE practices (Ma et al., 2015). Using CE to address the efficiency and environmental issues of each enterprise at the micro-level is the basis for achieving sustainable development. Therefore, depending on the CE implementation scales, the CEEP method is designed for and limited to the workshop level of the enterprises (i.e., micro-level), which is also the first stream level that supports the GL-thinking principles for manufacturing.

2.3 Green-lean production and CE solutions

To identify the intersection between GL and CE concepts, a comprehensive analysis was performed using Venn diagrams. The corresponding results are shown in Figure 1. It can be noted that the operational green solutions from environmental GL implementation pertain to **avoidance**, **substitution**, and **circulation** (Kurdve & Bellgran, 2021). The **avoidance** solution aims to avoid non-value adding consumption (Abreu et al., 2017), e.g., avoiding NVA activities, ensuring the proper maintenance of equipment to avoid breakdown, or terminating processes when not active. The **substitution** solution focuses on replacing technology and material or energy input. The **circulation** solution includes circular systems and converts waste output to resource input; the goals of this approach are similar to those of CE.

In contrast to the implementation of operational green solutions in the manufacturing process, CE solutions focus on a core point, i.e., **looping**, which includes slowing down loops (design for longevity (Kim et al., 2003) and maintenance systems solutions) or circulate looping (i.e., reuse, remanufacture refurbishing and recycling (van Buren et al., 2016)).

Circulation in this case pertains to material and energy loops and aims at ensuring narrow loops (Blomsma & Brennan, 2017). The specific CE solutions, shown as small bubbles in the figure, are important connotations of CE.

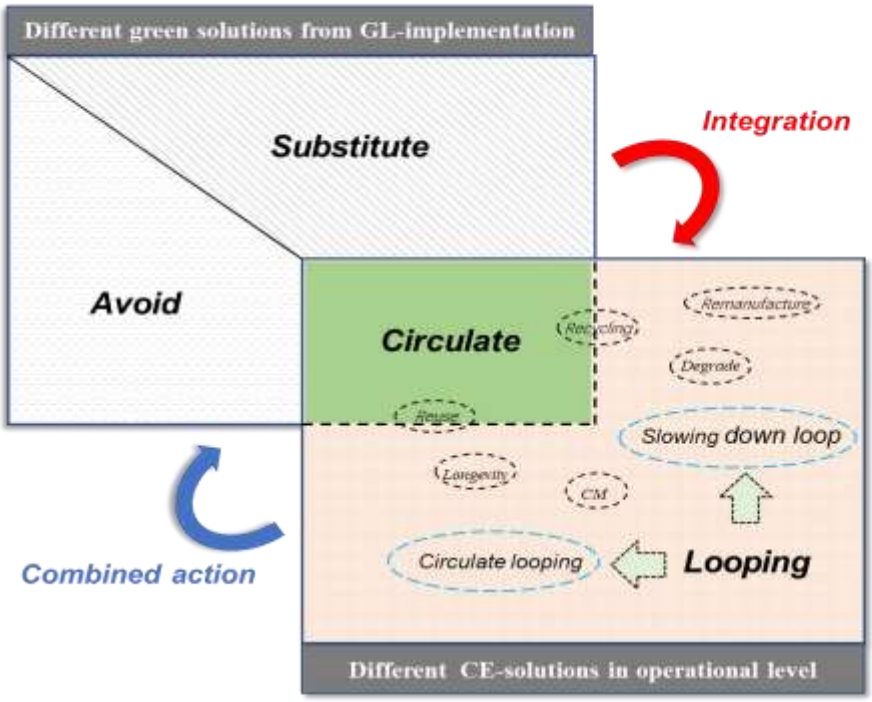

Figure 1. Venn diagram of green solutions based on GL implementation and CE solutions at the operational level.

In general, the CE and GL concepts are complementary. The **avoidance** and **substitution** solutions are not covered by the CE concept. However, the **circulation** solution is similar to the CE and GL concepts, and thus, a partial overlap occurs, as indicated in green in Figure 1. Considering these aspects, this study combines the similarities and differences of GL and CE solutions as the basic structure in the CEEP method. This integration can exploit the advantages of GL and CE and help achieve the common goals of eco-efficiency, RE and economic benefits in production and operation.

3. Presentation of the CEEP method

Although GPM is a proven tool for implementing CE at the workshop level (Shahbazi et al., 2019), the original purpose of the developers was only to focus managers on environmental aspects rather than introducing the CE concept (Kurdve & Bellgran, 2021). In this study, further analysis was done based on GPM to obtain the results of Figure 1 with the purpose of combining CE with GL. In addition, in order to achieve a structured utilization of such results, it is necessary to resort to the idea of continuous improvement. Alves and Alves (2015) proposed a sustainability model and used five sequential stages to implement the model. Pampanelli et al. (2014) proposed a GL model, which is also based on five sequential steps to achieve improvement. Wen et al. (2021) proposed a model for manufacturing process energy improvement based on three sequential phases of energy loss modeling, analysis, and improvement. Based on this, the CEEP method will draw on this line of research and embed the results of the integration of CE and GL in multiple phases for continuous improvement. Concretely, the method includes three consecutive phases to identify, analyse, weigh, visualize, implement, track, and evaluate the concerns associated with the RE and environmental improvements in the production process, as shown in Figure 2.

- **Phase 1**: Identify the opportunities. This phase aims to identify the improvement opportunities from several subdirectories in the contexts of both environmental aspects and impacts and production sustainability. In this manner, managers can accurately determine the potential opportunities and corresponding processes to achieve the goals.
- **Phase 2**: Strategy quadrant analysis. A strategy quadrant model is developed to provide managers with appropriate directions to consider. As a key component of the integration, the model includes four specific strategies, which result from the combination of GL and CE.
- **Phase 3**: Improvement determination and assessment. This phase is aimed at formulating the most reasonable improvement action and evaluating its effectiveness under the guidance of the strategy quadrant. The trade-off model in this phase allows managers to consider the advantages and disadvantages of each measure and make the most suitable decision.

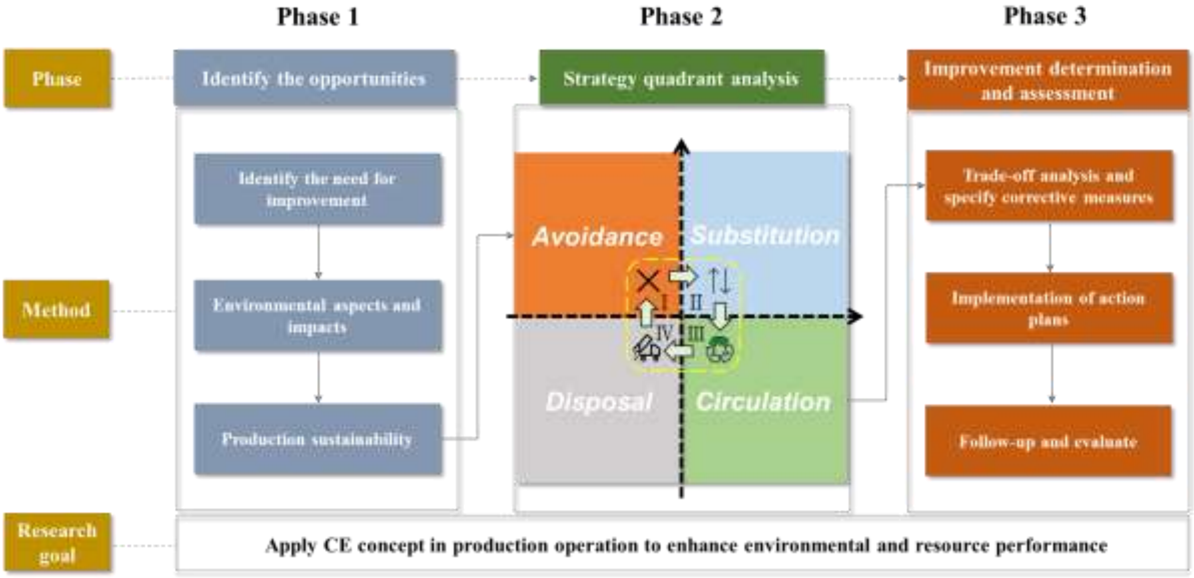

Figure 2. Overview of the CEEP method.

The manufacturing floor should satisfy certain prerequisites to be a candidate for improvement: 1) A stable production process (Urbinati et al., 2020). 2) Maturity of lean improvement. 3) Supportive management team.

3.1 PHASE 1. Identify the opportunities

Production operations are processes in which various elements, such as humans, machines, materials, methods, and the environment, interact. Researchers should explore every opportunity for improvement in the production process. The objects of improvement can include the process equipment, supply chain, energy and living elements. Based on these characteristics, problem diagnosis can be performed in two main directions, as shown in Figure 3.

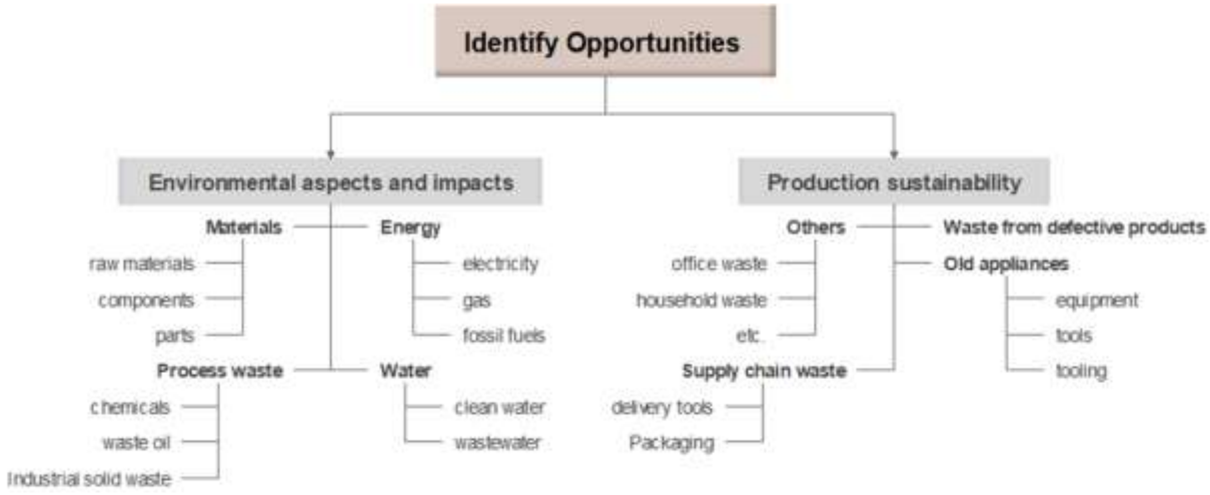

Figure 3. Reference framework for diagnosing a problem.

3.1.1 Identify the environmental aspects and impacts

The scope of improvement in the manufacturing process is defined by identifying the environmental aspects and value stream impacts. Environmental impacts are changes in the environment caused by the inputs and outputs of a unit (Pampanelli et al., 2014). Researchers can identify improvement opportunities in these directions, as shown in Figure 3, which are integrated through the elements of the environmental value streams (EVS) based on manufacturing characteristics: 1) energy (electricity, gas, and fossil fuels); 2) water, including clean water and wastewater, corresponding to the input and output, respectively; 3) process waste (industrial solid waste, waste oil, and chemicals); and 4) materials (raw materials, components, and parts), with a focus on the material renewability.

3.1.2 Focus on production sustainability

The scope of improvement is defined by identifying the issues affecting production sustainability and RE in the production process. Because certain scopes overlap with environmental aspects and impacts, the following aspects are considered: 1) old appliances (equipment, tools, and tooling); 2) waste from defective products (WDP); 3) supply chain waste (packaging and delivery tools); and 4) others wastes (office and household waste).

To more clearly identify the problems, several management or technical tools can be used, such as the fishbone diagram analysis, brainstorming, process flow charts, rationalization suggestions, on-site investigations, and problem escalation mechanisms.

3.2 PHASE 2. Strategy quadrant analysis

The strategy quadrant analysis stage is a critical part of the method. As shown in Figure 2, the model divides strategies into four types, known as strategy quadrants: 1) avoidance, 2) substitution, 3) circulation, or 4) disposal. The different quadrants pertain to different problem-solving directions, and the users should start from the first quadrant (avoidance) and end at the last quadrant (disposal) to examine whether they can act on the opportunities defined in Phase 1. Note that the strategies do not apply only to the final products; the target objects may be the subassembly and materials disassembled from the defective parts (Favi et al., 2019; Marconi et al., 2019) or even the water, energy, and production waste in the production process.

3.2.1 Quadrant 1: Avoidance

In the strategy quadrant analysis, the first step is to analyse whether the root cause of the wasted material can be eliminated. In other words, for the opportunities identified in Phase 1, the user must first consider whether any specific solutions can be used to avoid the problem; this thought direction pertains to the avoidance strategy.

In this context, eliminating (i.e., avoiding) the root cause of the problem is the optimal choice, for example, by modifying the process parameters or work behaviour. When harmful materials are involved in the input stage or hazardous waste is present in the output stage, an avoidance strategy must be used to eliminate these entities. Moreover, material flows can be controlled to minimize the waste and effluent generation.

It is impossible to manufacture an end product without waste generation. For example, production equipment in operation always consumes energy and generates CO_2, and product processing always produces trimmings. Therefore, it is extremely difficult to implement the avoidance strategy in practice. Even if certain specific implementation solutions can achieve waste avoidance, the manufacturing costs incurred by those solutions may be prohibitive. In general, the decision of managers to adopt the avoidance strategy as the direction to solve a problem must be based on a combination of economic, technical, environmental, and other factors.

3.2.2 Quadrant 2: Substitution

When the avoidance strategy cannot effectively solve a problem, the next strategy quadrant, that is, the substitution strategy must be considered. Typically, the priority is to substitute hazardous materials with non-hazardous materials and replace fossil-based materials with renewable materials. For example, switching to cleaner-burning fuels or lower-waste additive manufacturing techniques can help enhance the RE in the manufacturing process. Substituting incandescent bulbs/sodium lamps/metal-halide lights with LEDs in manufacturing plants can help increase the energy efficiency and reduce the electricity overhead. Both the avoidance and substitution strategies pertain to the GL and are not CE concepts.

3.2.3 Quadrant 3: Circulation

If the first two quadrant strategies cannot support users in finding the direction to solve the problem, the next quadrant strategy, circulation, must be considered. The circulation strategy contains several detailed problem-solving directions that pertain to CE concepts. As shown in Figure 4, inspired by the waste hierarchy model (Kurdve & Bellgran, 2021), the CEEP method uses a ladder hierarchy model to refine the circulation strategy to clarify the available choices. The ladder model has three levels, each corresponding to a different circular strategy: 1) 3Rs (reuse/repurpose, remanufacture, and recycle), 2) degradation, and 3) other circular manufacturing (CM) strategies.

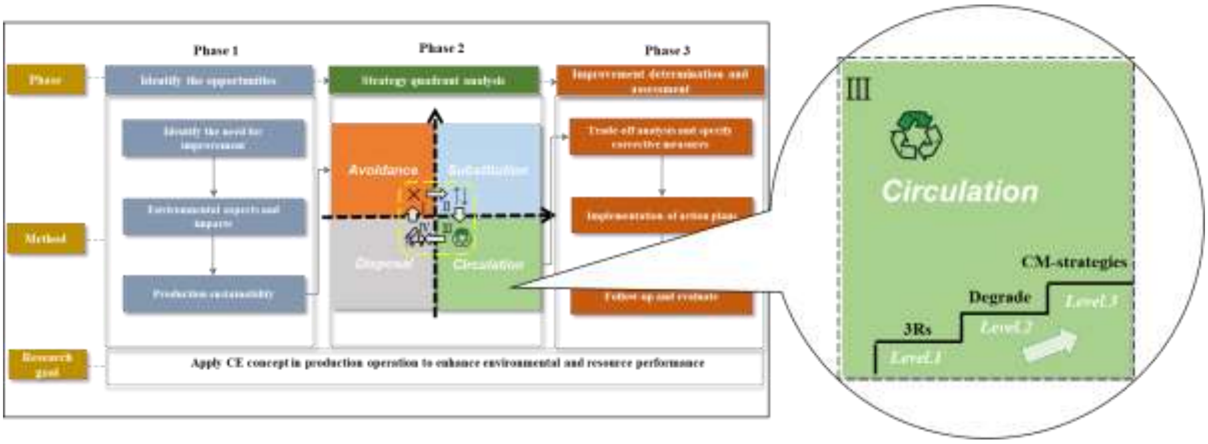

Figure 4. Ladder hierarchy model in circular strategy.

- **Level 1**: The 3R (reuse/repurpose, remanufacture, and recycle) concepts have been recognized as a valuable tool to adopt the CE strategy (Hasegawa et al., 2019). According to the reuse concept, the product is directly reused at the end of its life-cycle (Liu et al., 2018). The objects reused in this case are not only products and may include any object in the production process. According to the remanufacture concept, a used product is restored in compliance with the original quality, performances, and specifications by certain manufacturing techniques (Sitcharangsie et al., 2019). Recycling refers to the reuse of certain parts or materials to reduce the resource consumption and pollution (Zhong & Pearce, 2018). Repurposing is a hybrid strategy between reuse and recycling; when the product is economically or technically limited and cannot be directly reused, repurposing is performed (Coughlan et al., 2018).
- **Level 2**: Certain wastes may not be adequate as initial raw materials, and managers may use them in less demanding situations, through a concept known as degraded use. For example, when the equipment in an intelligent workshop cannot meet the current production requirements, the manager can choose to downgrade the equipment to be used in a small trial production workshop. Such CE solutions are aimed at slowing the loops or increasing the number of loops.
- **Level 3**: Circular manufacturing (CM) is defined as simultaneously adopting different CE strategies to satisfy the needs of stakeholders by relying on the internal and external activities of manufacturers to reduce resource consumption, extend the resource life-cycle and close the resource loop (Acerbi & Taisch, 2020). Considering the fact that not all CM strategies are applicable to manufacturing workshops, a CM-strategy matrix is presented in Table 1. The sixth column in Table 1 indicates the relevance of different CM strategies to the production operation. Depending on the

implementation scale, the micro part of the strategy is more suitable for managers to adopt in production management. Certain technologies that have emerged to support the physical implementation of CM strategies include additive manufacturing, cleaner and green technologies, I4.0, cloud manufacturing, and tracking technologies (Acerbi & Taisch, 2020). This paper only presents certain CM strategies for researchers to refer to and does not analyse them in detail, as this aspect is not the focus of this paper.

Table 1. Scale adopted by different CM strategies (modified from Acerbi and Taisch (2020)).

	CM-strategies	Scale of adoption			Correlation with production
		Micro	Meso	Macro	
1	Circular business model	●	○	○	√
2	Waste management	●	○	○	√
3	Disassembly	○	—	—	
4	Cleaner production design	●	○	—	√
5	Servitization	○	○	○	
6	Some 3Rs techniques	●	○	○	√
7	Close-loop supply chain and Reverse logistics	○	●	—	
8	Industrial symbiosis and Eco-industrial parks	○	●	—	
9	Circular design practices	●	○	—	√

Note: "●" represents mass adoption; "○" represents rare adoption; "—" represents almost no implementation.

In general, solutions based on the circulation quadrant are more readily available than those associated with avoidance or substitution, and such solutions pertain to the CE action, for instance, using renewable energy sources at procurement and production sites, reducing water use through on-site treatment or recycling; maximizing the use of pallets and renewable or recyclable packaging materials; repairing defective parts and ensuring that these parts can be reused; using single-use materials multiple times, e.g., using single-use gloves more than once in the manufacturing plant; and recycling any rare earth elements involved in the production process to alleviate their environmental and economic burden.

3.2.4 Quadrant 4: Disposal

The fourth strategy quadrant, disposal, is the last resort for waste and effluent management. Strategies for disposal include not only landfilling but also recovering the waste for useful purposes, e.g., energy recovery and road surfacing. Compared to landfilling, energy recovery from waste is more in line with the concept of CE.

Environmental protection actions can be divided into pollution transfer, treatment, and prevention. Only pollution prevention may generate profits for enterprises (King & Lenox, 2001). In other words, among the four strategies, avoidance or substitution strategies are prioritized, followed by reuse, recycling, or degradation in the circulation quadrant, with landfilling or energy recovery being the last resorts. The general principle is to keep the value of the surplus material as high as possible without sacrificing excessive profit of the manufacturer.

3.3 PHASE 3. Improvement determination and assessment

3.3.1 Trade-off analysis and specification of corrective measures

The analysis in phase 2 only provides the direction to address the problems and not specific corrective measures. Therefore, once a manager has clarified the strategic direction, the specific measures to be used from these directions must be identified and prioritized.

The manager must fully understand the production status and evaluate or clarify the following aspects: (1) the problem that needs to be solved; (2) the strategies identified in phase 2 that must be selected as the direction of improvement; (3) refinement of the improvement measures according to the actual situation of the production workshop; (4) weighing of the measures based on several key elements, including material savings (MS), energy/water (E/W) savings, pollution reduction (PR), resource efficiency (RE), cost reduction (CR), quality improvement (QI) and delivery rate improvement; (5) determination of whether the measures should be implemented based on the balance analysis and actual situation; (6) degree of urgency of implementation of the measures (high/medium/low); (7) types of improvements (one-time completion or Kaizen); (8) end time; and (9) delegation of responsibilities.

Moreover, the managers must perform an extensive trade-off analysis for rational strategies, for instance, to examine whether these strategies are economical, meet the process requirements, or affect the product quality. Notably, small and medium manufacturing enterprises tend to adopt measures that are inexpensive, easy to implement, and do not significantly impact the productivity. Therefore, managers must leverage several key elements provided by the small trade-off model to balance the various measures in this phase. To assist the managers in decision-making, several trade-offs for common actions, modified from Fu et al. (2017), are listed in Table 2. Fu et al. (2017) conducted a 2-year field study and obtained the results of the trade-offs in Table 2 with serial numbers 1-5. Based on this, two processes, QC and SCM, were added to this study to better fit the scope of this study. After several discussions with some experienced manufacturing managers, the positive and negative effects of these two processes are given based on actual production experience. Notably, the model is only used as a reference for improvement, not as a determinant. Its purpose is to remind managers to weigh improvement measures in multiple dimensions.

All these measures must be iteratively evaluated. Although multiple preparatory measures may exist for the same problem, only one measure can be implemented.

Table 2. Trade-offs for common actions (modified from Fu et al. (2017)).

	Process	MS	E/W saving	PR	RE	CR	QI	D (T)
1	Water recycling		+	+	+	+		
2	Electricity saving		+			+		
3	Elimination of plastic film	+		+	+	–		
4	Accessory adding standardization	+	+	+	+	+	+	+
5	Clean production design	+		+		–		
6	Quality control (QC)	+		+		+	+	+
7	SCM			+	+	–		+

Note: "+" and "-" represent positive and negative effects, respectively; the effect of non-marked entities depends on the situation.

3.3.2 Implementation of action plans

This step involves implementing the improvement action plans. The types of implementation measures in a manufacturing plant can be divided into one-time completion and continuous improvement. Continuous improvement measures can be incorporated into the plant's daily lean manufacturing plan. The optimal choice is to incorporate circular design practices into plant design considerations before the plant is set up.

3.3.3 Follow-up and evaluation

The final step is to track the actions that have been implemented and assess the impact. Periodic reviews must be conducted to verify the effectiveness of these measures. Moreover, managers should evaluate whether the actions achieve the desired effect.

In the CE framework, the direct evaluation methods for individual products include Sankey chart analysis, input-output analysis (Kalmykova et al., 2018), material flow analysis (MFA), and life-cycle assessment (LCA). Most of these approaches evaluate the recycling rate of materials flow or energy (Graedel et al., 2011; Harris et al., 2021). These methods are feasible if accurate and relevant data are available.

As suggested by Moraga et al. (2019), several indirect indicators can be used to evaluate the environmental performance and RE. While these evaluations pertain to CE-related areas, they do not necessarily encompass circularity. For example, Pampanelli et al. (2014) used the rate of cost change of a production cell in the case study to assess the improvement of GL. Therefore, considering the complexity of the production process and the fact that the CEEP method involves GL improvement, certain indirect evaluation methods may be more appropriate in this context.

Some specific assessment indicators include: (1) energy: electricity and gas consumption are collected using meters and standardized with cost; (2) water: water consumption is collected using water meters and standardized with cost; (3) sewage: sewage volume and environmental compliance status is monitored using meters; (4) waste: all waste generated in the workshop at a given time. Use unit consumption to calculate and unify with cost; (5) oil and chemicals: collect and monitor the trend of oil and chemical usage in the workshop and unify with cost.

4. Case study

To verify its effectiveness and practicability, the proposed method was implemented in the car production base of an automobile company, a national leader in Chinese automobile production. As one of the pillar industries of China's economy, the automobile manufacturing industry has a high degree of process complexity, a large supply chain, a lot of waste generation and serious pollution compared to other industries. This car production base has been in operation for four years, aims to build a green, intelligent, and networked car production plant. According to an internal survey, the production site already has a certain level of lean improvement, but still faces challenges in terms of green and efficiency. Therefore, the purpose of this case study is to collaborate with the factory to implement the CEEP method. On the one hand, it is possible to further verify the practicality of CEEP, and on the other hand, it is intended to meet the requirements of green and efficiency as requested by the factory leaders.

The implementation object was the assembly workshop in the car production base, which is responsible for the assembly and quality inspection of the entire vehicle in this automobile company. First, we conducted a site visit to the production workshop while observing the entire production process. Second, we interviewed several managers in the workshop, including a general manager and six department managers. In particular, we sought advice from manufacturing and environmental managers. We learned about the organization and operation mechanism, and further, reviewed a large number of paper and electronic documents of the workshop, including production management sheets, financial statements (water, electricity, and gas bills), environmental documents, bill of materials, etc. Finally, we encouraged workers to identify problems, and, with the help of workshop managers, rewarded workers who provided suggestions.

4.1 Current-state description

The assembly workshop has been performing stable production for many years, with a design capacity of 240,000 units. The jobs-per-hour (JPH) of the workshop is 60, which means that on average, one vehicle can be assembled every 60s. The workshop has a complete production process, a high degree of automation, and a certain level of GL improvement. For example, the on-time delivery rate of the workshop is always 100%, the maximum first-time-through (FTT) level is 90%, operators are literate in terms of the standardized operation and 5S, technicians are proficient in 6-sigma tools, and a special environmental monitoring task force is present.

First, we visualized the entire production process through a field investigation and with the help of engineers, as shown in Figure 5. Most processes at the production site have physical inputs and outputs, e.g., parts, components, accessories, and additives. Notably, to assemble a vehicle, the workshop consumes considerable energy in the form of electricity and gas. In addition, the workshop has 1593 employees, including 1572 operating workers (806 and 766 in the day and night shifts, respectively) and 21 technical management staff, which generate domestic waste such as domestic sewage. These key elements involve several opportunities for RE and environmental improvement.

As shown in Figure 5, to support the operation of the CEEP method, a team of leaders and multi-sectoral stakeholders is present in the central location of the production site, known as the *circular economy improvement room* (CEIR). Because direct data are the most reliable, the authors of this article served as part of the team. The CEIR was the overall management unit that supported the operation of the CEEP method, including the promotion and implementation of the method, formulation and management of measures, relevant training of employees, data collection, and monitoring of implementation effects.

In general, the workshop meets the selection criteria proposed by the CEEP: 1) A stable production process. 2) Maturity of lean improvement. 3) Supportive management team.

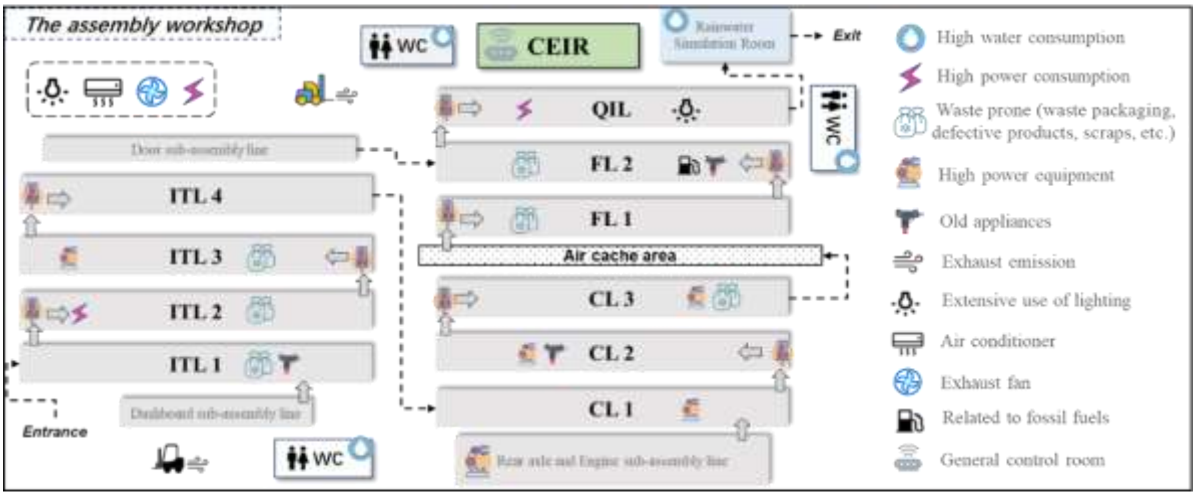

Figure 5. Overall operation status of the workshop.

4.2 Implementation and critical examination

From the EVS perspective, we identified several points of opportunity based on the information and data collected, e.g., recycling of workshop energy. In addition, for certain complex problems related to production sustainability, we identified causes and direction through in-depth communication with an experienced engineer and workers, e.g., waste associated with defective plastic parts. In accordance with the managers’ suggestions, we analysed each opportunity in detail, examined trade-offs based on the actual situation of the workshop, selected the most appropriate strategy quadrant, and developed more detailed improvement measures. The detailed improvement strategies and trade-offs are presented in Table 3, and certain typical analysis cases are listed, as follows:

- The wastewater improvement effect was remarkable. The workshop used approximately 2500 tons of water per month, mainly for domestic use and rainwater simulation room, accounting for 70% and 30% of the total consumption, respectively. We chose the strategy of reuse in the circulation quadrant to optimize the domestic water use, i.e., by reusing water by installing low-cost pipes and using this water to wash cars, water plants and flush toilets. In this way, we not only enhanced the efficiency of water resources but also saved costs for the workshop. Moreover, we added a set of filter equipment in the rainwater simulation room to recycle the monitored water. Although this strategy also pertains to the circulation quadrant, costs were incurred for purchasing the filtration equipment.
- The electricity use in the workshop could be optimized to save energy and reduce carbon emissions. Figure 6 shows the proportion of electricity consumption in the workshop. Notably, lighting and air conditioning accounted for approximately 30% of electricity consumption. First, we recommended the substitution of incandescent lamps with LED energy-saving lamps for short-term cost and long-term benefits. In addition, we posted energy-saving signs to remind employees to switch off lights and air conditioners to save energy, although the effect was not significant. Therefore, we requested the system suppliers to integrate the information interface between the energy management system (EMS) and manufacturing execution system (MES) to achieve real-time matching of the energy and production requirements. The control of workshop lighting and air conditioning was replaced by CEIR. Finally, we issued energy usage rules: According to the production schedule, the lighting was activated 15 min before the start of the shift, and the lighting in the production area was automatically turned off 10 min after the end

of the shift. When the temperature in the workshop was not between 10–25°C, the CEIR switched on all the air conditioners in the production area and switch on only the exhaust fan at other temperatures.

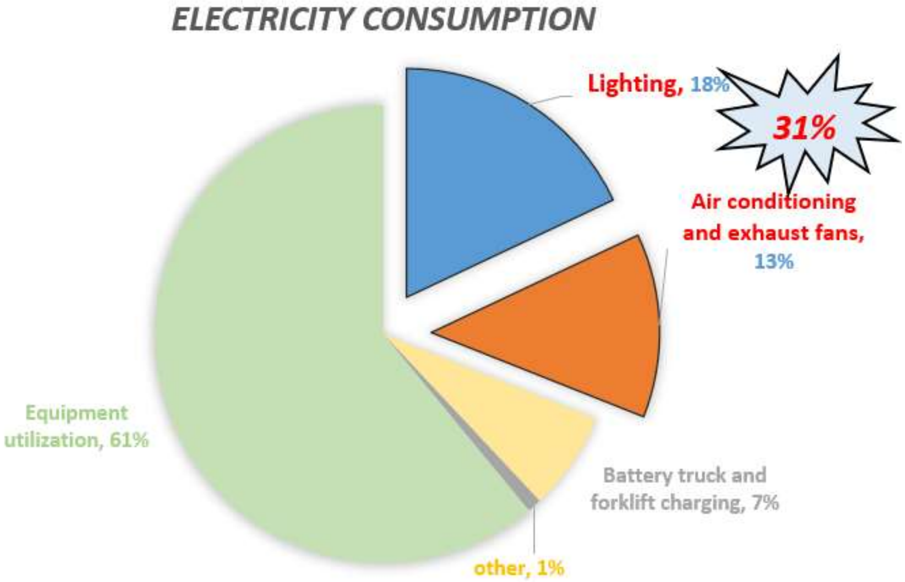

Figure 6. Proportion of electricity consumption in the workshop.

- Non-degradable plastic packaging materials were considered. It was noted that the assembly workshop has many transportation links, and suppliers often choose plastic film to package parts for ease of transportation and dust control. Plastic films are non-degradable and non-recyclable. Due to the low price of plastic film, it was not a focus of the workshop management. Most plastic films were thrown directly into landfills, which not only incurred additional costs but also caused irreparable damage to the environment. Therefore, a circulation strategy was established, in which the suppliers were contacted to replace plastic film with recyclable packaging (e.g., cloth bags or baskets). Moreover, the supplier was requested to collect the used recyclable packaging for recycling at the next delivery.
- The large amount of WDPs in the workshop was examined to enhance the production sustainability. Plastic parts represent important automotive materials and are being increasingly used in automotive components owing to their high quality and performance (Keoleian & Sullivan, 2012). However, plastic parts are vulnerable to damage (e.g., scratches and material defects) and generate production waste. In the workshop, although certain problems had been solved using lean tools, a certain amount of plastic waste remained unaddressed. Therefore, we opted for a circulation strategy. We designed a

simple CE BM (Figure 7): suppliers were contacted to place a technical worker in the workshop who could oversee the repair of defective product to be reused. Expensive parts that could not be repaired in the workshop (e.g., bumpers with damaged paint or scratched car headlights) were sold to dealers at a low price who sold these products at low prices and high discounts to customers who were not concerned about a slightly damaged appearance. Materials such as light bulbs in headlights could also be sold to recyclers. In this manner, the utilization of resources could be maximized instead of directly landfilling defective products. Note that this mode only applied to aesthetic parts, and defective performance parts were not allowed to be reused.

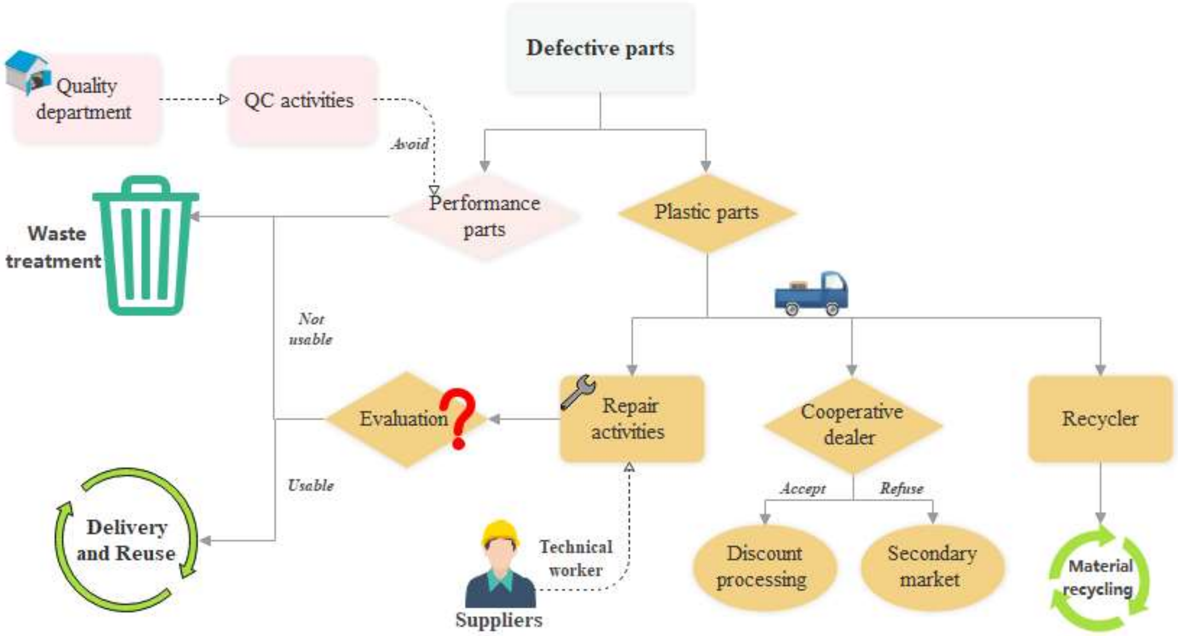

Figure 7. Simple BM to maximize value in the workshop.

Table 3. Detail improvement strategies in the workshop.

Classification	Problem description	Strategy quadrants	Corrective measures	Trade-off							UD	Improvement type	
				MS	E/W	PR	RE	CR	QI	D (T)		One-time	Kaizen
Raw material area	A large amount of foam is used for packaging and distribution of automobile roof materials, resulting in packaging waste.	Circulate	Cooperate with suppliers to replace heavy flannelette packaging and recycle flannelette.				+	+			M	√	
Raw material area	There are many defective materials in the interior trim line and finish line, which causes pollution after the plastic parts are buried.	Circulate	Establish recycling business models with suppliers, spare parts distributors, and recyclers for remanufacturing	+		+	+	+			H		√

			or downgrading.								
Raw material area	The material of front and rear headlamps is easily scratched during transportation, resulting in material waste.	Circulate	1.Use foam compartments instead of plastic boxes to transport materials. 2.Work with dealers to downgrade the use.	+		+		+	M		√
Raw material area	A large number of waste logistics distribution cars are directly discarded.	Circulate	The waste distribution car is modified and remanufactured into a traveling workbench.			+	+		M	√	
Raw material area	Wiper motor wiring harness plug is easy to damage, resulting in a large number of waste products.	Substitute	Carry out QC activities, and the initial measure is to change the packing method.	+		+	–		H		√
Raw material area	The rubber plug of a sheet metal hole gives off pungent smell in summer, which fails to reach the certification standard of REACH.	Substitute	Switch suppliers and use a more environmentally friendly plug.		+		–	+	H	√	
Production area	Some solid wastes and scraps are directly buried (e.g., metal supports, etc.).	Circulate	Sold to solid waste disposal suppliers for recycling.		+	+	+		H	√	
Production area	A large number of battery drills and other assembly tools are directly discarded after damage.	Circulate	Replace the battery after disassembly, repair, and reuse.			+	+		M		√
Production area	Oil leakage occurs during refueling of vehicles on the completion line, which wastes resources.	Avoid	Monitoring stop manually when needed.		+		+		H		√
Production area	Many equipment, tools, tooling, and spare parts of the discontinued vehicles are idle, resulting in waste.	Circulate	Transfer to a small trial production workshop, degraded use.			+	+		L		√
Production area	Cotton gloves are heavily used by workers on the chassis operating line.	Circulate	Formulate replacement standard and require gloves to be reused at some workstations.			+	+		H		√
Production area	Disposable plastic film is used to pack the material of interior decoration.	Circulate	Contact the supplier to replace the packaging film for recycling.	+	+	+	–		H	√	
Production area	Some spare parts in the production site.	Circulate	Simple repair and reuse by the			+	+		H		√

			repairman.										
Production area	Some spare tools in the production site.	Circulate	Simply repair it and then use it for other purposes.				+	+			H		√
Production area	A large number of disposable patches are used in bolt holes of body sheet metal, resulting in waste.	Substitute	The coating workshop replaces the patch with bolts in advance, and reuses the bolts.				+				H	√	
Production area	The engine wire fastener is easy to be damaged in the assembly process, resulting in waste.	Avoid	Use lean improvement to adjust the station for easy operation to avoid waste generation.	+			+		+		H		√
Production area	A large number of used bolts in the production site.	Circulate	Repaired the screw teeth, and re-used the bolts that meet the use requirements in the workshop.				+	+			H		√
Production area	A large number of discarded color markers are discarded, resulting in metal waste and paint pollution.	Disposal	Make waste color code recycling box, unified treatment.			+	+				L		√
Production area	Unnecessarily wasted plastic part due to process complexity, ending in material recycling.	Avoid	Optimize process to avoid material waste.	+		+	+	+			H		√
Production area	A large number of disposable containers are used to install the engine.	Circulate	Self-made LCIA engine lower guard plate rotating platform, to achieve the purpose of recycling the loading.				+	+			M	√	
Finished product area	Use of welding reworking electrode cap in repair area.	Circulate	Recycle the discarded electrode cap after repair.				+	+			H	√	
Finished product area	Rain detection equipment makes heavy use of water resources.	Circulate	Add filtration system, recycle test water.		+		+	+			M	√	
Finished product area	Excess outdoor (diesel) forklifts driving, resulting in emissions to air and noise.	Avoid	Self-monitoring of driving distance to reduce emissions.			+					M	√	
Finished product area	A large number of high-power forklifts transport materials, leading to high pollution, high cost and noise.	Substitute	Buy AGV cars instead of forklifts to reduce labor and electricity costs and improve the environment.			+	+	–		+	L	√	

Finished product area	Car glass cleaning station use a large number of non-recyclable white gauze.	Circulate	Make multiple gauze balls and recycle them.				+	+	L	√	
Living area	The report production and distribution system should be trained and formally activated in the workshop.	Circulate	Train and formally implement report production and release system to reduce carbon emission and paper use.			+	+		H		√
Living area	The floor of the workshop is marked with toxic paint extensively.	Substitute	In some unnecessary occasions, use tape instead of paint for marking.			+			H	√	
Living area	Domestic water consumption is large, resulting in waste.	Circulate	Add some pipes to recycle the waste water.		+	+	+	+	H	√	
Living area	A large number of labor protection service damage and worse, increasing unnecessary costs.	Avoid	Establish the replacement standard and change the special labor protection service for the special type of work.				+	+	H		√
Living area	The workshop lighting has high power and cost.	Substitute	Replace some incandescent lamps with LED headlights.		+			–	H	√	
Living area	The workshop lighting has high power and cost.	Avoid	Integration of MES and EMS systems, overall control by CEIR.		+			+	H		√
Living area	Workshop air conditioning has high energy consumption and high cost.	Avoid	Issue rules for air conditioning to avoid energy waste.		+			+	H	√	
Living area	A large number of waste computers in the production team.	Circulate	Disassemble and recycle the used computer parts to reduce the maintenance cost.				+	+	L	√	
Living area	Large use of paper on production site (e.g., for application, technical change, technical demonstration, etc.).	Avoid	Promote paperless office and avoid excessive use of paper.	+			+	+	H		√
Living area	Remove the air conditioner of the old cleaning machine and use it as a spare part of the air conditioner of the electrical cabinet.	Circulate	Remove the old air conditioner parts and use them as spare parts.				+	+	L	√	

Note that the information in Table 3 is incomplete in the interest of commercial confidentiality. Moreover, owing to the limited space, three columns of information (*whether to impose*, *end time* and *responsible person*) are not presented, as they are not the focus of this article. In addition, these measures do not have a one-to-one correspondence. Because many operating stations have the same problem, the list is not repeated. Notably, the strategies and measures were formulated according to the actual situation of the assembly workshop. Different production plants should formulate the relevant improvement measures according to the actual situation, although users can identify the directions to solve the problem through the strategies in the four quadrants.

4.3 Effectiveness assessment

Considering the inconvenience of obtaining value stream data such as those of materials and energy in the assembly workshop, we used indirect indicators for the evaluation and unified them to determine the cost. These data yielded preliminary results. Several measures were not implemented immediately and were incorporated in Kaizen events for continuous improvement. Therefore, the data do not reflect all the results.

Since the difference in the monthly vehicle output significantly affects the overall data and may distort the results, the monthly consumption value of a single vehicle was used in the evaluation. These measures were studied and implemented in December of 2020. We took the average data for the three months (Sep.-Nov.,2020) before implementation (BI) of the measures as the reference object, and compared them with the data for the first month (Jan.,2021) post implementation (PI) of the measures. All data, including output, water consumption, etc., are actual values for the month, as shown in Table 4. Finally, as shown in Figure 8, the specific water consumption (SWC), specific electricity consumption (SEC) and production waste cost per vehicle (PWCPV) decreased by 6.45%, 8.26% and 5%, respectively. In addition, through downgrading, recycling and other ways, idle and waste appliances (equipment, tools, tooling) in the workshop contributed to the surplus value. Moreover, the advantages of recycling several office supplies and labour protection supplies were significant.

Table 4. Change in the indicators change before and after the implementation of measures.

	Unit	Value (BI)			Mean value (BI)	Value (PI)	Rate of change
		Sep.	Oct.	Nov.		Jan.	
Output	vehicle	16180	19191	19443	18271	19105	
Water	m^3	1506	1806	1771	1694.33	1653	

consumption							
SWC	m^3 /vehicle	0.093	0.094	0.091	0.093	0.087	**6.45% ↓**
Electricity consumption	kWh	245100	283164	315293	281185.67	269610	
SEC	kWh/vehicle	15.15	14.76	16.22	15.38	14.11	**8.26% ↓**
Production waste cost	yuan	10193.4	10938.87	11471.37	10867.88	10889.85	
PWCPV	yuan/vehicle	0.63	0.57	0.59	0.60	0.57	**5% ↓**

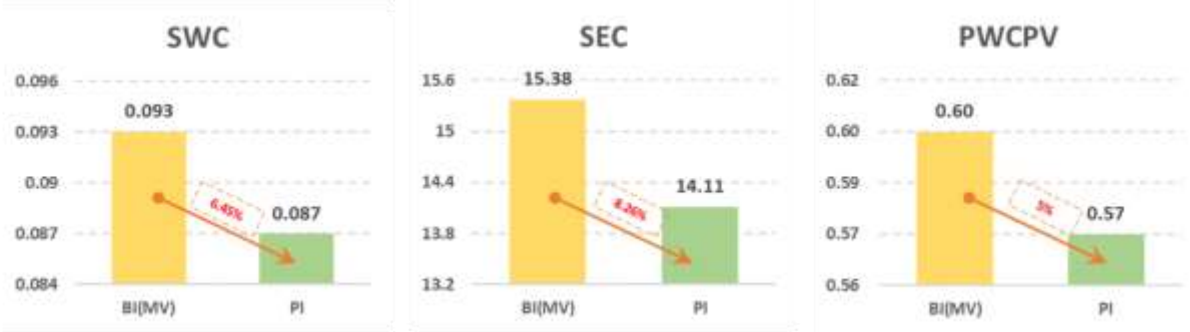

Figure 8. Percentage decline in SWC, SEC, and PWCPV.

The reduction in the environmental burden of certain measures was reflected in the trade-off column in Table 3. The trade-off results indicated that many measures could help enhance the environment. Unfortunately, this information could not be concretely reflected. Notably, we paid a return visit to the management team of the workshop and received their unanimous praise. The packaging materials of parts and components occupied a major part of the solid waste disposed in the workshop, and the associated cost was reduced through recycling. Because the recycling and disposal was performed by a service provider, the relevant data could not be obtained.

5. Discussions, implications and limitations

5.1 Discussions

The strategy quadrants are the foundation of the CEEP method. The quadrants were inspired by the waste recovery model presented by Kurdve and Bellgran (2021). However, contrast to the recycling model, the paper not only analysed the similarities and differences between the solutions of GL and CE (Figure 1) but also used the results as the basis for the strategy quadrants in combination with the continuous improvement principle (Kaizen) to formulate the CEEP method (i.e., phases 1–3). This framework can allow the CE concept of utilization of waste resources to be integrated into the production process, which has not been considered in the existing studies.

The circulation strategy is considered a necessary solution, according to the literature research and practical cases. In particular, the avoidance and substitution strategies pertain to GL and emphasize the elimination of the root cause of the problem, which in many cases, is impossible to achieve. A production process involves many waste resources (especially in heavy manufacturing companies), and recycling these waste resources is the most logical step. Therefore, the proposed method of integrating the recycling thought process of CE with the GL management is of significance to enhance the RE in the manufacturing industry.

In general, the specific advantages of the CEEP method combining GL and CE include: (1) adopting the CEEP method allows enterprises to be lean and environmentally friendly. Lean has been proven to be strongly related to cost and time consumption, while green is closely related to the environmental load; (2) like other green practices, one of the goals of CEEP is to enhance the use of natural resources and reduce environmental impact, but CEEP focuses more on the flow of materials and energy from the production process to identify improvement opportunities; (3) the CEEP method places greater emphasis on collaboration across the supply chain, providing a reference for companies operating in the entire value chain; (4) unlike the conventional CE deployment approach (top-down), the CEEP method also enables bottom-up deployment for improvement; (5) the CEEP method is a promising and convenient tool for manufacturing companies to embrace CE.

5.2 Implications

The manufacturing industry is being increasingly subject to review by regulatory agencies and the public to prevent any potential environmental hazards and heavy waste of resources from the production operations of manufacturing companies. Therefore, manufacturing companies are continuously seeking breakthroughs in sustainability. Gupta et al. (2021) argued that CE and cleaner production are becoming increasingly important as innovative approaches to contribute to sustainable development, but the existing literature does not report on the combination of these innovative methods, as also indicated by our review. The idea of combining CE and GL solutions can facilitate further research in this field to improve the sustainability of manufacturing companies.

CE solutions are not useful in all situations. In contrast, GL solutions are more direct and effective in the context of improvement actions in production operations. For example, in the empirical case of improvement, the improvement strategies for avoidance and substitution outperform those for circulation and disposal. However, in the context of defective product management, SC packaging improvement, and transportation management problems, solutions can be identified through the circulation strategy in cooperation with suppliers. The implementation of most CE strategies requires the joint efforts of the industry chain, including the upstream suppliers and downstream distributors. Thus, while GL is more direct and convenient for the manufacturing process, CE is more suitable to enhance the sustainable operation of different types of or multiple value chains. This conclusion supports the findings of Kirchherr et al. (2017).

According to the case study, only environmental performance improvements cannot help achieve the sustainability goals in manufacturing. Notably, the improvements associated with environmental issues are scant, and the manufacturing process is focused on ensuring the rational use of process waste and energy savings or recovery. This finding supports the finding presented by Gupta et al. (2021): sustainability cannot be achieved by improving the environment alone. In future studies, researchers can perform analyses in related fields, focusing on the respective proportions of environmental improvement and RE in achieving sustainability.

Based on the above analysis, companies can design a BM with small loops embedded in large loops by using the CEEP approach. Although the application scenario of the CEEP approach is the manufacturing floor, improvement measures under CE thinking always emphasize full value chain activities, which involve more or less upstream and downstream partners, such as the case in Figure 7. Therefore, the implementation of the CEEP method within the manufacturing floor can be considered as a small cycle, while the upstream and downstream value chain activities are considered as a large cycle. To operate this BM successfully, the level of SCM is a challenge. As Urbinati et al. (2020) argues, value creation occurs within the value network dimension of a company's BM, and requires SCM and key relationships with suppliers, manufacturers and retailers.

5.3 Limitations

This study involves certain limitations. In the evaluation stage, a systematic evaluation model is not used, and only indirect evaluation indicators or qualitative evaluation methods are used. In the future, we consider the utilization of tools such as energy efficiency management, material efficiency indicators and material flow accounting monitoring systems, and the unification of key performance indicators. With this approach it is possible to delve into special evaluation models for CE in the production process.

6. Conclusions

The existing studies to combine the GL with CE-related concepts to improve the sustainability of manufacturing processes are limited. To address this research gap, this study analyses the relationship between GL and CE solutions and visualizes the relationship using Venn diagrams. Additionally, this study uses the result (i.e., the four strategy quadrants) to develop the CEEP methodology. The CEEP method is based on the principle of continuous improvement and consists of three successive phases to achieve closed-loop management of RE and environmental improvements in the production process. In addition, this paper verifies the effectiveness and practicality of the proposed method by considering the assembly shop of an automobile company as an example. The result shows that by implementing reasonable strategies, the SWC and SEC in the workshop were reduced by 6.45% and 8.26%, respectively. After recycling the defective product waste, the PWCPV was reduced by 5%.

Notably, this study develops a systematic methodology to investigate the possibility and impact of implementing the CE concept in the production process, which is a pioneering concept. Several meaningful conclusions can be derived. First, considering the sustainability requirements, manufacturers should actively research techniques to exploit the advantages of concepts or technologies such as CE, I4.0, and cleaner production to optimize production in a green manner. However, decision-makers must first understand that embracing these applications is not expected to incur considerable costs associated with the introduction of high-end technologies, and instead, a shift in thinking and management is necessary. Second, the combination of the CE-related concepts and GL indicates that the two concepts are compatible; such results may also positively influence the production sustainability. Finally, practical cases show that the CEEP method is an innovative way to implement the CE concept in production operations and is a novel management concept for sustainable operations. The CEEP method is convenient and effective in the context of manufacturing industries and can provide decision-makers with real and feasible strategies to optimize production with CE, which may facilitate the transition to CE for companies.

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