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Circular Economy Maturity Models: A Systematic Literature Review

D. Kreutzer, S. Müller-Abdelrazeq, I. Isenhardt

***Abstract*—**Resource scarcity, energy transition and the planned climate neutrality pose enormous challenges for manufacturing companies. In order to achieve these goals and a holistic sustainable development, the European Union has listed the circular economy as part of the Circular Economy Action Plan. In addition to a reduction in resource consumption, reduced emissions of greenhouse gases and a reduced volume of waste, the principles of the circular economy also offer enormous economic potential for companies, such as the generation of new circular business models. However, many manufacturing companies, especially small and medium-sized enterprises, do not have the necessary capacity to plan their transformation. They need support and strategies on the path to circular transformation because this change affects not only production but also the entire company. Maturity models offer an approach to determine the current status of companies' transformation processes. In addition, companies can use the models to identify transformation strategies and thus promote the transformation process. While maturity models are established in other areas, e.g., IT or project management, only a few circular economy maturity models can be found in the scientific literature. The aim of this paper is to analyze the identified maturity models of the circular economy through a systematic literature review (SLR) and, besides other aspects, to check their completeness as well as their quality. For this purpose, circular economy maturity models at the company's (micro) level were identified from the literature, compared, and analyzed with regard to their theoretical and methodological structure. A specific focus was placed, on the one hand, on the analysis of the business units considered in the respective models and, on the other hand, on the underlying metrics and indicators in order to determine the individual maturity level of the entire company. The results of the literature review show, for instance, a significant difference in the number and types of indicators as well as their metrics. For example, most models use subjective indicators and very few objective indicators in their surveys. It was also found that there are rarely well-founded thresholds between the levels. Based on the generated results, concrete ideas and proposals for a research agenda in the field of circular economy maturity models are made.

***Keywords*—**Circular economy, maturity model, maturity assessment, systematic literature review.

I. Introduction

POLITICAL goals such as the European Union's climate targets for 2030 and societal changes such as the growing sustainability awareness of entire generations have a major influence on manufacturing companies [1]. On the one hand, they have the goal of maximizing profits and operating cost-efficiently, and on the other hand, they must and want to consider social, ecological and political factors. Manufacturing companies cannot ignore these factors, also due to political framework conditions such as the goals of the European Union (EU) or also media interest, such as in the Fridays for Future movement, as this can have a direct or indirect influence on their customer segments [2]. In order to remain viable for the future, companies are increasingly focusing on sustainable business practices [2].

Due to increasing resource scarcity worldwide, the need to reshape the "metabolism of humanity" in relation to finite raw materials has been recognized in the recent past [3]. Since the early 21st century, therefore, the notion of the circular economy has increasingly become the focus of industry, governments and economic alliances. The idea of the circular economy has been around for more than 50 years. However, it has only recently gained widespread attention due to increasing threats such as climate change [4]. Acute problems such as the shortage of raw materials or climate change are becoming difficult to solve due to the established linear economy with end-to-end chains for raw materials, from extraction, use to disposal [5]. The principle of circular economy, where material flows consist of e.g., materials designed for circulation in socio-economic systems with recycling as a key strategy, has generated more and more attention in recent years in the wake of the increasingly urgent need for a more sustainable "industrial metabolism" [3].

On a political level, the circular economy is listed as a measure of the European Green Deal for sustainable development and has many potentials to achieve the planned climate neutrality of the EU. Between 45% and 70% of global CO_2 emissions can be reduced through a circular economy [6]. Frans Timmermans, Executive Vice-President for the European Green Deal, also sees the shift from linear value creation to the circular economy as necessary not only to strengthen but also to maintain the economic competitiveness of businesses [7]. The circular economy has the essential difference to linear value creation that products gain "value" along the value chain (purchase to disposal), as they flow into the value chains of other products and do not lose "value" [5].

In order to achieve a far-reaching establishment of the principle of the circular economy, manufacturing companies must be shown ways and strategies of how to implement a change in their structures and processes to this end. It is important not to remain in a general and theoretical framework, but to provide concrete and clearly defined methods for practice. Particular attention should be paid to small and medium-sized enterprises (SMEs), as they represent 99% of

D. Kreutzer*, S. Müller-Abdelrazeq and I. Isenhardt are with RWTH Aachen University, Chair of Production Metrology and Quality Management & Institute for Information Management in Mechanical Engineering, Germany, 52068 Aachen, Dennewartstr. 27 (*corresponding author, phone: +49 2418091174, e-mail: dennis.kreutzer@ima.rwth-aachen.de).

European enterprises [8]. As the transition to circular company structures is very complex, a broad base of know-how is needed, which is not available to many companies [9]. The concept of the circular economy is largely based on new technologies and business models [9]. It also requires structural changes in all areas of business, from product development, resource sourcing and supply chains to the structure of use and end-of-life design [9], [10].

Maturity models (MM) are helpful tools to support these business challenges [11]. MM comprise a sequence of maturity levels for a class of objects and thereby describe a desired or typical development path of these objects in successive, discrete ranks, starting at an initial stage up to full maturity [12]. Progressing along this development path means a steady increase in the performance or quality of the object under consideration, with the MM serving as a scale for assessment [12].

Evaluation systems are used to calculate and present maturity. According to Bensiek, a distinction can be made here between the two approaches of scoring and stage-based maturity levels [13]. In scoring, points are awarded for different characteristics. These points are added up and represent the developmental stage depending on the total number of points. In the case of stage-based maturity levels, it is defined that a maturity level can only be reached if all the requirements set for the maturity level are met, whereby skipping a stage is basically not possible. In this context, maturity levels can be assigned organization-wide or specific to a field of action. [13]

The aim of this paper is to explore the development of MM in the area of circular economy for manufacturing companies. Bensiek [13] and Becker et al. [12] emphasize that before developing a new model, it is preferable to examine existing models and their possible adaptability. Therefore, this paper identifies existing circular economy MM for manufacturing companies through a SLR and evaluates them according to defined analysis criteria.

II. Method

SLRs collect answers from the literature on specific questions or hypotheses, consolidate the results and identify the need for further research on a particular research topic [14]. In the context of this paper, an SLR was chosen to identify and contrast circular economy MM for manufacturing companies and to highlight the respective focus of the model, as well as the research gaps. These results are useful for academia to get a time-saving overview of the research field of MM in the circular economy and to drive further research based on the synthesized results. For traceability, therefore, objectivity and replicability must always be present when conducting an SLR [15]. For this reason, SLRs follow a fixed procedure, but the number of steps varies from author to author. Kitchenham and Charters [16], for example, propose a three-stage procedure consisting of the main phases: (1) planning, (2) implementation and (3) reporting, which is further subdivided into several sub-phases. Denyer and Tranfield [17], on the other hand, recommend a similar procedure according to the phases: (1) formulation of the research question, (2) finding studies, (3) study selection, and (4) analysis and synthesis, as well as (5) reporting and use of the results. Another scientifically recognized approach is based on the *Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)* method [15]. This divides the SLR into the four phases of identification, screening, eligibility and inclusion.

Building on these approaches, our SLR is divided into the five phases of (1) problem formulation and question identification; (2) literature search; (3) eligibility criteria and screening/evaluation of research; (4) research analysis and interpretation; and (5) presentation of results. This approach is also inspired by Correira et al. [18], who conducted an SLR on MMs in supply chain sustainability. Fig. 1 presents a diagram of the methodology that depicts the five phases of the SLR. In this chapter, the first four phases are discussed in more detail, whereas the results are consolidated in Section III.

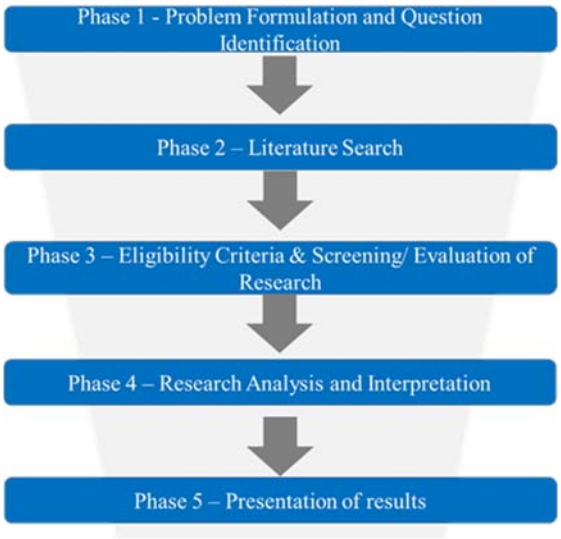

Fig. 1 Procedure for the SLR

Phase 1 - Problem Formulation and Question Identification

MM are intended to represent changes in an entity's competencies in a stage or stadium-like manner and along a desired or logical pathway [19]. These stages are represented by levels or stages, which represent a path from a baseline state to full maturity. Each level/stage contains criteria and characteristics that must be met in order to reach it, as well as concrete approaches for advancing to higher levels [20]. The application of the models is mainly limited to the analysis of actual states in order to determine the maturity level of a company in the predetermined characteristics. Through the maturity approach, companies can also use the models to identify transformation strategies and thus continuously drive the transformation process forward [21]. Concrete improvement approaches can then be formulated from the descriptions of the levels and incorporated into the company's strategic planning [12].

Due to this relevance, it is of high importance for manufacturing companies to obtain an overview of existing

MM from the scientific literature, which can support them in their model selection and thus promote their circular business transformation. In the research area of MM in the circular economy, some literature analyses have already been carried out, but these were related to other sectors, such as IT, project management or supply chain management (e.g. [22]). Correiera et al. identified 11 MM to assess and promote sustainability in the supply chain [18]. Montag et al. identified 35 models and frameworks to develop a Circular Supply Chain Maturity Model based on them [23]. However, structural changes are needed in all areas of the company, from product development, resource procurement and supply chains to the structure of use and the conception of the product's end of life [9]. Accordingly, there is currently a lack of a review of the literature on holistic MM for manufacturing companies, which leads to the first research question as follows:

- RQ1: Which circular economy maturity models already exist for manufacturing companies at micro level in the literature?

The selected characteristics of the model on the basis of which maturity is determined is a critical point, as these form the basis of the model. According to Akkasoglu, the maturity-relevant characteristics are subject to the five requirements of goal conformity, independence, completeness, interpretability and influenceability [24]. Considering previous literature from other research areas, the selected criteria may vary depending on the MM. Correiera et al. identified variations in their SLR MM from missing to 24 characteristics, for example [18]. Considering the maturity measurement for manufacturing companies, it is of great importance by which characteristics maturity is captured, which leads to the following research question:

- RQ2: What characteristics influence the circular maturity of a manufacturing company?

In addition to the definition and number of maturity-relevant characteristics, the measurement method is also crucial for determining the maturity level. The measurement method includes the type of questions used to gather information for the respective characteristic. According to Bensiek, three measurement methods occur in MM [13]: open-ended questions, closed-ended questions and Likert scale questions. The commonly used Likert scale allows users to indicate their level of agreement ("strongly agree" to "strongly disagree") with a statement [25]. In a survey with closed questions, several concrete expressions of the characteristic are given for answering. In contrast, open-ended questions do not give any answer options [11], [26]. Thus, questionnaire-based models insist on self-assessments and thus involve a certain subjectivity or fuzziness compared to the use of exact values with units of measurement [27]. This leads to the third research question:

- RQ3: Which measurement methods are used to record the characteristics relevant to maturity?

Phase 2 - Literature Search

In the second phase of the SLR, the search strategy for the literature search is determined and databases are searched using keywords. Due to the increasing publication on the internet, we concentrated exclusively on scientific electronic literature databases. According to Gusenbauer and Haddaway, the four well-known academic literature databases SCOPUS, Web of Science, EBSCOhost and ScienceDirect are suitable for an SLR [28]. In view of the selected research area, the titles and abstracts were examined by means of a keyword search of the four databases in the fixed period from 2000 to 2023. The results were continuously narrowed down using a three-stage keyword entry procedure linked with AND operators ("Circular Economy" AND "Maturity"; "Circular economy" AND "Maturity" AND "Model"; "Circular economy" AND "Maturity" AND "Model" AND "Manufacturing"). This three-step process allows circular economy MM for manufacturing companies to be identified without losing any models in the last search function if one were to start with this one. Through this process, a total of 533 publications were identified across all four databases. The keyword searches of the SCOPUS and Web of Science databases yielded more than twice as many publications as ScienceDirect and EBSCOhost. The overview of the number of identified models per search term and database is shown in Table I.

TABLE I
KEYWORD SEARCH USED IN THE DATABASES

Keyword Search	SCOPUS	Web of Science	ScienceDirect	EBSCOhost	Total
Circular economy AND Maturity	121	122	50	44	337
Circular economy AND Maturity AND Model	55	60	22	21	158
Circular economy AND Maturity AND model AND manufacturing	13	14	6	5	38
Total	189	196	78	70	533

Phase 3 - Eligibility Criteria & Screening/Evaluation of Research

In the third phase, the scientific literature identified is narrowed down using eligibility criteria to identify only the most relevant literature [29]. Since the literature search was conducted separately for each database, all duplicates were excluded in a first step. This resulted in 162 publications from the original 533 publications. During the subsequent screening process, the titles and summaries of all results were read in order to exclude the publications that did not fall within the scope of the circular economy MM for manufacturing companies. This resulted in the exclusion of 117 publications. This included some readiness models that will not be considered in this SLR. Although the term "readiness" is understood in a very similar way to "maturity" and both terms refer to an evolutionary process, the term "readiness" refers to the readiness of an organization to start the development process and the term "maturity" refers to the level of maturity the organization is already at [30].

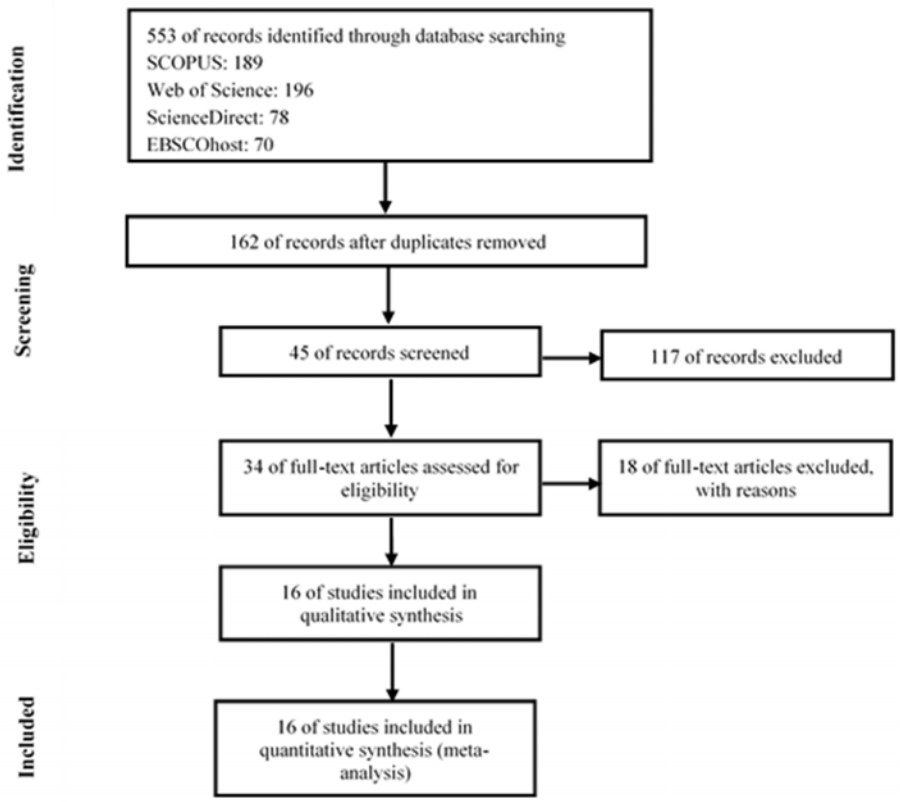

Fig. 2 PRISMA diagram

Subsequently, all remaining publications were checked for additional criteria:

- *Written in English:* The publication must be written in English so that it is accessible to a broad scientific community.
- *Published in scientific journals or conferences:* The literature must have been published in a scientific journal or presented at a scientific conference. This excludes unpublished literature and guarantees scientific quality.
- *Presentation of a maturity model as output:* This excludes publications without a clear model. This exclusion criterion was defined in order to be able to derive clear phases and maturity-relevant characteristics or their measurement methods.
- *Focus on micro-level:* This excludes publications whose circular economy MM focus on meso-level (e.g., networks) and macro-level (e.g., nations).

Based on these criteria and the number of models identified, 16 models were identified for further analysis. The entire search process is illustrated by the PRISMA flowchart in Fig. 2.

Phase 4 - Research Analysis and Interpretation

The fourth phase describes the analysis of the identified publications for specific analysis criteria in order to obtain statements about the research questions. Seven analysis categories with different numbers of subcategories were defined. We followed the analysis categories of Correira et al., but added "maturity-relevant characteristics" for RQ 2 and "measurement method" for RQ 3 (see Table II) [18]. If no sufficient information could be identified in a subcategory, this was marked as "not identifiable".

III. Results

In this chapter, the 16 identified refection models are analyzed using the criteria from Table II and the results are described in detail. Fig. 3 shows the number of publications and the type of publication over time. It is noticeable that 14 of the 16 MM were published in journals and only two as conference proceedings. In addition, the number of models increases with the years, whereby 2023 is still excluded due to its incompleteness.

Scope, Typology and Architecture of the MM

According to Bensiek, the scope of a MM can be action-specific or organization-wide [13]. To answer RQ 1, it can be stated that all 16 models have a holistic approach to organizational maturity assessment, but differ in the specific task focus. Brendzel-Skowera [33], e.g., focuses on the implementation of business models for SME, whereas Heazendonck and van den Berghe [34] examine Belgian ports on their circular maturity. This focus on the holistic approach is also reflected in the maturity-relevant characteristics for answering RQ 2, which are explained in more detail in the subchapter components.

TABLE II
CATEGORIES FOR THE LITERATURE REVIEW ANALYSIS PARTLY BASED ON CORREIRA ET AL. [18]

Category	Subcategories	Description
Paper identification	Authors	List of authors
	Publication date	Year of publication
	Publication type	Journal article, conference proceedings, etc.
Scope	Maturity Scope	Process, whole company
Typology [31]	Structured models	A formal and complex structure, similar to the CMMI
	Maturity grids	A set of maturity levels that address different aspects of a research field
	Likert scale questionnaires	A series of questions where survey participants rank the company on a scale of 1 to n
	Hybrid models	A combination of characteristics of maturity grids and Likert scale model structure
Architecture [32]	Staged	A cumulative set of areas that define each level. All areas of a level must be successfully achieved before the next level can be entered.
	Continuous	A set of areas that can be addressed separately. Instead of addressing all areas of a given level, the focus of optimization can be on a specific area
	Others	Other information not included in the previous subcategories
Components [31], [32]	Number of maturity levels	Count of the number of maturity levels
	Descriptors	The name for every level of maturity
	Level description	The value is "Yes" if it contains the description or summary of the characteristics of the individual levels, otherwise "No".
	Maturity-relevant characteristics	Various approaches to analyzing or assessing the level of maturity, taking into account one or more common characteristics. Alternatively, it may be a set of activities that contribute to achieving a number of objectives that contribute to attaining a higher level of maturity.
Measuring method	Metrics	Subjective/fuzzy or objective/distinct measuring method
Validation	Validation	Information about the validation and number of validation phases
Model development	Development basis	Building on a model or own developed concept

Although all models focus on the circular economy maturity assessment for companies or organizations, the model of Kayikci et al. [35] provides a broader framework for consideration. In addition to circular maturity, it also measures circular readiness as well as maturity and readiness for Industry 4.0 transformation.

The MM typology can differ from model to model. Of the 16 models, nine models can be assigned to a structural typology (e.g. [36]). Despite this predominant typology among the models, other models can be assigned to a different typology, such as the maturity model by Uztürk and Büyüközkan [37] which applies to a maturity level grid representation. Other authors also use a grid representation, but combine this with a Likert scale questionnaire to form a hybrid model, such as by Sacco et al. [38]. The models of Górecki [39] and Vegter et al. [40] could not be assigned to any of the other typologies and were therefore labelled "Others".

The most commonly used form of maturity model architecture is the stage-by-stage representation of circular economy maturity. Eleven out of 16 models, such as Acerbi et al. [36], prefer this representation. The continuous representation is taken up by four models, such as. e.g., Golinska-Dawson et al. [41]. Only one model, that of Górecki. [39] uses neither a stepwise nor a continuous representation, but tabulates the maturity of each component separately. The detailed analysis and comparison of the identified MM are shown in Tables III and IV.

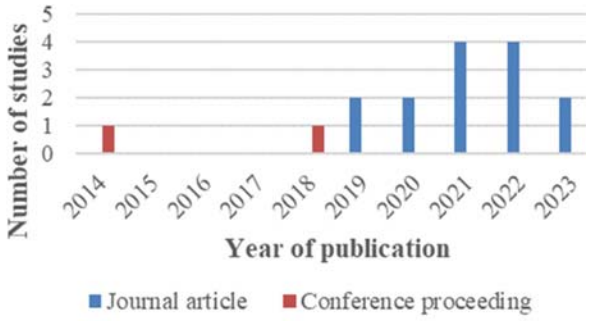

Fig. 3 Number of identified MM per year

Validation and Model Development

According to Bruin et al., it is of particular importance to test the MM after their development and to validate them for validity, reliability as well as generalizability [11]. 13 of the 16 identified models name a validation process, although this varies widely: Some models apply their model to a different number of companies, e.g., Brendzel-Skowera [33] which tests its model on 99 SMEs. Another form of validation consists of interviewing experts, as done by Ünal & Sinha [42] who interviewed 17 CEOs from different companies. However, not only through interviews, also through workshop concepts, as by Acerbi et al. [36] can also be used to validate the MM. A comprehensive validation approach was used by Sacco et al. [38] who tested their model for completeness and reliability in three validation iteration steps (1. self-validation, 2. expert validation, 3. company validation). Only the models of Górecki [39], Romero & Molina [43] and Uhrenholt et al. [44] do not mention any validation steps.

TABLE III
COMPARISON OF THE MATURITY MODELS

Paper	Scope	Typology	Architecture	Validation	Model development
Acerbi et al., 2021, Journal article [34]	Manufacturing companies, whole company	Structured model	Staged	Two complementary workshops evaluating its applicability and value	New model
Brendzel-Skowera, 2021, Journal article [31]	Business models for SMEs; whole company	Hybrid: structured model and Likert scale)	Staged	Model was tested at 99 SMS	Combination of Business Model Canvas, the CMMI and R2Pi classification of CE Business models [40]
Golinska-Dawson et al., 2021, Journal article [39]	Responsible Resource Management in Remanufacturing for SMEs; remanufacturing as an CE transition practice	Hybrid: maturity grid and Likert scale)	Continuous, based on score (0-100%)	Tested at 4 SMEs	New model
Górecki, 2019, Journal article [37]	Companies in the construction industry	Other (no levels, staged etc.), not mentioned	Others	Not identifiable	New model
Haezendonck & van den Berghe, 2020, Journal article [32]	Belgian Ports	Structured model	Staged	Tested through 5 Belgian ports	New model, maturity level based on R-strategies from Potting et al. [41]
Howard et al., 2018, Conference proceedings [42]	Whole company	Structured model	Staged	Tested with 8 cases from dairy and baking sector in UK	Based on CMM
Julkovski et al., 2022, Journal article [43]	Whole company, example on craft breweries	Structured model	Staged	Tested with 22 craft breweries from Portugal and Brazil	Adapted from Grant and Pennypacker [44]
Kayikci et al., 2022, Journal article [33]	Whole company, focus on SMEs	Hybrid: maturity grid & questionnaire	Continuous	Different rounds through DELPHI method; tested with Turkish fashion industry	New model, level based on Grant and Pennypacker [44]
Romero & Molina, 2014, Conference proceedings [45]	Whole company, Green Virtual Enterprise Breeding Environments	Structured model	Staged	Not identifiable	New model
Sacco et al., 2021, Journal article [36]	Whole company	Hybrid: maturity grid & questionnaire	Continuous	3 validation rounds	New model, Categories based on Porters Value Chain [46]
Sehnem et al., 2019, Journal article [47]	Whole company, Business model in production chain	Structured model	Staged	Applied to 105 Business models in Brazil	Adaptation: Level based on Grant and Pennypacker [44], Characteristics based on EMF-CE-Model [5]
Sehnem et al., 2020, Journal article [48]	Whole company, wine chain production	Structured model	Staged	Applied to 105 Business models in Brazil	Adaptation: Level based on Grant and Pennypacker [44],Characteristics based on EMF-CE-Model [5]
Uhrenholt et al., 2022, Journal article [49]	Whole company	Structured model	Staged	Not identifiable	New model
Ünal & Sinha, 2023, Journal article [50]	Whole company	Structured model	Staged	Validated through 17 interviews with CEOs from firms	New model
Uztürk & Büyüközkan, 2022, Journal article [35]	Whole company, agriculture as an example	Maturity grid	Continuous	Tested with an example agriculture farm in Turkey	New model
Vegter et al., 2023, Journal article [38]	Maturity model is focused on material flow through a CE supply chain	Not identifiable	Staged	Only the dynamic flow diagram is tested	Not identifiable

In terms of model development, the models of Brenzel-Skowera adapt [33] and Howard et al. [45] adapt the Capability Maturity Model Integration (CMMI) to classify maturity levels into 1 - Initial, 2 - Managed, 3 - Defined, 4 - Quantitatively managed and 5 - Optimizing. Four other models ([35], [46]-[48]) use the designation of maturity levels according to Grant and Pennypacker with the levels zero meaning non-existent, one - executed, two - managed, three - established, four - predictable, and five - optimized [49]. Another aspect of model development concerns the combination of different model components, such as Brendzel-Skowera, who combines the Business Model Canvas with the CMMI and the R2Pi to create a new extended model [33].

Components

This subchapter answers RQ 2. An important component of a maturity model is the maturity levels, which represent to the user how advanced the transformation to a specific area is [12]. Table IV shows that the number of maturity levels, but also the way they are presented, varies in terms of scale. While 14 of the 16 models use fixed levels in the form of an ordinal scalar, such as Romero & Molina [43] (L1: performed; L2: managed; L3: Standardized; L4: Innovating), the model according to Sacco et al. [38] uses an interval scale from 0% to 100% [50]. All 16 models use an upstream literature review for the maturity-related characteristics, such as Sacco et al. which is oriented towards the eight enterprise domains of the Porter Value Chain to be able to map a holistic enterprise maturity [38].

TABLE IV
COMPARISON OF THE MATURITY MODEL COMPONENTS

Author	Components				Measuring method
	Number of maturity levels	Descriptors	Level description	Maturity-relevant characteristics	Metrics
Acerbi et al. [34]	5	1 – Linearity; 2 - Industrial CE Piloting; 3 – Systematic Materials Management; 4 - CE Thinking; 5 - Full Circularity	Yes	no fixed set, exemplarily mentioned: • 1 (legal responsibilities, company performance) • 2 (company interested in changing, pilot experimentation, process parameter material and energy consumption, the strategic level) • 3 (reuse, refurbish, recycle, and remanufacture materials; controlling; stakeholder management) • 4 (stakeholder management, controlling) • 5 (strategic, process, stakeholder management)	Not identifiable
Brendzel-Skowera [31]	6	L1 (initial); L2 (managed); L3 (defined); L4 (quantitatively managed); L5 (optimizing)	No	- L1: lack of knowledge about the assumptions of circular economy and business models dedicated to it; low environmental awareness; failure to limit the negative impact on the environment; environmental activities undertaken for pragmatic reasons; - L2: low level of knowledge about circular economy and business models dedicated to it; most of the processes regarding the area of environmental activities are identified and defined; environmental impact awareness; pragmatism in activities limiting negative impact on the environment; monitoring environmental indicators - L3: awareness of the impact on the environment and awareness of the existence of circular economy; environmental management system (formal or not) defined processes for the area of environmental activities; pragmatic and altruistic reasons for limiting negative impact on the environment; qualified employees for environmental protection - L4: familiarity with the rules of circular economy; work on redesigning the business model towards circular economy formalized environmental management system; process quality measures are built into the enterprise's decision-making system; the causes of process deviations are eliminated - L5: circular business model implemented; improvement of the organization through process monitoring in terms of possible improvements; formalized environmental management system; raising awareness of the company's stakeholders when it comes to ecology	Not identifiable
Golinska-Dawson et al. [39]	5	ML1 (very low); ML2 (low); ML3 (medium); ML4 (high); ML5 (very high)	Yes	All based on the characterization of the responsible resource management practices: 4 Resource groups: Water, Emissions, Energy, Material	Not identifiable
Górecki [37]	Not identifiable	No	No	Human resources; technical infrastructure; organizational culture; Organizational structure; management of construction projects; organization management	Not identifiable
Haezendonck & van den Berghe [32]	3	Energy Recovery; Recycling; Orchestrating new cargo streams	No	Not identifiable	Not identifiable
Howard et al. [42]	5	1 - Initiate; 2 - Manage; 3 - Improve; 4 - Inspire; 5 - Govern	No	Not separated into clear dimensions: • 1 (within firm) - Efficiency focus; Waste reduction • 2 (within firm) - Effective measures: materials, energy, water; Linear connections, CE awareness • 3 (supply chain) - Cont. improvement; Supplier improvement; some closed loops; Known nutrients; Optimized SKUs (Stock Keeping Unit); Skills focus; • 4 (sector) - Leads the sector; Drivers best practice; Regenerative and restorative; Regional capability; Investment plans; People focus • 5 (whole system) - System governance; policymaker links; Informs 6 informed by civic society; Includes wider stakeholders, NGOs; CE vision connects local, regional and national interests	Not identifiable
Julkovski et al. [43]	6	Non-existent (0); Executed (1); Managed (2); Established (3); Predictable (4); Optimized (5)	Yes	Based on technical and biological cycles: collect, retain/extend, share, reuse/redistribute, remanufacture/renew	Not identifiable
Kayikci et al. [33]	6	Non-existent (0); Executed (1); Managed (2); Established (3); Predictable (4); Optimized (5)	No	Economic, Environmental, Social, Policy, Process, Product, Strategy, Technology	Not identifiable

Author	Components				Measuring method
	Number of maturity levels	Descriptors	Level description	Maturity-relevant characteristics	Metrics
Romero & Molina [45]	4	L1: Performed L2: Managed L3: Standardized L4: Innovating	Yes	Material; Energy; Transportation; Marketing; Human resources; Information and communication system; Environment, health and safety; Production processes; Quality of life and community connections; Waste management	Not identifiable
Sacco et al. [36]	0-100%	No	No	• Firm Infrastructure: Strategy & Vision; Environmental management; Cooperation & industrial symbiosis • HR Management: Training; Employee satisfaction & participation • Technology development: Eco-design • Procurement: Supplier selection & auditing • Inbound & Outbound logistics: Direct logistic, Reverse logistic, • Operations: Resource consumption, Waste management, • Marketing & Sales: Marketing & communication	Subjective: 23; Objective: 3
Sehnem et al. [47]	6	Non-existent (0); Executed (1); Managed (2); Established (3); Predictable (4); Optimized (5)	Yes	Technical Cycle: Collect; Keep/Extend; Share; Reuse/Redistribute; Remanufacture/refurbish Biological Cycle: Collect; Cascade Exploitation; Extraction of biochemical raw materials; Anaerobic digestion; Biogas; Biosphere regeneration; Biochemical raw materials; Agriculture/collection	Not identifiable
Sehnem et al. [48]	6	Non-existent (0); Executed (1); Managed (2); Established (3); Predictable (4); Optimized (5)	Yes	Technical Cycle: Collect; Keep/Extend; Share; Reuse/Redistribute; Remanufacture/refurbish Biological Cycle: Collect; Cascade Exploitation; Extraction of biochemical raw materials; Anaerobic digestion; Biogas; Biosphere regeneration; Biochemical raw materials; Agriculture/collection	Not identifiable
Uhrenholt et al. [49]	6	None; Basic; Explorative; Systematic; Integration; Regenerative	Yes	Value creation; Governance; People and skills; Supply chain and partnership; Operations and technology; Product and material	Not identifiable
Ünal & Sinha [50]	5	1 - Basic; 2 - Bronze; 3 - Silver; 4 - Gold; 5 - Platinum	No	Material Health; Material reutilization; Renewable energy; Water stewardship; Social fairness	Not identifiable
Uztürk & Büyüközkan [35]	4	Emerging; Established; Leading; Ultimate	No	Product; Process; Business Model; Technology; Stakeholder	Not identifiable
Vegter et al. [38]	4	1 - virgin materials only; 2 - combination (virgin and recovered materials); 3 - recovered materials only; 4 – deterioration	Yes	Not identifiable	Not identifiable

The model by Górecki [39] does not specify a number of levels. Regarding the naming of the individual levels, six models use the names of other known MM, as described in the subchapter *Validation and Model Development*. Regarding the description of the individual levels, the SLR shows that half of the models give a description of the levels and the other half only mention the levels but do not go into more detail about the particular classification of the respective maturity level.

Table IV shows that the definitions and also the number of elements used to capture the respective maturity vary depending on the model and are not uniform. Some models, such as Uhrenhold et al. [44], use the same six maturity-relevant characteristics, such as “value creation”, which have different characteristics depending on the level of the six maturity levels, consistently throughout the entire model. Other models, such as Howard et al. [45] cite a different number and also definitions of maturity-relevant characteristics per maturity level that is significant for the respective level. In addition, there are also models that use a combination of both variants. Brendzel-Skowera, for example, uses individual characteristics such as “Knowledge about circular economy and business models dedicated to it” [33] consistently, but also adds additional characteristics per level. This insight also includes the threshold between the levels, which are sometimes not mentioned in detail or the delimitation of the maturity levels is described by characteristics such as "absent" to "low level" (e.g. in [31]). None of the models uses numerical threshold values that can be used to identify the assignment to a specific maturity level.

This wide variation of the models in terms of definition also relates to the number of characteristics used. Fig. 4 shows the number of maturity levels used (Y-axis) in relation to the number of characteristics used (X-axis) in 15 of the 16 models. Due to the interval scale of the model by [36], no clear assignment can be made with regard to the maturity levels,

therefore it is not listed in Fig. 4. It is clear that the number of maturity levels lies between three and six levels, with four models each having five levels (e.g., Acerbi et al. [36]) and six models six levels (e.g., Kayikci et al. [35]). Only for the model of Górecki [39] no maturity levels are given.

The variance in the number of levels is also evident in the number of characteristics. Here, the number ranges from none mentioned characteristics (Haezendonck and van den Berghe [34] and Vegter et al. [40]) to 26 maturity-relevant characteristics (Howard et al. [45]). The mean value across all models is about eight characteristics.

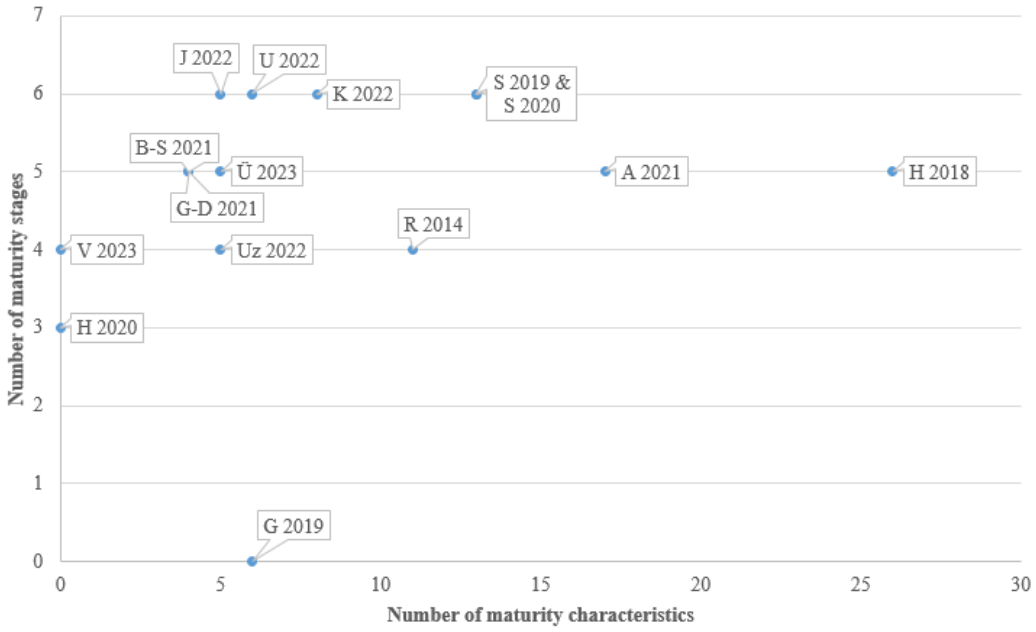

Fig. 4 Number of stages depending on the characteristics. Legend: A 2021 - Acerbi et al. [36]; B-S 2021 - Brendzel-Skowera [33]; G-D 2021 - Golinska-Dawson et al. [41]; G 2019 - Górecki [39]; H 2020 - Haezendonck & van den Berghe [34]; H 2018 - Howard et al. [45]; J 2022 - Julkovski et al. [46]; K 2022 - Kayikci et al. [35]; R 2014 - Romero & Molina [43]; S 2019 - Sehnem et al. [47]; S 2020 - Sehnem et al. [48]; U 2022 - Uhrenholt et al. [44]; Ü 2023 - Ünal & Sinha [42]; Uz 2022 - Uztürk & Büyüközkan [37]; V 2023 - Vegter et al. [40]

Measuring Method

To answer RQ 3, the measurement methods of the maturity-relevant characteristics were analyzed. In questionnaire-based MM, in this study mostly hybrid models, the availability and transparency of the underlying questionnaire have a great influence on the answering of the research question. With structured models, such as the MM according to [44], it is necessary to provide information about the measurability of the individual (sub-)characteristics. After analyzing all MM, it can be concluded that very few models provide sufficient information about the underlying metrics or questionnaires used. Only the model, according to Sacco et al. [38], allows a division into subjective or "fuzzy" and objective or "distinct" measurement methods. Here, self-assessments using e.g., Likert scales are classified as subjective or "fuzzy" measurement methods and values with clear units (e.g., kg, etc.) as objective measurement methods. In the Sacco et al. model, circularity is also assessed in addition to the question about the maturity of the company [38]. Due to the focus of this study on maturity, only the questions related to maturity were considered. It was possible to index 23 subjective and three objective measurement methods of the individual questions, whereby the objective questions referred to relative numbers in % (e.g., question item 17 "Which percentage of your suppliers are audited with regard to their circular economy practices?" [38]).

IV. Discussion

The results of this SLR show the great variety and high diversity in the individual circular economy MM for manufacturing companies in terms of typology, architecture, number and definition of maturity-relevant characteristics as well as the number of maturity levels. With regard to the design of the MM, the SLR shows that 11 of 16 models use a tiered representation. This representation is based on the assumption that specific criteria must be met in order to reach a maturity level [20]. To reach a higher level, all criteria of the lower level must be fulfilled. In contrast, four models use a continuous representation. This representation addresses the evolutionary nature of change and is based on the assumption that development is dependent on situational factors, which means that not all criteria need to be met to reach a higher level of maturity [51].

As a rule, the number of maturity levels varies among the models, whereby the higher the number of maturity levels, the greater the precision of the assessment, but also the complexity of the characteristics relevant to the maturity level [52]. The SLR confirms the variations in the number of maturity levels,

which ranges from three to six. The variations can also be seen in the type and number of maturity-relevant characteristics, which form the basis of any MM. According to Correira et al., there is no ideal number of characteristics for determining maturity in MM, as the trade-off between perceived complexity and independence of the characteristics should be taken into account when creating the model [18]. In the identified models, the number of characteristics used varies from zero to 26, with an average of eight characteristics, and thus most models include less than ten characteristics for assessment. This can be justified by the fact that these models are more general in design and are not fixed to a specific industry to be applied by many organizations.

TABLE V
CLASSIFICATION OF THE MATURITY-RELEVANT CHARACTERISTICS TO PORTER'S VALUE CHAIN

Porter's Value Chain Categories	Maturity-relevant characteristics	Reference
Firm infrastructure	Stakeholder management; Strategic management	Acerbi et al. [36]
	Circular business model/Environmental management/Awareness of the company's stakeholders	Brendzel-Skowera [33]
	Organizational culture/Organizational structure/Organization management	Górecki [39]
	Circular economy vision	Howard et al. [45]
	Policy/strategy	Kayikci et al. [35]
	Quality of life and community connections/Environment,	Romero & Molina [43]
	Strategy & Vision/Environmental management/Cooperation & industrial symbiosis	Sacco et al. [38]
	Value creation/governance/partnership	Uhrenholt et al. [44]
	Business model/Stakeholders	Uztürk & Büyüközkan [37]
HR management	Knowledge about circular economy	Brendzel-Skowera [33]
	Human resources	Górecki [39]
	Social	Kayikci et al. [35]
	Human resources/health and safety	Romero & Molina [43]
	Training; Employee satisfaction & participation	Sacco et al. [38]
	People & skills	Uhrenholt et al. [44]
	Social fairness	Ünal & Sinha [42]
Technology development	Technical infrastructure	Górecki [39]
	Technology	Kayikci et al. [35]
	Information and communication system	Romero & Molina [43]
	Eco-design	Sacco et al. [38]
	Technology	Uhrenholt et al. [44]
	Technology	Uztürk & Büyüközkan [37]
Procurement	Supplier improvement/Regional capability	Howard et al. [45]
	Supplier selection & auditing	Sacco et al. [38]
	Supply chain	Uhrenholt et al. [44]
Inbound & outbound logistics	Transportation	Romero & Molina [43]
	Direct logistic/Reverse logistic,	Sacco et al. [38]
Operations	reuse, refurbish, recycle and remanufacture materials/Process management	Acerbi et al. [36]
	Project management	Górecki [39]
	Water, Emissions, Energy, Material	Golinska-Dawson et al. [41]
	Efficiency measurements: materials, energy, water	Howard et al. [45]
	Collect, retain/extend, share, reuse/redistribute, and remanufacture/renew	Julkovski et al. [46]
	Product/Process	Kayikci et al. [35]
	Material Energy/Waste management	Romero & Molina [43]
	Resource consumption/Waste management,	Sacco et al. [38]
	Technical Cycle: Collect; Keep/Extend; Share; Reuse/Redistribute; Remanufacture/refurbish	Sehnem et al. 2019 [47] & 2020 [48]
	Biological Cycle: Collect; Cascade Exploitation; Extraction of biochemical raw materials; Anaerobic digestion; Biogas; Biosphere regeneration; Biochemical raw materials; Agriculture/collection	
	Operations/Product and material	Uhrenholt et al. [44]
Operations	Material Health; Material reutilization; Renewable energy; Water stewardship	Ünal & Sinha [42]
	Product/process	Uztürk & Büyüközkan [37]
Marketing & sales	Economic	Kayikci et al. [35]
	Marketing	Romero & Molina [43]
	Marketing & communication	Sacco et al. [38]
Service	-	-

Another variation is evident in the definition or meaning of the maturity-relevant characteristics of the models. Although all models use a holistic approach to determine maturity, the definition of the model-dependent characteristics is different. In

Table V, the characteristics are assigned to the ranges of Porter's Value Chain [53] which represents the value creation of interrelated company activities and divides the company units involved into eight areas. It is noticeable that all models (e.g., *Firm infrastructure* or *Operations*) and other categories, such as *Inbound & outbound logistics*, represent some categories according to Porter only by individual models. The category *Service* cannot be assigned to any model and is therefore completely missing. This distribution may be due to the fact that the characteristics are named differently and therefore there may be overlaps between the categories. In addition, the characteristics are named in varying degrees of detail, so that the characteristics of individual models possibly address the services category, but do not mention them by name or do not distinguish them.

Every MM has the goal of assessing performance, which should primarily be done objectively [21], [13]. However, the models studied do not provide much detailed information about their underlying assessment method based on metrics. On the one hand, this lack of information is reflected in the absence of threshold values between two maturity levels, since in all models it is not comprehensible at which level of a characteristic relevant to the maturity level the change to a higher maturity level takes place. On the other hand, the lack of information is also reflected in the transparency of the questionnaire, which is a preferred method for assessing the performance of the identified models. Although it is mentioned that a questionnaire is used and the answer options are Likert-based, there is a lack of information about the concrete questions in most MM. Only the model according to Sacco et al. [38] is transparent in this respect, so that all questions were accessible for analysis. For this reason, an analysis of the measurement method can only be carried out for this model. The distinction between subjective (or fuzzy) and objective (or "distinct") measurement methods gives an indication of the objectivity of the performance evaluation. In the model, the method of subjective self-assessment predominates over the objective one, illustrated by the use of units or relative references in %.

MM are used to determine the current situation, to derive and prioritize improvement measures on this basis and then to monitor the success of their implementation [12]. However, the analyzed MM only represents rough steps to improve the maturity level. This lack of information was also noted by Correrira et al. in their analysis of maturity levels [18]. Although the MM with a stage representation represent a more detailed information base for transformation than the continuous representation method, they also lack concrete guidelines.

V. Conclusion, Limitations and Future Research

The SLR aimed to provide a systematic overview of existing circular economy MM for manufacturing companies. By applying keyword combinations in the four electronic databases EBSCOhost, SCOPUS, Web of Science and ScienceDirect, 16 MM were selected. The results show that the number of published models is steadily increasing over time, but is at a low level compared to the absolute number of models identified. This confirms the need for research in this area.

The identified MM were examined for various analysis criteria, including the considered frame of reference of the MM. This allowed the first research question (RQ1) to be answered. All models focus on the entire company with a holistic approach to maturity assessment, but differ in their concrete use case (e.g., [34]). Differences also show in the different structure and architecture of the models. With regard to the model typology, a structural approach predominates, followed by the grid representation. The preferred variant of the architecture is the stepwise representation, which 11 of 16 models use.

With regard to the maturity-relevant characteristics (RQ2), the SLR shows that these vary in number and definition and are model-dependent. Some models consider the same characteristics across all maturity levels, while other models apply a different number and definition of characteristics depending on their level. This variation is also reflected in the number and definition of maturity levels, which are adopted or redefined from known MM, depending on the model analyzed.

To answer the third research question (RQ3), the measurement methods of the models were analyzed, which are often questionnaire-based. The results of the SLR show that the models provide little information about the underlying metrics and their questionnaires and lack transparency. Only the MM, according to Sacco et al. [38], allowed a clear conclusion about subjective and objective measurement methods. Here, subjective self-assessments by Likert clearly outweigh objective measurement methods through the reference to measurement units.

Research Implications for Research and Practice

The SLR contributes to a comprehensive overview, analysis and synthesis of the literature in the field of circular economy MM. By consolidating the different models, their focus, measurement methods and characteristics, academia as well as business organizations such as manufacturing companies can compare the individual models. The paper also provides the basis to engage more with the emerging research field of circular economy MM and can serve as a basis for model selection for manufacturing companies that want to assess their circular maturity.

Limitations and Future Research

It should be noted when using the SLR that authors were limited in some areas. By conducting a literature search, there is very often a risk that not all relevant literature can be identified through the use of electronic databases. On the one hand, this concerns the four databases used, but also the choice of keywords, which, although applied in a three-stage search procedure, cannot give any indication of completeness. In addition, one criterion for the selection of literature was scientific publications at conferences or in scientific journals. Some consulting firms develop their own models, but these were not included during the research because insufficient information was available on the structure.

The SLR provides the basis for further research in the area of

circular economy MM. In the following, indications for further research activities are given:

A. Maturity-Relevant Characteristics

The SLR identified a large variance in the maturity-based characteristics used across the models. In addition, Porter's service category was not addressed by any of the models [53]. This evidence should be addressed in further research activities. Through a detailed analysis of the identified characteristics and the interdependencies between them, interdependencies can be identified and a basic set of indicators can be established that allows the maturity of manufacturing companies to be assessed. When creating the indicator set, however, care should be taken to ensure that it can be adapted depending on the industry, etc. The first basis could be the overview of characteristics and interdependencies. A first basis could be the overview of the characteristics in Table V and the inclusion of circular economy readiness models. In addition to MM, readiness models indicate the readiness of an organization for a transformation. These are often also questionnaire-based and it could be examined to what extent indicators are suitable for adaptation in the area of MM.

B. Thresholds between Levels and Measurement Methods

Due to the identified lack of description of the MM in the models, it is necessary that the individual maturity levels are described in more detail. In addition, the threshold values between the levels should also be addressed in the future creation of the models. Due to the lack of detailed description and the lack of quantitative data, the focus of future work should be placed on the integration of data-based thresholds in order to be able to represent the distinction between maturity levels numerically. This also applies to the chosen measurement methods of the characteristics. Here, it should be clear which measurement method is used in the questionnaire. In addition, the future focus should also be on the integration of objective measurement methods, e.g., through indicators with measurement units. Through this, different methods for aggregating subjective and objective measurement methods should be tested.

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