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Realizing Product-Packaging Combinations in Circular Systems: Shaping the Research Agenda

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Recent years have shown a shift in the focus of sustainable development from eco-efficiency (minimizing negative impacts) towards eco-effectiveness (optimizing positive impacts). Currently, a focus on circular models can be identified; Cradle to Cradle and circular economy are main examples of such models. However, the current number and variety of models and tools focusing on circular systems are limited with regard to packaging development.

This paper explores packaging development models and tools in relation to circular systems, in order to identify the current status of the circularity focus. A range of identified models and tools is structured into two categories (generative and evaluative tools) which cover three types (protocols, diagrams and evaluations). This is in line with the distinction between early and later phases of development and the cumulative nature of environmental lock-in. Protocol-type models and tools come in different forms, such as principles, guidelines and checklists (e.g. Cradle to Cradle and DfE). Aside from these, eight diagram-type models are analysed, focusing on packaging development, sustainable development and sustainable packaging development. In contrast to generative design tools, evaluation-type models and tools (e.g. LCA) are most useful in the later stages of development processes.

Resulting from the analysis of the models and tools, three types of integration – integrated product-packaging development, the cross-functional integration of actors and the front-end integration of sustainability considerations – are appropriate for the development of product-packaging combinations for circular systems. This leads to an agenda which shapes research directions towards achieving this development. © 2016 The Authors Packaging Technology and Science Published by John Wiley & Sons, Ltd.

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INTRODUCTION

Recent decades have shaped an increasing awareness of the environmental impact of human activity. Since the publication of *Our Common Future*,[1] better known as the Brundtland report, sustainable

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development has been high on the agendas of policy makers, companies and academia. Within industry, the transition from end-of-pipe solutions (reducing post-production emissions and waste) to addressing environmental considerations in product development characterized the initial shift.[2,3] The traditional approach is to minimize the negative environmental impacts products have, also known as eco-efficiency. This approach focuses on balancing social, economic and environmental factors, also known as the triple bottom line.[4] A linear model in which take–make–dispose patterns represent products' material flows characterizes eco-efficient approaches.[5] Recent years have shown a shift towards paradigms which aim for continuous material cycles, in which materials can be recycled without a loss of quality. Examples include Cradle to Cradle[6,7] and circular economy.[5] These models target the optimization of products' positive environmental impacts, which is known as eco-effectiveness.

Packaging has received much attention in terms of sustainability.[8,9] The traditional perspective on packaging focuses on features that become apparent after purchase (the later stages in a supply chain): perceived superfluous or excessive amounts of packaging and packaging waste. This perspective materializes in developments towards the reduction of packaging in order to respond to policies targeting packaging waste, such as EU directives 94/62/EC[10] and 2015/720.[11] However, by considering packaging separate from its contained product, this perspective fails to take the integration of product and packaging into account and ignores the functions packaging fulfils in a supply chain.[8]

Models and tools can facilitate the development of product-packaging combinations for eco-effective circular systems. This paper explores and structures the current models and tools that address sustainable development from the perspective of design and marketing teams. In contrast to existing taxonomies and classifications of sustainable product development models and tools (e.g.[12–14]), this research draws attention to the implementation of sustainability considerations in current packaging-specific models and tools. In addition, we focus on the gaps and issues limiting the alignment of packaging development and circular systems. This leads to research directions appropriate for the development of product-packaging combinations tailored for circular systems.

LINEARITY VERSUS CIRCULARITY

Linear take–make–dispose systems rely on easily accessible raw materials as input ('take'),[5] of which limited quantities return to the system ('dispose') after manufacturing ('make') and use. This results in a depletion of raw materials and a surplus of waste. By definition, this imbalance makes linear systems finite. The negative environmental impact per product unit can be reduced by focusing on efficiency in linear systems; however, this eco-efficiency does not result in a restored balance of inputs and outputs within the system.

Circular systems focus on maintaining material quality in biological and technical cycles.[5,8] The concept of material quality does not only address materials in terms of economic and technical value but also targets the elimination of material toxicity.[5,19] In order to achieve this, all outputs from the different steps within a circular system form inputs for other steps. This results in (theoretically) endless cycles of materials, without loss of quality, and the opportunity of providing a positive environmental impact: eco-effectiveness.

Circular systems provide solutions for issues related to linear systems. The first issue is the mentioned imbalance between input and output streams. In linear systems, the sourcing of materials does not rely on the outputs of other processes, while the end-of-life fates of materials (either landfill or incineration for energy recovery) do not result in inputs for other processes within the same system. Another issue related to linear systems is the loss of quality in recycling. In Figure 1, this is illustrated by means of dotted lines. After the use phase, materials can be recycled [input for the production of

Figure 1. Linear packaging system: sourcing, production, use and post-use (based on[15–18]).

(packaging) materials] or remanufactured [input for (packaging) production]. However, because of the loss of quality in linear systems, these material streams are only partially applicable as process inputs.

In circular systems, inputs and outputs are balanced in both biological and technical cycles. In Figure 2, this balance is illustrated: The upper lines (green) indicate biological cycles; the lower lines (blue) indicate technical cycles. None of the processes lacks either an input or an output flow of materials, which results in continuous cycles. After the use phase, materials which are suited for technical cycles can either be recycled on the material level (recycling), the component level (remanufacturing) or the product level (re-use).[5] In all cases, maintaining material quality is essential. In a biological cycle, materials can enter the biosphere in which restorative processes take place. Examples include the composting or incineration of packaging, as long as the outputs form nutrients for the growth of new (packaging) materials. Also, packaging materials such as paper or biodegradable plastics cycle in biological systems because they ultimately return to the biosphere after one or more post-use cycles.[19] Important to notice is the absence of landfilling as an end-of-life fate. Because this results in a surplus of waste, landfilling is not part of circular systems. Both linear and circular systems require energy inputs in order to function; specifically, the management of material flows relies on efforts regarding the collection, sorting, disassembly and recycling of post-use materials.[20]

The following section explores the characteristics of packaging and packaging development in relation to product development. Subsequently, we characterize and discuss models and tools.

PACKAGING DEVELOPMENT CHARACTERISTICS

The field of product development has been researched for several decades. The considerable number of methods, models, tools and guidelines targeted at this field from different perspectives provides ample proof (e.g.[21–23]). In contrast, the number and variety of models and tools tailored for the development of packaging are limited.[18,24,25]

Different characteristics result in packaging being regarded as a separate category within product development. The first packaging characteristic is its role as facilitator of a product's ability to provide added value to a supply chain. This facilitator perspective on packaging differs greatly from the redundancy perspective, which characterizes packaging according to its environmental impact after purchase and use. Without packaging, it would be difficult for producers and brand owners to have products reach customers in the state they are intended to be. This commensalism leads to packaging that is a beneficial add-on to the product and that fulfils functions during different steps of a supply chain.[26] Consequently, a product-packaging combination is the main element in a complex and cross-functional network of actors forming a supply chain.[27–29] Therefore, the integrated development of product and packaging is important to develop optimal product-packaging combinations.[18,30,31]

Another distinguishing factor is the difference between structural and graphical design. Structural design deals with three-dimensional packaging properties (shapes and sizes), while graphical design deals with the two-dimensional properties of packaging (colours and graphics).[32–34] This difference is in line with packaging's primary functions. Even though the specific description of its functions varies throughout the literature (e.g.[18,35–37]), the following are generally considered primary packing functions, in order of priority:

1 Protection: protecting contained products from the environment and vice versa.

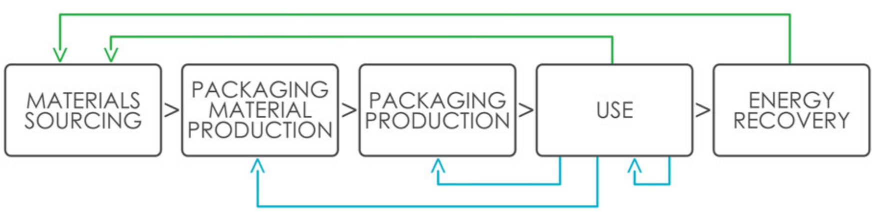

Figure 2. Circular packaging system: sourcing, production, use and post-use in biological and technical cycles (based on[5]).

2 Utility: enabling product distribution and use.
3 Communication: informing stakeholders about the contained products.

Structural packaging design is mainly concerned with the protection and utility function; graphical packaging design focuses on the communication function.

The iterative development process comprising analysis, synthesis, simulation and evaluation (typical of product development cycles) is suitable for packaging development. However, the distinguishing characteristics of packaging are not explicitly considered in generic product development models and tools, which makes these only partially applicable for specific packaging development.[18,30] Therefore, tailored packaging development models and tools, which act as an extension of generic product development models, can be beneficial for higher levels of packaging development specification.

In the following section, we explore the current field of packaging and packaging development with a focus on sustainable development and circular systems.

DEFINITIONS OF SUSTAINABLE PACKAGING

Currently, there is no generally agreed upon definition of environmentally conscious or sustainable packaging.[38,39] Two organizations have established definitions of sustainable packaging: the US-based Sustainable Packaging Coalition (SPC)[40] and the Australian Sustainable Packaging Alliance (SPA).[41] These definitions describe sustainable packaging characteristics, several of which appear in both organizations' definitions. First of all, both the SPA and the SPC value a focus on the complete life cycle and on packaging's functional requirements or performance. Further, packaging that is safe and healthy (for people and the environment) as well as efficient in material and energy use is mentioned in both definitions. A focus on continuous material cycles and renewable materials represents circularity, which is included in both definitions. However, it should be noted that the SPA and the SPC consider material flows on two levels: continuous cycles (maintaining material quality) and down-cycling (recovering materials as a trade-off between material quality and economic feasibility). The latter cannot be regarded a continuous material cycle in the strict sense because, according to the definitions, materials may flow into lower-grade systems such as landfill. The SPC definition adds a focus on clean manufacturing technologies and the use of renewable energy throughout the manufacturing, transport and end-of-life of packaging. Neither of the two definitions focuses specifically on a description of the integrated development of product and packaging as part of a sustainable approach.

Packaging is regarded as an important tool in the marketing mix.[42–45] Packaging helps producers distinguish their product from those of competitors.[8] It is often described as the 'fifth P' – an addition to the traditional four Ps of the marketing mix: product, price, place and promotion.[46] However, it should be noted that many literature descriptions mainly describe packaging according its communication function. The value of packaging as a facilitator in a supply chain has been largely overlooked in marketing-oriented literature. When sustainable packaging is considered, several authors' perspectives hint at packaging as a facilitator in a supply chain (e.g.[15,47]). This hint is substantiated by terminology associated with packaging redundancy and eco-efficiency, describing elimination and reduction as options towards sustainable packaging. Therefore, we can conclude that a circularity perspective on packaging is under-researched in marketing literature.

An analysis of current development models and tools can expand these perspectives on packaging in relation to sustainable development and circular systems. The following section addresses this analysis.

DEVELOPMENT MODELS AND TOOLS

Within product development processes, there is an identifiable contrast between the early and later phases.[48–50] In the early phases, design and development teams have a large degree of freedom, while the costs of design changes are low. This phase is often addressed as the fuzzy front end of innovation.[48,51,52] In contrast, the relatively high costs of change and a limited degree of freedom, as a result of the major decisions made during the process, characterize the later phases of the development process.

In terms of sustainability-focused development or development for circular systems, it is important to consider the cumulative environmental lock-in. This is a result of design decisions made during the development process, which determine the environmental impact a product will have. Similar to the costs of change of design decisions, the environmental lock-in will increase as a development process progresses.[53–55] Figure 3 illustrates the contrast between the early and later phases of development processes: the degree of freedom versus the costs of change and environmental lock-in.

The current literature describes a number of models and tools aimed at different sections of the product development field. In this paper, packaging development models and tools targeting sustainable development or development for circular systems are the main subject of study. However, the analysis also considers models and tools that address general sustainable development and general packaging development.

The difference between the models and tools aimed at sustainable product development echoes the contrast between the front-end and back-end phases of development processes.[14,52,54,56] Models and tools can be grouped into two types: generative and evaluative models and tools. Generative tools (ideation and design tools) are aimed at integrating environmental considerations into the development process. This is most relevant during the earlier phases of development when the level of fixed product characteristics (and thus the environmental lock-in) is relatively low. During the later stages of the development process, most of a product's properties and characteristics are specified. This specification allows for the evaluation of a product's sustainability and life cycle, which increases the relevance of evaluative tools (assessment tools).

Authors who describe development models and tools emphasize specific characteristics by means of the model's representation. This paper addresses three main groups of representation types: protocols, diagrams and evaluations. In general, the groups of protocols and diagrams comprise generative tools, with evaluative tools comprising the remaining group. Protocol-type models and tools generally aim at providing prescriptions of sustainability considerations. Diagram-type models address representations of process phases. Previous research identified similar divisions (e.g.[14,27,57]), to which we add the specific perspective of packaging development for circular systems.

Model type: protocols

Protocol-type models and tools come in different forms, of which principles, guidelines and checklists are the most frequently occurring types. Of these types, principles and guidelines are most similar, with a slight difference in connotation. When discussing product development processes, guidelines are specific statements addressing the course of action. In contrast, principles are (sets of) statements which act as a source of inspiration. For example, a principle for environmental considerations in material selection could be '*reduce hazardous substances*', while an associated guideline could be '*eliminate colorants containing heavy metals*'.

Cradle to Cradle and circular economy. When considering packaging development for circular systems, two protocol-type paradigms are highly relevant: Cradle to Cradle (C2C)[6,7] and circular economy.[5] Both approaches contradict the current eco-efficient industrial models which are characterized by

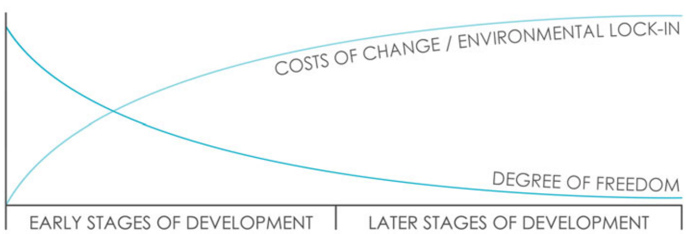

Figure 3. Contrast in degree of freedom versus costs of change and environmental lock-in in early and later stages of development processes (schematic; based on[48–50,53–55]).

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linearity (take–make–dispose patterns) and replace these with the concept of biological and technical nutrients, the notion of designing for continuous cycles of non-toxic materials and the dependency on renewable energy sources. Both C2C and circular economy criticize linear models which are characterized by efforts to minimize products' negative impacts. Instead, these protocol-type paradigms propose eco-effective models that target the optimization of the positive impacts of development, production and consumption. This contrast between eco-efficiency and eco-effectiveness is visualized in Figure 4.

Their largely similar key principles describe both C2C and circular economy. The main principle of the two paradigms is 'waste equals food', which relates to cycles in which recycling can occur without loss of quality. Further, the reliance on renewable energy and the recognition of the value of diversity, which gives systems resilience, are a key in both C2C and circular economy. Both frameworks mainly focus on material flows during manufacturing and post-use, while the issue of energy use during the use phase of products is hardly addressed.[20,59] By means of these principles, the aims are similar: improving product quality without health risks and providing an economic and ecological benefit.

An important factor which differentiates C2C from circular economy is its certification framework, aimed at certifying compliant products. Within C2C certification, products are evaluated against five categories: material health, material reutilization, renewable energy, water stewardship and social fairness.[19] The applied ABC-X assessment methodology, which classifies materials based on the chemical risk and recyclability in their (theoretical) biological and technical cycles, is important within the material health category. Materials, (sub-)assemblies and finished products are eligible for C2C certification on five levels: Basic, Bronze, Silver, Gold and Platinum. The current certification program is primarily oriented from a Western cultural perspective.[19] Currently, the number of packaging concepts which are C2C certified is very limited. Examples are listed on the website of the Cradle to Cradle Products Innovation Institute.[60] The framework is not limited to specific industries or product types,[59] with the exception of food products, buildings and products with ethical issues.[19]

It is important to notice that C2C's theoretical paradigm and practical certification framework are not, by definition, in line. The major issues which separate theory and practice relate to the certification framework's strong focus on material assessment (of which the requirements are not transparent), the monopolist position of accredited institutes and the reliance on non-disclosure agreements, which can hamper innovation.[59,61]

A concept which is in line with C2C and circular economy is biomimicry – the study of applying mechanisms and functions in nature to design and engineering.[57,61–63] The Blue Economy,[64] which has a number of principles that are similar to the material cycle approach in circular economy and C2C, is an example of this nature-inspired design.

These circular models do not specifically consider packaging. However, because of the generic nature of the C2C and circular economy concepts, packaging development according to their principles is possible. The continuous material cycle concept is of primary importance for packaging development. In current packaging development, material reduction is an important point of focus, as this addresses regulations regarding packaging waste (measured by weight). This reduction results in complex materials such as laminates, which eliminate the possibility for material recycling without a loss of quality.[8] These types of inseparable material combinations hinder the development of products and packaging for circular systems and thus for paradigms such as C2C and circular economy.

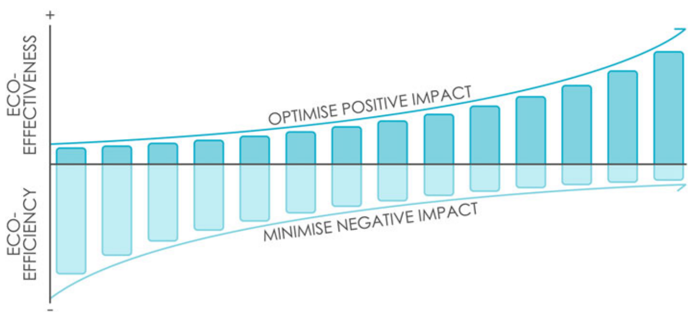

Figure 4. Eco-effectiveness versus eco-efficiency (edited from[58]).

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Design for Environment. An often addressed type of guideline for an environmentally conscious design is Design for Environment (DfE). This protocol-type concept lacks generally accepted or established principles and guidelines. This ambiguity goes two ways: First, the term DfE is found throughout literature but addresses different (similar) concepts. Second, there are different terms for approaches similar to DfE, such as 'Design for Sustainability', 'environmentally conscious design', 'ecodesign', 'green design', 'life-cycle design' and 'clean design'.[65–67]

Different examples of guidelines can be identified within the domain of DfE, such as the ECD Factor Framework,[65] Information/Inspiration,[68,69] the Twelve Principles of Green Engineering,[70,71] the Ten Golden Rules,[14,49] and the DfE Principles Compilation.[54] These guidelines are comparable on different levels, such as the focus on material and energy efficiency, the elimination of hazardous substances and the minimization of material diversity. In industry, several companies have developed guidelines and checklists targeting environmental considerations in development. In many cases, these guidelines and checklists address materials. Examples include Volvo's White, Grey and Black lists (containing, respectively, clean, cautionary and prohibited materials)[72–74] and Philips' Regulated Substances List.[75]

Table 1 shows corresponding principles of the Twelve Principles of Green Engineering, the Ten Golden Rules and the DfE Principles Compilation. This comparison shows three DfE-type guidelines and their similarities and differences. It does not address every single principle or guideline but is intended to provide a visualization of the similarities.

A widely used DfE-related tool is the life-cycle design strategy wheel. This product benchmarking tool provides designers with an overview of improvement opportunities for product designs. The life-cycle design strategy wheel incorporates eight environmental strategies structured on three levels: product system, product structure and product component. Two or more products or product designs can be compared by means of the tool by scoring alternatives on each of the eight strategies. The tool then provides a visualization of environmental improvement options.[12,76] However, the relative importance of each of the eight strategies is not known, which can limit the interpretation of results.[57]

Conclusion: protocols. A gap in the addressed protocol types is the lack of tangible descriptions. The models and tools provide inspiration or identification of opportunities but fail to address how they can be implemented in practice (also mentioned by e.g.[68,77]). In addition, the tools lack a clear description of their targeted users. The eco-effective conceptual models, such as C2C, circular economy and biomimetics, are not limited to providing inspiration to specific users. On the other hand, many of the addressed guidelines and DfE descriptions target 'designers' as the main actor during the front-end

Table 1. Twelve Principles of Green Engineering[70,71] versus Ten Golden Rules[14,49] versus DfE Principles Compilation.[54]

	TPGE	TGR	DfEPC
Avoid toxic materials	○	○	○
Minimize waste	○		○
Minimize material use	○	○	○
Minimize material diversity in products	○	○	○
Minimize weight		○	○
Use renewable/recyclable materials			○
Minimize energy consumption	○	○	○
Use renewable energy	○		○
Use clean production processes			○
Design for durability	○	○	○
Design for repairability		○	○
Design for re-use	○	○	○
Design for life-cycle scenarios		○	
Design for disassembly		○	○
Avoid 'one size fits all' design	○		
Replace the function of packaging through design[1]			○

[1]This does not necessarily address the redundancy perspective on packaging. Product design can be executed in such a way that packaging replaces certain product functions instead of compromising them.

phases of innovation. However, the meaning of this term can vary, depending on the author's perspective, which is not clear in most of the literature.

The considerable number and variety of protocol-type models and tools indicates that this is often the 'go-to' type for design and marketing teams. The frequent use is a result of their high level of flexibility and adaptability, which the generative front-end phases of development processes require. However, the use of checklists and guidelines can limit the main goal of the front-end phases: innovation. Moreover, checklists based on current solutions might be insufficient when completely new solutions arise.[18] The required background knowledge that users must possess is another issue related to the use of protocols. For instance, valorizing inspiration aimed at exploring alternative material options requires a certain level of material knowledge.[27,78] This leads to the risk that users of the protocols may merely choose (or 'cherry-pick') easy-to-comprehend or easy-to-implement solutions. Of the addressed protocol-type models, only C2C contains a certification program including fixed goals and requirements.

The practical application of DfE-related models and tools has been poorly researched. In some cases, studies present pilot projects as proof-of-principle together with the described models and tools. However, a follow-up implementation in the form of an introduction into industry-based product development is scarce.[79] Overall, protocol-type models and tools struggle with the trade-off between flexibility (all actors, all products) and accuracy (specific, practical application). On the whole, the current literature has very little research on dedicated circularity-focused packaging development protocols.

Model type: diagrams

Within (product) development, many models and tools are presented in the form of diagrams. Displaying development processes as a cycle or chain of steps is common in the literature and industry. We address eight relevant diagram-type models and tools from three backgrounds: *packaging* development, *sustainable* development and *sustainable packaging* development. The main characteristics describe these models and tools, but this paper omits their graphical representations. We discuss the application of the models primarily related to the development of product-packaging combinations for circular systems.

Packaging design process. The packaging design process (PDP) is one of the earliest models that specifically address packaging development.[18,80] The model describes the steps that packaging designers execute in practice and is focused on integrated product-packaging development and on the hierarchy of decision-making. It echoes the typical generic analysis–synthesis–simulation–evaluation design steps. The model is based on the analysis of the literature, packaging development experience and MSc projects of Industrial Design Engineering at Delft University of Technology.

Generic package development process. The generic package development process (GPDP)[30] addresses the issue of integrating the development of product and packaging. The process aims at providing a holistic approach on packaging development. Like the PDP, the GPDP is based on the typical generic product development process. Consequently, the models' general steps are similar; both models start with a planning/assignment stage that determines the boundaries of a project. The GPDP explicitly addresses the integration of product and packaging by means of the 'package system development' and 'package system integration' phases.

Ideal-eco-product approach. The ideal-eco-product approach (IEPA)[81] aids designers with the implementation of environmental considerations in product development and focuses on complex technical products. IEPA comprises six steps focused on product functions. Step 1, determine the main and secondary functions; step 2, determine the principal technical solutions; step 3, investigate what kinds of environmental impact the identified technological possibilities may have; step 4, develop 'extreme versions' of concept solutions; step 5, cross-check the fulfilment of secondary functions; and step 6, unify the 'extreme versions' into an 'ideal solution' to create an environmentally optimized product.

Environmental review process. The environmental review process (ERP)[56,78] focuses on the integration of environmental issues into existing product development processes. The proposed process is based on and integrated into the existing stage-gate product development process at Black & Decker. From an environmental perspective, it mirrors the company's safety reviews during different development stages. The ERP provides an overview of the sequence of environmental considerations in product development by means of relevant metrics at the different development process stages.

Scenario, Task, Experience, Materials. Scenario, Task, Experience, Materials[82] is an ideation tool to develop eco-solutions during the early phases of development processes. This process tool is intended for the ideation and creation phases of (sustainable) product design by including eco-attributes into ideation phases. The tool provides designers with a generic list of sustainable attributes for each of the phases (scenario modelling, task analysis, experience and material choice). These attributes produce 'eco-innovative' solutions rather than a mere redesign.

Sustainable packaging design. The sustainable packaging design (SPkD) model[24] integrates product and packaging development with ecodesign strategies and tools. Comparable to the PDP and the GPDP, SPkD describes the steps from planning to post-launch. The model identifies six packaging development phases (packaging planning, concept design, detail design, proving functionality, packaging launch and packaging review) and links these to the accompanying product development process's six parallel phases. This model can be applied by working in two teams (product and packaging), interacting when necessary, to integrate product and packaging development.

Holistic integrated sustainable design. The holistic integrated sustainable design (HISD) framework[83] for biopolymer packaging aims at replacing conventional polymers with bio-derived alternatives in the design of primary packaging for consumer and retail markets. HISD was developed as a framework for the implementation of material considerations in packaging development processes. Three stages have been identified: strategic evaluation, material selection and sustainability assessment. HISD can be considered a supplement to existing packaging development processes and is focused on streamlining the implementation of bio-derived polymers in packaging.

Integrated sustainable packaging development. The integrated sustainable packaging development (ISPD) model[17] aims to reduce material disposal and CO_2 emissions in supply chains. The model balances technical design, supply chain design and environmental design. Comparable to the HISD framework, the ISPD model can be classified as a material selection and guidance tool. The ideation and development of packaging concepts are not part of the model. ISPD was developed as a tool to address trade-offs in the use of paperboard material in supply chains and was validated by means of a case study.

Overview. The eight diagram-type models and tools differ in various aspects. Therefore, a comparison of the different aspects is useful: the applicability (packaging development, sustainable development or sustainable packaging development), the main target group, the development process section for which it applicable and claimed strengths and weaknesses (refer to Table 2). The first three aspects address the focus of the described models and tools.

Conclusion: diagrams. It should be noted that this analysis of eight relevant diagram-type models and tools is by no means exhaustive. In the literature, more models and tools can be identified. However, these models and tools are omitted in the detailed description because of their limited relevance for packaging development for circular systems. There are no large numbers of models which address sustainability considerations or a specific focus on circularity in packaging development in the current literature. Further, the variety in models and tools is limited. Many of the addressed models are based on generic product development processes and thus have a similar sequence of steps.

The integrated development of product and packaging is largely overlooked in many of the described models and tools. This lack has also been addressed in previous research (e.g.[26]). Some models that address packaging development recognize the need for an integrated development of product and packaging, such as PDP[18] and GPDP.[30] However, in other cases, this is not explicitly addressed (e.g. HISD[83] and ISPD[17]). Only one model, SPkD,[24] explicitly targets the front-end integration of environmental considerations in packaging development. In addition, the addressed models and tools do not take the cross-functional integration of actors into the chain into account. Only the ERP[56,78] explicitly describes the application for cross-functional teams. The described models and

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Table 2. Comparison of eight diagram-type models and tools.

	Applicability	Target group	Process section	Claimed strengths	Weaknesses
PDP	PD	Packaging designers	Total developm. process	○ Based on development process in practice ○ Integration of product and packaging	○ No integration of environm considerations ○ Generic; application is not specified ○ Unclear usability for cross-functional teams
GPDP	PD	Packaging designers	Total developm. process	○ Integration of product and packaging	○ No integration of environm. considerations ○ Generic; application is not specified ○ Unclear usability for cross-functional teams
IEPA	SD	Designers	Front end (concept developm.)	○ Unifying extreme versions into ideal solutions	○ Applicability for packaging is unclear ○ Must be extended with DfE tools ○ Unclear usability for cross-functional teams
ERP	SD	Product developm. teams	Total developm. process	○ Includes post-launch review and feedback loop ○ Integration in existing processes	○ Must be extended with DfE tools ○ Generic; application is not specified
STEM	SD	Designers	Front end (ideation phases)	○ Ideation tool ○ Incorporates designers' way of doing	○ Applicability for packaging is unclear ○ Steps are not specified (e.g. 'make it cyclic').
SPkD	SPD	Packaging designers	Total developm. process	○ Includes post-launch phase ○ Front-end integration of environm. considerations ○ Integration of product and packaging development ○ Includes communication of environm. considerations to consumers	○ Generic; application is not specified ○ Unclear usability for cross-functional teams ○ Must be extended with DfE tools
HISD	SPD	Packaging engineers	Material selection	○ Supplement to current processes	○ Applicability beyond biopolymers is unclear ○ Must be extended with material information
ISPD	SPD	Packaging engineers	Material selection	○ Trade-offs between technical properties and environm. metrics	○ Applicability beyond paperboard is unclear ○ Must be extended with material information

tools insufficiently address the integration of actors beyond product-packaging development teams, such as managerial decision makers, suppliers and consumers.[28,80]

The papers which describe packaging development models only address the practical applicability of the proposed models partially. These models' limitations are not elaborately described, resulting in generic models (e.g. GPDP[30] and PDP[18]). However, without further substantiation, these generic models cannot, by definition, be valid because of the complexity of supply chains in which packaging interacts. Another issue relates to the background knowledge that users of the different models require. The users of material-focused and DfE-focused models are required to possess a certain level of knowledge. Most of the addressed models do not specifically refer to this issue. Moreover, the models that address environmental considerations align these with an eco-efficient approach. Eco-effective or circularity-based models tailored for the integrated development of product-packaging combinations in this category of model types are not found in the current literature.

Model type: evaluations

This section addresses the evaluation-type models and tools. In contrast to generative (front-end focused) design tools, evaluation-type models and tools are used in the later stages of development processes. During these stages, the environmental lock-in of products is relatively high[53–55] (refer to Figure 3). Therefore, the evaluation and comparison of the products' sustainability are most suitable during these development stages.

Life-cycle assessment. The major evaluative environmental tool is life-cycle assessment (LCA). By means of this quantitative tool, the environmental impacts of a product's complete life cycle can be analysed, from a resource perspective. This includes the impact of the raw materials, production, product use and end-of-life scenario. LCA accounts for the inputs (raw materials and energy) and the outputs (emissions to air, soil and water) in each of the phases of a product's life cycle.[9,54,84,85] Each life-cycle phase causes interventions, which contribute to one or more environmental effects. Every effect has a reference; for example, a product's impact on the greenhouse effect is often measured in CO_2 equivalents.[84–86] The outcome of an LCA process can be used for internal purposes such as product evaluation or improvement and external purposes such as marketing and competitive benchmarking.[9]

Life-cycle assessment is considered a rigorous tool to assess products' environmental impacts. However, this rigor also means that a full LCA is time-intensive.[85,87,88] A required level of product-related inputs and outputs, which can only be specified in the later stages of product development processes[89] as a result of the cumulative nature of a product's environmental lock-in (refer to Figure 3), determines the applicability of LCAs within design processes. This limits the application of LCA as a standalone front-end design tool. After the specifications of a design have largely been determined, LCAs can be used to compare alternative concepts and adjust the design direction. Once a project has been completed, the value of a LCA lies in the opportunity to assess the environmental impact of the finished design and to integrate these insights into new or follow-up projects.

Life-cycle assessment is in line with an eco-efficient approach to development because it is focused on the reduction of negative environmental impacts.[8] Further, it does not result in a qualification of what is 'more sustainable' but offers a platform for comparison between alternatives.[90] Throughout the process of LCA, interpretation is crucial.[91] Because LCAs represent a specific moment in time,[9] system boundaries and assumptions must be considered and communicated to the stakeholders of the executed LCA.

Streamlined alternatives to LCAs have been developed to overcome the limitations regarding the efforts required for the execution of LCAs.[92,93] Examples of streamlined LCA tools for packaging include Packaging Impact Quick Evaluation Tool (Sustainable Packaging Alliance),[39,94] Comparative Packaging Assessment (Sustainable Packaging Coalition)[95] and Tool for Optimization of Packaging (Netherlands Packaging Centre).[96] Even though it is widely understood that the integrated analysis of both product and packaging in LCAs is important,[28,80,97] these and other tools in many cases do not explicitly take the impacts of product manufacture or product loss into account.[16,80]

An example of an LCA-related tool is the holistic methodology for sustainable packaging design, a tool which considers the product-packaging combination as a system.[80] This model is based on a

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compilation of different methods which characterize the most important requirements of product-packaging combinations. These requirements are categorized into five main categories that target the environmental performance, the distribution costs, the quality preservation, marketing features and the user-friendliness of a product-packaging combination.[25,80,90,97] The latter two categories are specifically unique to an evaluative tool. Holistic methodology for sustainable packaging design primarily visualizes impacts on the supply side (distribution costs), retail phase (market acceptance) and post-purchase phase (user-friendliness) of product-packaging combinations,[90] assisting cross-functional product-packaging development teams in balancing the different requirements and evaluating alternatives.[80]

Another example of a partially LCA-based tool is the eco-costs/value ratio model.[90] The eco-costs/value ratio model goes beyond LCA approaches by including the assessment of functionality, which is expressed in the form of created value. By linking the value of product-packaging combinations to the environmental impact, the model leads to a more eco-effective approach than standard LCA models (which merely focus on the reduction of environmental impacts), distinguishing it from the redundancy focused, eco-efficient perspective on packaging.[8]

Conclusion: evaluations. Evaluation-type models and tools, of which the majority is similar to or based on life-cycle assessment, are very useful for a comparison and evaluation of a product's environmental impact. LCA's results can be used to take actions aimed at improving the environmental performance of products or packaging. However, even though life-cycle assessment is widely used for the analysis of packaging,[9] the focus on integrated product-packaging combinations is limited. When product losses are not taken into account in an LCA of packaging, the validity of the results is limited.

Evaluative models and tools, such as LCA, are most applicable in the later development stages, as a result of a required level of design specification. This limitation results in a 'traditional' LCA having limited suitability as a stand-alone tool for the front-end integration of sustainability considerations during development processes. As far as design iterations are concerned, LCAs are most applicable either during a development project (e.g. the assessment of concept alternatives) or after its completion (e.g. the evaluation of a completed concept).

DISCUSSION

Several issues and gaps are addressed with the analysis of models and tools focusing on circular systems in the field of packaging. This discussion focuses on the main issues limiting the alignment of packaging development and circular systems.

The current literature mainly focuses on the theoretical implications of the transition from linear to circular systems (e.g.[5,6,19]), while practical examples of packaging concepts suited for circular systems are very scarce. In packaging development for circular systems, the main practical challenges are related to the post-use sections of the process. In order to close the material cycles in circular systems, both material quality and quantity must be maintained. This requires high-quality collection, sorting and recycling of materials, in either technical or biological cycles, which must be considered during design processes.[20] As a result, structured packaging development for circular systems requires models and tools which address this from the perspective of design and marketing teams. This perspective is largely overlooked in the packaging development models and tools which are described in this paper.

The integrated development of product and packaging is important within packaging development for circular systems.[18,30,31] Even though this is not a new insight, the validation and application of this integration are poorly researched in many of the current models and tools. Packaging is recognized throughout the literature as an essential part of complex supply chains (e.g.[27–29]). However, the analysis shows that many of the addressed models do not fully take this complexity into account. The generic description of models and tools, which does not address the specific cases in which they are or are not applicable, illustrates this lack of consideration. The cross-functional integration of actors in supply chains is hardly considered in many of the current models and tools. This goes not only beyond cross-functional product-packaging development teams but also refers to managerial decision makers, suppliers and consumers.[28,80] When considering product-packaging development within circular systems, the point of departure is the design, leading to designers, marketers and engineers as the major actors responsible for the implementation of environmental considerations within cross-functional teams.[18,98]

The addressed dichotomy between generative and evaluative models and tools is an important consideration in sustainable development, which we addressed in the previous sections. Generative models and tools are relevant for the front-end integration of sustainable considerations in order to develop product-packaging combinations for circular systems.[14,82] A design brief can be a useful tool to address this integration as a well-established example of one of the earlier steps in development processes.[22] However, in the models and tools addressed in this paper, design briefs are largely neglected. Further, the literature largely overlooks the value of evaluative models and tools, such as life-cycle assessment, before the completion of development projects. Once the initial design steps of development are concluded, evaluative tools can contribute to the environmental assessment of concept alternatives. The connection between front-end generative tools and evaluative tools that are useful in later development stages is important to consider in product-packaging development for circular systems.

CONCLUSIONS

In current packaging development models and tools, there is a limited focus on the development integration of product-packaging combinations for eco-effective circular systems. This paper addresses the field of packaging development in relation to circular systems by identifying and analysing development models and tools. The focus on circular systems is in line with the transition towards eco-effective models and tools.[8] Different factors, such as the role of packaging as a facilitator in a supply chain[26] and the difference between structural and graphical packaging design,[32–34] characterize packaging development. This distinguishes packaging development from general product development. Generic product development models and tools do not explicitly consider typical packaging characteristics. Consequently, they are only partially applicable to packaging development.[18,30]

Three types of models and tools are identified (protocols, diagrams and evaluations) in two categories (generative and evaluative models) to address the development of product-packaging combinations in circular systems. This separation stems from the contrast between the early and later phases in product development[48–50] and the cumulative nature of the environmental lock-in during development processes.[53–55]

Each model type has limitations that prevent the application for the development of product-packaging combinations for circular systems. For the protocol-type models and tools, the main issues are the limited description of the applications for which the models are suited, the poor description of the target groups and the largely neglected risk of users' 'cherry-picking' easy-to-comprehend or easy-to-implement solutions. Within the analysed eight diagram-type models and tools, an important factor is the limited number and variety of models tailored to the development of circularity-focused packaging. Moreover, the limited description of specifically suitable applications is also an issue with this type of model. Evaluation-type models and tools are mainly based on LCA processes. This type of method is most suited for the later stages of development processes as a result of the required level of design specification.

The analysis of the models and tools identified three types of integration that are important when considering the development of product-packaging combinations for circular systems: the integrated product-packaging development, the cross-functional integration of actors and the front-end integration of sustainable considerations. The relevance of these types of integration is not limited to specific types of product-packaging development. In order to determine possible research directions targeting these types of integration into future packaging development, we suggest a research agenda in the following section.

RESEARCH AGENDA

This research results in options for a transition towards the development of product-packaging combinations for circular systems. The addressed current gaps and issues can be targeted by (re)developing

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and improving the packaging development models and tools in which the previously discussed three types of integration are important.

The implementation of the cross-functional integration of actors into the packaging chain calls for specific research on the current dynamics and interrelation of interdisciplinary packaging design and marketing teams with a direct influence on packaging development. In order to address a broader set of relevant actors, this research can be focused on the structured implementation of the influence of consumers and end-of-life stakeholders (such as recycling companies) on packaging development processes. This relates to the practical challenges during the post-use sections of circular systems (reverse logistics[20]): high-quality collection, sorting and recycling of materials, in either technical or biological cycles.

A second research opportunity addresses the front-end integration of sustainability considerations. When considering the (re)development and improvement of packaging development models and tools, design briefs could be a useful subject of study. In the current models and tools, design briefs are largely neglected even though they play a role in the earlier phases of development processes.[22] In the later stages during development, evaluative tools can accompany the front-end integration of sustainability considerations.

Third, one research opportunity relates to the issue of the poorly addressed specific applications for which current models and tools are suited. Generic models are not in any case applicable in complex packaging supply chains. However, this is currently hardly considered from the perspective of design and marketing teams within circular systems. Research relating project-defining factors to sustainability outcomes of packaging development projects should address this issue. In the current literature, there are hints regarding the type of factors that determine the applicability of models and tools. The following paragraphs explore a selection of factors and the hypothesized relationship between these factors and the outcome of packaging development projects in relation to sustainability and circular systems.

Small and medium-sized enterprises are under-researched in the area of sustainability, even though these types of company comprise a large section of industry activity.[52] The literature recognizes company size as a factor influencing the product life cycle (e.g.[99,100]). Similarly, the current literature hints at the differences in development regarding the integration of external resources (e.g.[101]) and the division into internal and outsourced packaging design and development (e.g.[31]). However, the influence of these factors on the circularity-related outcome of product-packaging development processes is currently not clear. This also holds for the division between incremental and radical innovations,[102,103] which relates to checklists' limited applicability to radical development[18] and the required level of design specification that is relevant for evaluative models and tools such as LCA.[54] These issues influence the applicability (and thus outcome) of product-packaging development projects aimed at circularity.

The (re)development and improvement of packaging development models and tools can be used to address the structured development of product-packaging combinations for circular systems. In this regard, the consideration of specific project-defining factors (such as the factors discussed in this section) within the framework of the generically relevant types of integration (integrated product-packaging development, cross-functional integration of actors and front-end integration of sustainable considerations) provides a relevant research opportunity.

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