ResCoM Design Methodology for Multiple Lifecycle Products

Bakker, Conny; van Dam, Sonja; de Pauw, Ingrid; van der Grinten, Bram; Asif, Farazee

Publication date
2017

Document Version
Final published version

Citation (APA)
Bakker, C., van Dam, S., de Pauw, I., van der Grinten, B., & Asif, F. (2017). *ResCoM Design Methodology for Multiple Lifecycle Products*. Delft University of Technology.

D3.4 Report

The ResCoM design methodology

ResCoM WP 3

Deliverable 3.4 Report

ResCoM Design Methodology for Multiple Lifecycle Products

TU Delft

30-06-2017

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 603843

Dissemination Level:

☒ PU Public
☐ PP Restricted to other program participants
☐ RE Restricted to a group specified by the consortium
☐ CO Confidential, only for members of the consortium

Lead beneficiary	TUD
Author/s	TUD: Conny Bakker, Sonja van Dam; IDE: Ingrid de Pauw, Bram van der Grinten; KTH: Farazee Asif
Reviewed	IDE, INS, GRA, EUR, IPA-BT
Approved	

Project Number	603843
Project Acronym	ResCoM
Project Title	Resource Conservative Manufacturing - transforming waste into high value resource through closed-loop product systems
Start Date of Project	1 November 2013
Duration	48 months
Programme / Topic	FP7 / ENV.2013.6.3-1
Type of activity	Other
Deliverable reference number	
WPs contributing to the deliverable	3, 4, 5
Due date	30.06.2017
Actual submission date	
Revision	
Abstract	By combining the lessons learned from the four ResCoM cases, a generic methodology was developed for other companies that want to engage in the development of multiple-lifecycle products. This report describes a stepwise approach for developing such products. The approach includes a suite of design tools as well as a practical case study example to illustrate the implementation in practice.
Key Words	Product design, Design methodology, ResCoM tools

Table of Contents

1. Introduction

Within the ResCoM project, four original equipment manufacturers (OEMs) investigated how to transition to a more circular business proposition using multiple-lifecycle products. Design tools and guidelines were developed, specifically suited to the design processes of these companies and their challenges in circular product development. By combining the lessons learned from these four cases, a generic methodology was developed for other companies that want to engage in the development of multiple-lifecycle products.

This report describes a stepwise approach for developing multiple lifecycle products that can be integrated in the current design engineering process of OEMs. The approach includes a suite of design tools to address specific challenges in circular design, as well as a practical case study example that is used throughout the report to illustrate the implementation in practice. Using the tools will help create products that are more cost-effective, resource-efficient and sustainable than products that fit within linear manufacturing systems.

The case study example: Roetz-Bikes

To illustrate the ResCoM design methodology ('how to design a multiple lifecycle product'), the stepwise approach and tools are illustrated with a fictional example of the redesign of an electric bicycle, developed with the company Roetz-Bikes.

Roetz-Bikes is a social enterprise that refurbishes discarded bicycles from well-known Dutch brands and turns them into a line of fashionable (e)bikes for sale. This way, 30-40% of the old bicycles can be reused. In addition, Roetz-Bikes currently refurbishes 1000 public bicycles ("OV bike") per year for the Dutch Railways (NS), at a reuse percentage of 70%. The picture below illustrates the reuse potential of the different parts of an OV bike.

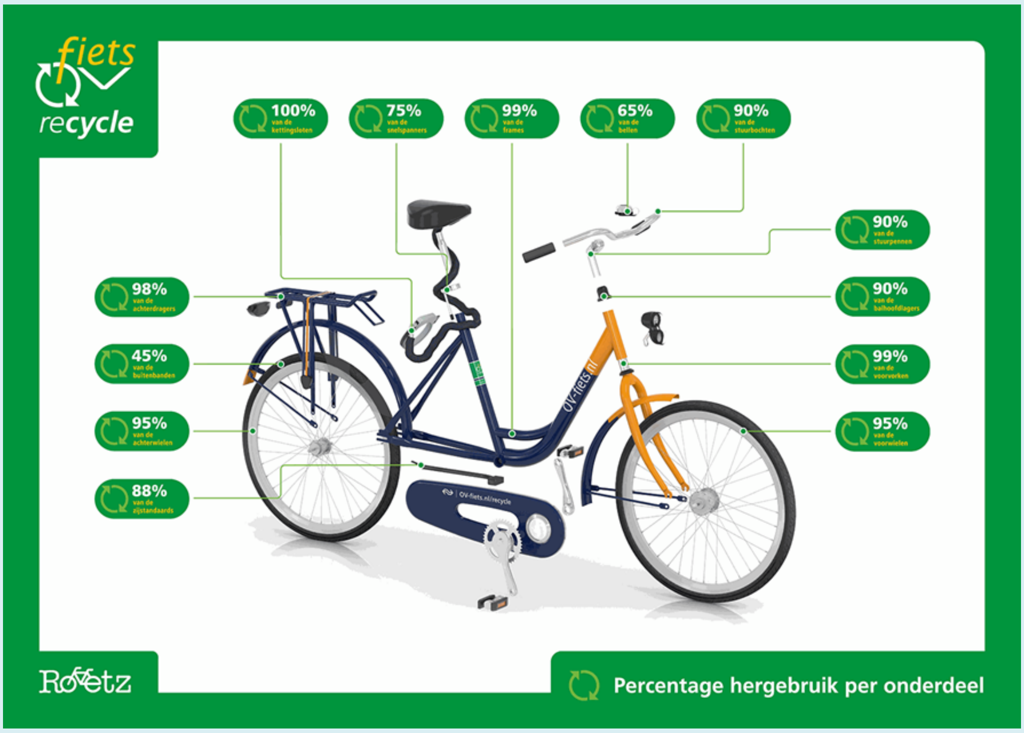


Figure 1: Roetz bikes & the remanufactured OV Bike (source: Roetz)

2. Eight steps to a multiple lifecycle product

The ResCoM design methodology consists of a stepwise approach with eight steps to guide companies in the development of multiple lifecycle products. This section explains what is meant with ‘multiple lifecycle products’, and introduces the eight-step approach.

Multiple lifecycle products are products with multiple ‘lives’. Within the ResCoM project, a lifecycle is defined as follows: A lifecycle of a product starts when it is released for use after it has been manufactured or remanufactured. It ends when it is disposed of (e.g. resold/landfilled/recycled) or dismantled to harvest/reuse its components. The lifecycle of some (or all) of the components can continue in new products when the lifecycle of a product ends. If an essential amount of components form part of the same new product, the product lifecycle continues in that product.

The ResCoM approach follows the basic ‘stage-gate’ design engineering process of OEMs, which generally consists of four product development stages, as shown in Table 1.

Stage		Description
1	Project Definition	In this stage, the activities are focused on discovering opportunities and generating new product ideas. This stage also includes a quick assessment of the (technical) merits of the project and its market prospects.
2	Concept Definition	In this stage, the product idea is defined in more detail, usually complemented with an assessment of the technical, market, and business feasibility of the product.
3	Design Definition	The product concept is designed and developed in detail, including the development of manufacturing and marketing plans. Extensive testing and validation (i.e. customer acceptance) also takes place in this stage.
4	Product Implementation	This stage marks the launch of the product and the beginning of full production and commercial launch.

Table 1: Generic stage-gate product development process

When implementing circular product development, crucial strategic decisions need to be made in the first two product development stages, project definition and concept definition. Consequently, the ResCoM design methodology focuses on these product development stages.

Table 2 shows the overview of the eight-step approach, with the different stages, steps and accompanying tools.

Stage	ResCoM steps	ResCoM tools
1. Project Definition	**Step 1**: State your Ambitions	
	Step 2: Identify circular product design strategies	- Circular Pathfinder
	Step 3: Determine circular potential of your strategy	- Circularity Calculator - Analytical tool
	Step 4: Visualize your circular strategy	
2. Concept Definition	**Step 5:** ResCoM product design	- Part planning - Upgrade Forecast - Reman Design Checklist - Multiple Lifecycle Product Design tool
	Step 6: Tracking performance	- Circularity Calculator - Enhanced EcoAudit - Analytical tool - Multi-method simulation
3. Design Definition	**Step 7:** Detail design	- Part planning - Upgrade Forecast - Reman Design Checklist - Multiple Lifecycle Product Design tool - Circularity Calculator - Enhanced EcoAudit - Analytical tool - Multi-method simulation
4. Product Implementation	**Step 8**: Implementation	- ResCoM PMLM system

Table 2: Overview of ResCoM tools for the four product development stages

Each of the following chapters of this report will address one stage and shortly explain the corresponding steps and tools. The actual ResCoM tools can be found via the ResCoM project website: www.rescoms.eu and visualisations from the website are used throughout this report.

3. Project definition (Stage 1)

In the Project definition stage of product development, four of the ResCoM approach steps are taken. This chapter explains these four steps and the accompanying tools.

3.1 Step 1: State your Ambitions

Companies have different motivations for going circular. Before starting a product development process, it is important for companies to understand their reasons for wanting to change to a (more) circular business, and what drivers and barriers they foresee for successfully implementing a circular product-system.

Step 1 at Roetz-Bikes

"We want to be the first to make a 100% circular bike. This is our dream. We believe that sustainable and convenient mobility should be available to a broad public."

During a ResCoM workshop, this ambition was translated into a set of key aspirations for Roetz and its bicycles: "Accessible, Easy to maintain, Traceable, Easy to disassemble and recycle, Modular, Close customer relation, High quality, Long lasting."

Drivers: "Now is the time". Roetz has CEO support for going circular, a company vision to match and a new factory capable of remanufacturing.

Barriers: "The devil is in the detail". Material innovations may be needed. How to deal with immature technology.

To aid the identification of potential drivers and barriers, table 3 shows examples of generic drivers and barriers that OEMs anticipate before starting their circular product development.

Possible drivers	Possible barriers
• Creating a strong market position in this field • Generating profit • Utilizing the long life of the product • Utilizing new technological developments • Aligning with personal ambitions within the organisation • Addressing environmental issues • Creating and benefitting from new partnerships	• Product complexity • Requires major organisational and/or product design changes • Time required to achieve results • Internal resistance to change • Costs for development and implementation • Customer acceptance • Legislation

Table 3: Overview of generic drivers and barriers for going circular

3.2 Step 2: Identify circular product design strategies

In Step 2, the most promising circular design strategies are identified, with the help of the Circular Pathfinder tool (figure 2).

The Circular Pathfinder is a starting tool for companies interested in circular economy thinking, allowing them to explore and identify the most suitable circular pathways for their products, by answering just a few questions. Informed by the best practices of other companies, the Circular Pathfinder guides the user towards circular pathways that have potential in their specific case. It explains why certain pathways, such as product remanufacturing, life extension, or recycling, are of interest, with examples from companies that have already applied them. Based on the outcomes, the tool suggests which ResCoM tools are applicable to the specific case at hand.

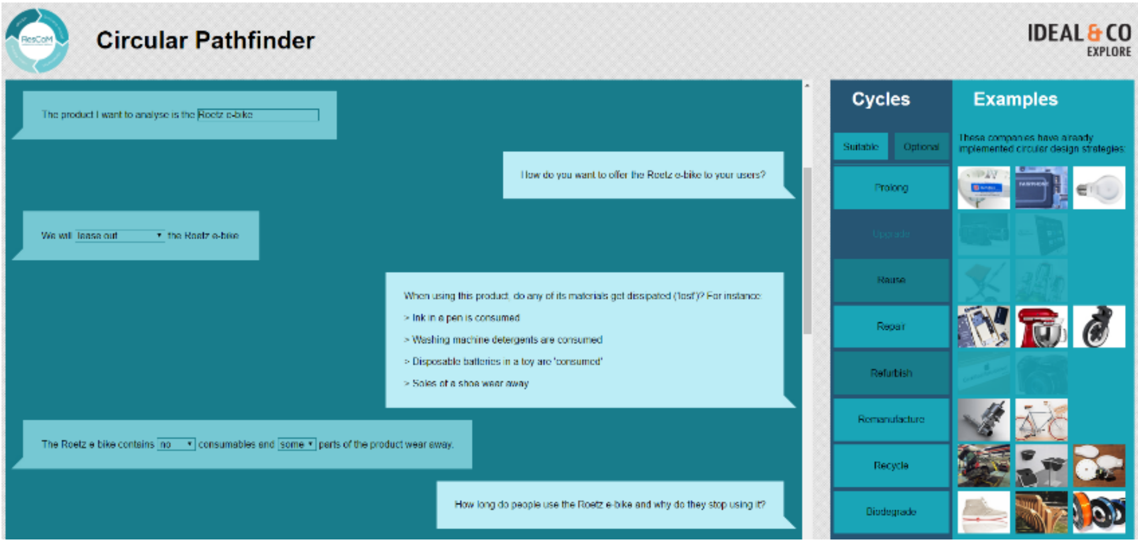


Figure 2: Screenshot of the Circular Pathfinder tool for a Roetz e-bike

Step 2 at Roetz-Bikes

The Circular Pathfinder for a Roetz e-bike showed that the reason why users will replace or discard their E-bike influences which strategies have potential. For bicycles, where the main reason for replacing or discarding of a bicycle is because it broke down, the pathfinder gave the following advice:

“Suitable strategies for a circular redesign of your product are design for durability, reparability, remanufacturing, recycling and biodegradation.”

However, for E-bikes this may be somewhat different, and users may replace their E-bike for a newer model before it breaks down, because new models have better specifications.
In that case, the pathfinder advises:

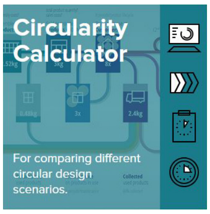
“…design for upgradability, refurbishment, remanufacturing, recycling and biodegradation.”

As both scenarios are realistic, it was decided to investigate two scenarios: one focussing on design for **repair** and **remanufacture,** and one including design for **upgradability**.

3.3 Step 3: Determine circular potential of your strategy

An important part of the Project Definition stage is making a quick and inexpensive assessment of the circular potential of the product idea, in order to determine whether the creation of multiple lifecycle products is a potentially viable strategy for the company.

3.3.1 Circularity Calculator



The Circularity Calculator helps designers that work in the early stages of product development to obtain a 'circularity instinct': an understanding of how strategic design decisions influence the degree of circularity of resource flows and the potential value capture within product-service-system.

The Circularity Calculator tool displays the potential mass and value flows of a product, based on whether the different parts are reused, remanufactured and/or recycled. With this tool, designers can model different conceptual design solutions and business models to explore and compare design scenarios and see their impact on performance indices such as overall circularity, recycling rate and value recovery potential. Both high level and more detailed analyses are possible.

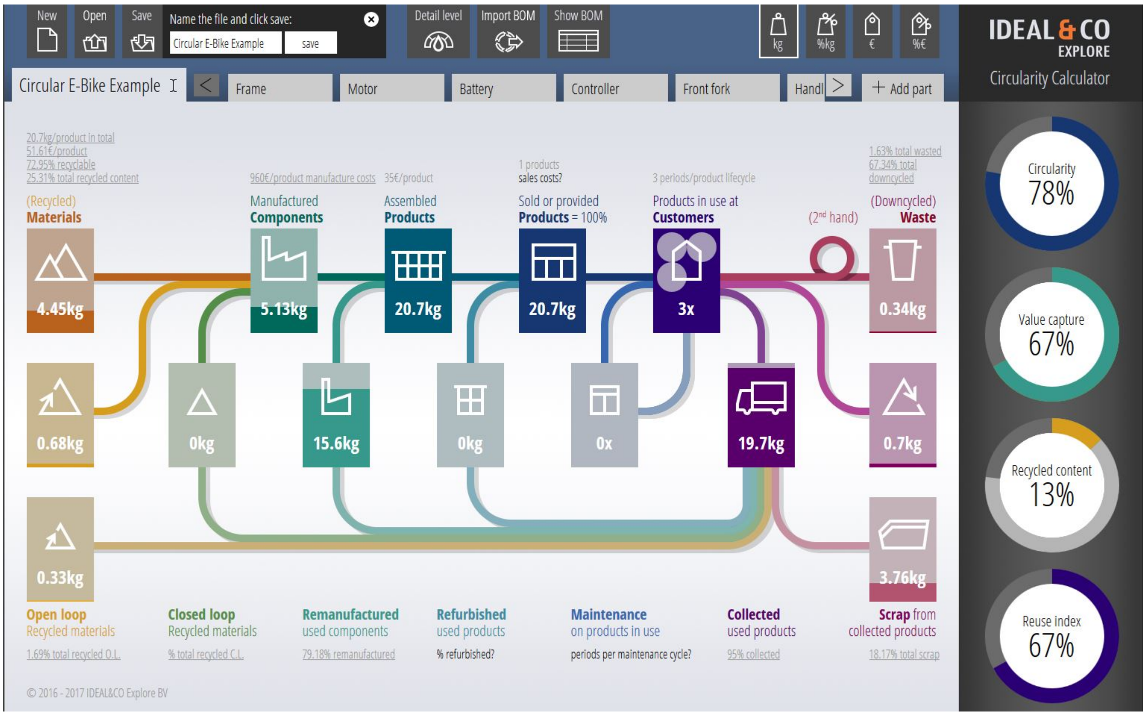


Figure 3: Screenshot of the Circularity Calculator for the Roetz E-bike

Figure 3 shows a possible remanufacturing scenario for an E-bike. As can be seen in the figure, the circularity indicator (78%) is a measure of the mass in kg that is looped back through remanufacturing and recycling. In a fully circular system (Circularity index of 100%) no virgin resources are used and no waste is produced. The value capture indicator (67%) is a measure of the potential value (in Euros) embedded in the materials, parts, products and waste flows.

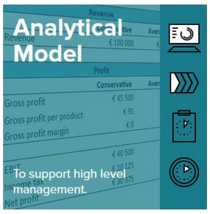
Step 3 at Roetz-Bikes

Roetz used the Circularity Calculator during a ResCoM workshop. Based on the assumption of a 95% return rate of used bicycles, remanufacture rates of 30% - 95% for the different parts, and recycling of most recyclable scrap materials, the calculator gave the following outcome:

"This scenario scores 78% on Circularity; 67% on Value capture; 13% on Recycled content, and 67% on Reuse index", reflecting the high potential of this scenario.

Variants for this scenario were also calculated, including upgrading of the battery, and refurbishment as well as remanufacturing of parts. This led to slightly different outcomes and sparked an animated discussion about the differences between refurbishment and remanufacturing.

3.3.2 Analytical tool

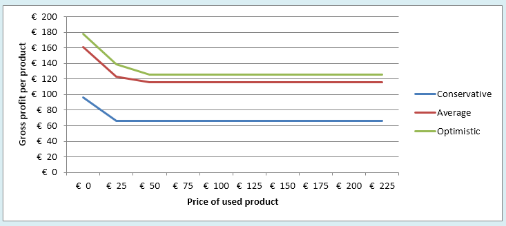


Following the outcomes of the circularity calculator, the Analytical Tool allows business managers to further gauge the potential profitability and environmental impact of different scenarios. In the Analytical Tool, conventional linear models can be compared with potential closed-loop scenarios to help OEMs compare the potential profitability and environmental performance (figure 4). A number of parameters related to cost (e.g. production costs, forward and reverse logistics costs) and critical factors (e.g. remanufacturing success rate, return rate) can be modified to test different cases. Investment costs for design, reverse engineering, or facilities can also be included where needed. CO_2 calculations provide insights into product scenario environmental performance. Sensitivity analysis helps the OEMs understand the boundaries of profitable closed-loop systems and what is needed to make the systems profitable in the future. With only a few input variables, the tool provides quick answers and directions for further in-depth evaluations of potential closed-loop business models.

Sensitivity analysis

The cells in yellow can be changed to select an appropriate range over which the results will be shown. All other values will be taken from the 'Input data' sheet.

Purchasing price of used product - Price paid to buy one used product	Gross profit per product		
	Conservative	Average	Optimistic
€ 0	€ 96	€ 161	€ 178
€ 25	€ 66	€ 123	€ 139
€ 50	€ 66	€ 116	€ 126
€ 75	€ 66	€ 116	€ 126
€ 100	€ 66	€ 116	€ 126
€ 125	€ 66	€ 116	€ 126
€ 150	€ 66	€ 116	€ 126
€ 175	€ 66	€ 116	€ 126
€ 200	€ 66	€ 116	€ 126
€ 225	€ 66	€ 116	€ 126



Selling price of remanufactured product	Gross profit per product		
	Conservative	Average	Optimistic
€ 0	-€ 89	-€ 89	-€ 89
€ 50	-€ 39	-€ 39	-€ 39
€ 100	€ 11	€ 11	€ 11
€ 150	€ 61	€ 61	€ 61
€ 200	€ 111	€ 111	€ 111
€ 250	€ 161	€ 161	€ 161
€ 300	€ 211	€ 211	€ 211
€ 350	€ 261	€ 261	€ 261
€ 400	€ 311	€ 311	€ 311
€ 450	€ 361	€ 361	€ 361

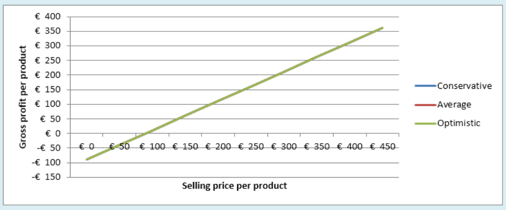
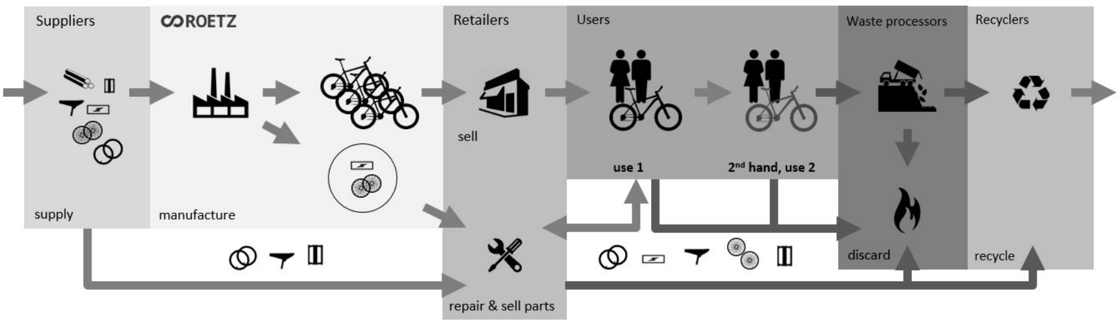


Figure 4: Analytical tool

3.4 Step 4: Visualise your circular strategy

Based on the outcomes of step 1-3, one or more circular design strategies may hold good potential. In this step, the basic layout of these circular scenarios is developed and visualised. The visualisation proves a useful step for discussing scenarios and for uncovering different interpretations that project members may have of a scenario.
Figure 5 shows two (fictional) scenarios for Roetz bikes, a purely linear scenario and a potential future scenario. These visuals are used as the templates for the next steps.

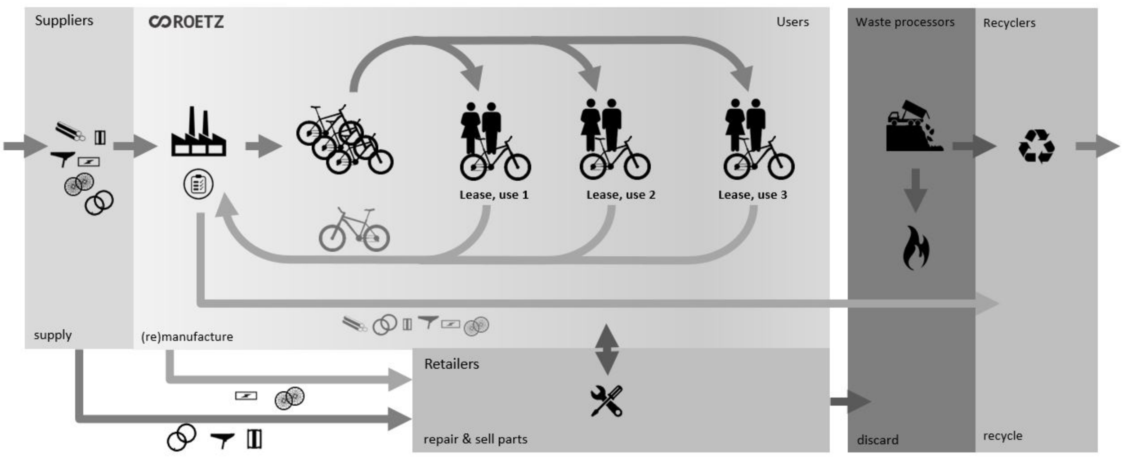
Scenario 1: Linear state - Selling



Scenario 1 depicts the current state of most E-bike manufacturers, where bicycles are:

- Produced using new materials and parts.
- Sold via retailers.
- Used for -on average- two use cycles, where the first users sell or give their E-bicycle to a second user (2 x 5 years in total).
- Repaired and maintained during use. Worn tires are replaced, and broken or ill-performing parts are replaced, either by the retailer that repairs the product, or by the user itself.
- Send to the general waste processors after the second use cycle, where part of the discarded materials will send to recycling.

Scenario 2: Future state – Leasing and remanufacturing



Scenario 2 depicts a future, circular state for E-bike manufacturers, where bicycles are:

- Leased to the users for a certain leasing period via the manufacturer (or a third party).
- Returned to the manufacturer after each use cycle, which enables high-quality reuse and recycling.
- Remanufactured after each use cycle (back to original performance) using parts from returned bicycles. Parts are -for now- assumed to last -on average- three use cycles (3 x 5 years in total).
- Repaired and maintained during use. Worn tires are replaced by the user (or an external retailer). Broken or ill-performing parts are replaced during remanufacturing or in-warranty by the manufacturer.
- No longer send to the general waste processors. Parts for which remanufacturing is no longer feasible are send to dedicated recyclers. It is assumed that discarded service parts may still end up being incinerated.

Figure 5: Visualise your circular strategy, example based on two fictional scenarios for Roetz.

4. Concept definition (Stage 2)

ResCoM identifies two steps in the Concept Development stage of product development: Step 5: ResCoM product design and Step 6: Tracking Performance. This following chapter explains these two steps and the accompanying tools.

4.1 Step 5: ResCoM product design

In addition to the common product design activities in stage two, several dedicated activities are needed to translate the strategic decisions made in stage one into requirements to be met in stage three. In doing so, conceptual solutions arise. To aid the design process in the Concept Definition stage, both generic design requirements and dedicated tools were developed within the ResCoM project. The design requirements were compiled from literature for the different circular strategies such as Design for Remanufacturing and Design for Recycling. The requirements include, amongst others, what type of materials or combinations thereof and connections between parts are advisable or should be avoided. They can be found on the ResCoM platform www.rescoms.eu along with the ResCoM product design tools. The tools themselves are described in further details in this report. Table 4 explains the four ResCoM design tools for step 5. Each of the tools is described separately in the following sections.

Tool	Short description
Part Planning	Analyse parts and discuss implications in order to create a strategic planning of carry-over parts.
Upgrade Forecast	Forecast technological trends to create products responsive to future needs
Reman Design Checklist	Checklist to assess, compare and improve the remanufacturability of parts and products.
Multiple lifecycle product design tool	Determine feasible circular strategies for the different modules, i.e. which modules can be reused, remanufactured or recycled

Table 4: Short descriptions of the ResCoM product design tools.

4.1.1 Part Planning

When designing for durability and good repairability, the availability of spare parts is a key issue to address within a circular business model. These parts need to be available for a long period, which may prove costly. One solution for offering spare parts in a way that is economically viable is to design for spare part compatibility across product generations. In that way, parts from newer generations can be used to service older products as well.

The Part Planning tool assists companies to plan the lifetime and reuse of parts and modules in advance. Within a workshop, an interdisciplinary project team develops a strategic plan for carry-over parts, by means of disassembling a product, analysing which parts can potentially be carried over to future generations, and discussing the design changes that would be needed to accomplish part compatibility. Figure 6 gives an impression of the workshop at Roetz.

Figure 6: Part Planning Tool. Impression of which parts can potentially be used more than one design generation. Showing respectively parts that cannot be reused (only usable 'now'), and parts that can be reused or 'carried over' up to the first (1), second (2) and third (3) generation of bicycles

Part Planning at Roetz-Bikes

For Roetz, Part planning is an important tool as they want to design their E-bike to be durable, remanufacturable, and easy to repair over multiple use cycles. Roetz applied the Part Planning tool during a ResCoM workshop, which provided them with:

- Motivated decisions on how many generations a part should or could last. Product durability and expected technological developments were considered the most important variables to influence part compatibility across generations.
- Specific suggestions for design changes to enable cross generation compatibility.

4.1.2 Upgrade Forecast

Many products, such as televisions and mobile phones, are subject to rapid technological developments. As a consequence, they are frequently replaced before they break down in favour of a new product with new capabilities. By allowing new features to be added to the product, its useful lifetime can be prolonged and it can offer better value for money to customers.

The Upgrade Forecast tool is designed to help OEMs determine what upgrade specifications to include in product design. The tool facilitates interdisciplinary teams involved in product development to visualise future trends, demands and disturbances, to select the product features that will require upgrading, and to determine the specifications of these future upgrades. The tool has been designed as an A0 template on which a graphical representation of technological trends over time can be made for key functionalities of the product. During a workshop with a multi-disciplinary product development team, the tool is filled in to develop an upgrade plan with design specifications.

Upgrade Forecast at Roetz-Bikes

If Roetz follows one of the alternative scenarios, in which many users will discard the E-bike because better technology becomes available, they have to design for upgradability (see results step 2). One of the key functionalities of the E-bike is the electric assist. Figure 7 provides an example of an upgrade forecast for the electric assist of an E-bike for three KPI's 'range', 'power', and 'weight'.

One of the outcomes of the forecast would be that the advancements in battery technology are considerable within the use life of the E-bike, and that Roetz should offer battery upgrades to allow faster charging in the future.
A conceptual design solution could be to allow for easy replacement of the battery, with a design freeze on the interface, and a controller that is already able to cope with higher future charging loads.

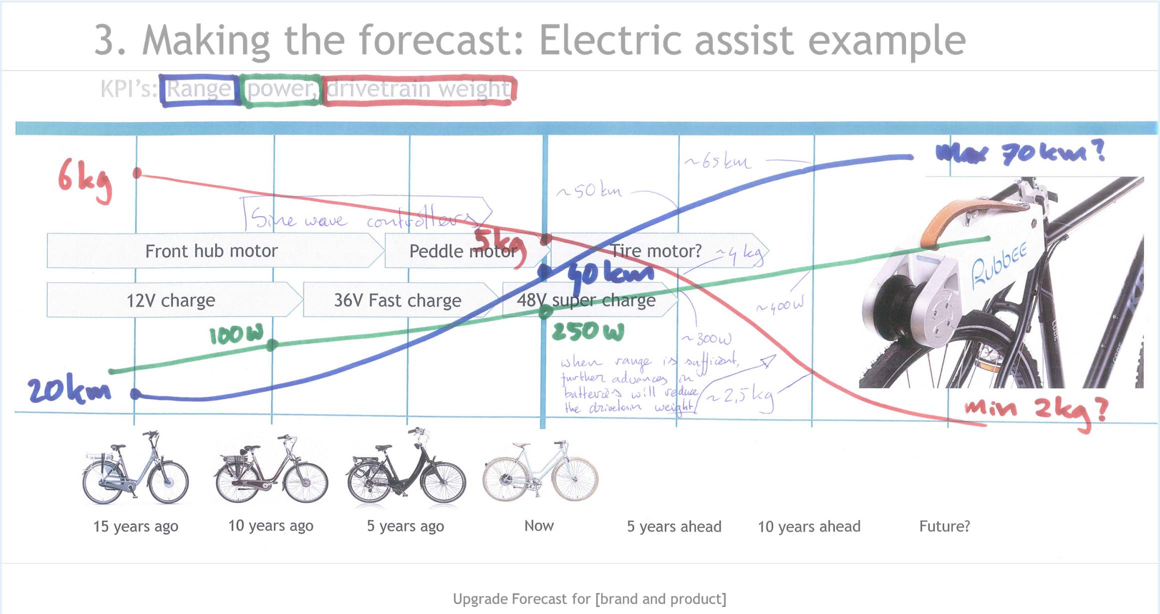


Figure 7: Upgrade Forecast tool. Impression of a template and forecast for an E-bike.

4.1.3 Reman Design Checklist

Currently, various durable products are already being remanufactured, as it allows companies to use their high-quality parts again and offers customers products that perform as well as the originals. However, the majority of products have not been designed with future remanufacturing in mind. When designing for Remanufacturing, the product is optimised for generating the highest economic and functional performance over the different lifecycles of the product.

The Reman Design Checklist helps product engineers explicitly consider the remanufacturability of a product design by analysing and scoring the remanufacturability of its components: information that allows the team to track progress between design iterations. The output of the tool includes an evaluation of product components and recommendations for further improvements.

The tool offers a multiple-choice checklist to assess the remanufacturability of a design concept and to compare two design variants. Products and their parts are scored on a five-point scale via ten questions to determine their remanufacturability. Questions include “Is the part easy to separate?” and “What is the anticipated quality of this part after normal use?”. The questions are multiple-choice and the tool supplies an instant score at part and product level on their remanufacturability and, where needed, shows improvement areas. Figure 8 gives an impression of the application of this tool for an E-bike, showing the scores for the E-bike frame.

ResCoM ROETZ Reman Design Checklist

Worksheet II: Checklist Design A

Product: **E-bike**
Grader: **IP**
Date: **10/02/2017**

description & steps to take

1. **Questions:** Please assess all product parts by choosing ar
2. **Evaluate:** In the Results section, each part/module receive
3. **Draw conclusion:** In the Conclusions section, please sele

A	Checklist nr.:	1
	Part ID:	1.01A
	Part name:	Frame

1. Questions 1-10:

		Answers: *(select from dropdown menu)*	Scores:
Q 1	Is this part a carry-over part?	no, the design of this part has changed (as compared to the previous product version) *> ok, please answer questions 2-10 for this part*	n
Q 2	When returned for remanufacturing, will this part have become outdated?	no, when still in good condition, this part could be used again	u
Q 3	What is the relative value of this part (production costs)?	this is a high value part (> I....,-), a high value subassembly (> I....,-) AND/OR a custom-made part (of any value)	h
			Score
Q 4	Is this part easy to identify?	once dismantled, parts can be easibly distinguished from other design variants	1
Q 5	Is this part easy to dismantle/separate from the product?	can be disassembled, but complex (e.g. requires multiple tools, complex handling, or has very small sizes)	0
Q 6	Is this part easy to clean?	easy to clean (fast, e.g. wipe, shape prevents dirt-accumulation, easy to handle)	1
Q 7	Is this part easy to test/inspect?	can be inspected with some effort	0
Q 8	What is the anticipated quality of this part after normal use?	restorable to 'as new' (...)	1
Q 9	How vulnerable is this part when treated rough (during use and/or transport)?	robust, little damage anticipated	2
Q 10	Can this part be recycled (or biodegraded)?	very well (base material can be recycled, recycling infrastructure is present; fasteners, stickers etc are compatible or do not influence recycling quality)	2

2. Evaluate results per part:

	Overall part score	
Overall part score *(=lowest part sub-score)*	**Frame**	**0**
Suggested actions per part **Part strategies:** remanufacture / replace / upgrade / recycle **Design strategies:** DfReman = Design for Remanufacturing DfD = Design for Disassembly DfU = Design for Upgrading DfR = Design for Recycling	This part could be used again and has a high value (and/or is custom made) but this part is not easy to remanufacture. CHECK the part scores above, to see what issues to improve upon!	DfReman
	When this part can no longer be used, it can be recycled	recycle

3. Conclusions per part:

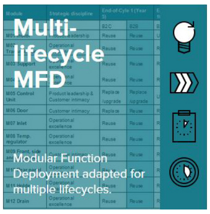
	Overall part score	
TEAM CONCLUSION from the assessment: > switch between either 'Maintain design' or 'Change design'	*Change design*	Change
Room to motivate conclusion: (especially when an improvement is suggested)	*Optimize for disassembly and inspection*	

Figure 8: Print screen of a part of the Roetz Reman Design Checklist.

Reman Design Checklist at Roetz-Bikes

Roetz already remanufactures existing bicycles, but these bicycles were not designed with future remanufacturing in mind. The company feels there is a gain to be made with a redesign. The Reman Design Checklist helps to pinpoint key parts to improve and provides design recommendations.
In this example, the checklist suggests to redesign the frame for improved remanufacturability, as it is a high value part that could be used again.
The suggestion is to redesign the frame for easy disassembly (requiring fewer different tools) and to optimize for easy inspection of its quality.

4.1.4 Multiple Lifecycle Product Design tool



Modular design is a key enabler of Circular Business models that rely on the exchange of components between products, product generations and product families. The Multiple Lifecycle Product Design (MLPD) tool uses the existing Modular Function Deployment (MFD) method and extends it for multiple lifecycles, allowing companies to plan their product modules along multiple use-cycles and lifecycles.

The tool helps to determine feasible circular strategies for the different modules, i.e. which modules can be reused, remanufactured or recycled. This tool takes a closer look into reasons for which a product will be replaced or discarded, on a module level. Modules are categorized into three strategic disciplines according to which modules are most likely to face emotional, technological or functional obsolescence. The outcome of the tool is a multiple lifecycle plan for the existing product. The three strategic disciplines are customer intimacy, product leadership and operational efficiency, each of which is more prone to face a certain type of obsolescence, see figure 9.

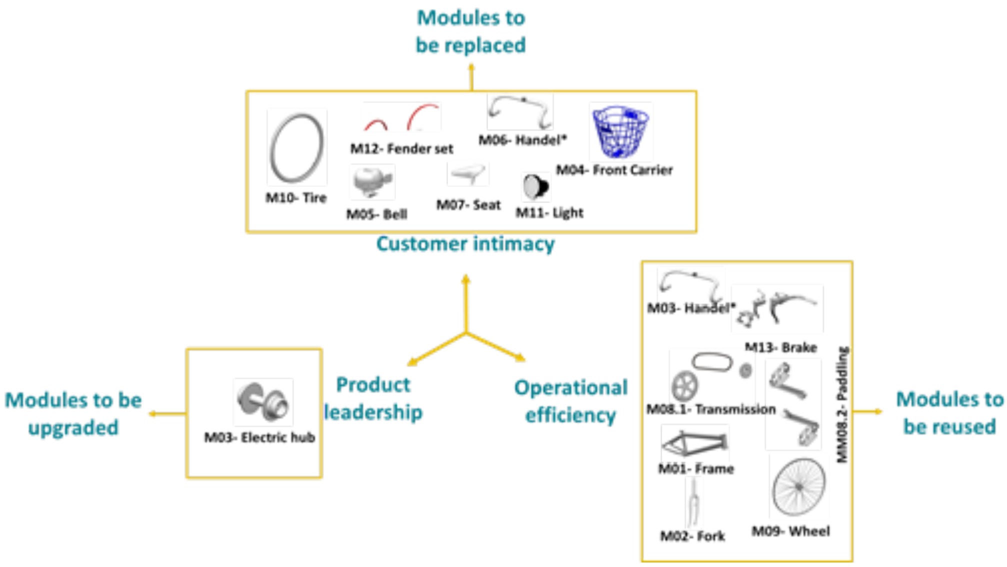


Figure 9: Multiple Lifecycle Product Design tool. Example of a categorisation of bicycle modules for multiple lifecycle planning. In this case it is assumed that the bicycle has been designed for private owners.

Modules that are developed keeping ***customer intimacy*** in mind are most likely to face emotional obsolescence, for example, aesthetic components of a bicycle such as the seat, chain cover, and front carrier. Similarly, modules that are developed keeping ***product leadership*** in mind, such as an electric motor or battery, are more likely to face technological obsolescence.

Modules that are not developed with customer intimacy or product leadership in mind are most likely to face functional obsolescence. For example, the inner wheel, frame and transmission are subject to wear and tear as well as functional obsolescence.

On the basis of this analysis the MLPD tool suggests a lifecycle planning for the bicycle. Table 5 shows an overview of the lifecycle planning for a bicycle using two scenarios: private owners and commuters.

Module	Strategic discipline	End-of-Cycle 1 (Year 5)		End-of-Cycle 2 (Year 10)	
		Private	Commuter	Private	Commuter
M01 - Frame	Operational excellence	Reuse	Reuse	Reuse	Reuse
M02 - Fork	Operational excellence	Reuse	Reuse	Reuse	Reuse
M03 - Electric hub	Product leadership	Replace upgrade	Replace upgrade	Replace upgrade	Replace upgrade
M04 - Carrier	Customer intimacy	Replace	Reuse	Replace	Reuse
M05 - Bell	Customer intimacy	Replace	Reuse	Replace	Reuse
M06 - Handle	Customer intimacy Operational excellence	Replace reuse	Replace reuse	Replace reuse	Replace reuse
M07 - Saddle	Customer intimacy	Replace	Replace	Replace	Replace
M08.1 - Transmission	Operational excellence	Reuse	Reuse	Reuse	Reuse
M08.2 - Paddling	Operational excellence	Reuse	Reuse	Reuse	Reuse
M09 - Wheel	Operational excellence	Reuse	Reuse	Reuse	Reuse
M10 - Tire	Customer intimacy	Replace	Replace	Replace	Replace
M11 - Light	Customer intimacy	Replace	Reuse	Replace	Reuse
M12 - Fender set	Customer intimacy	Replace	Reuse	Replace	Reuse
M13 - Brake	Operational excellence	Reuse	Reuse	Reuse	Reuse

Table 5: Lifecycle planning of the bicycle, designed to serve both private owners and commuters.

MLPD tool at Roetz-Bikes

The results in table 5 show a number of potential design strategies.

- One important observation is that the choice for circular strategy is dependent on the target users. It is assumed that commuters are less sensitive to emotional obsolescence of bicycles than private owners. Therefore, those modules that are categorised as customer intimacy modules in the scenario of private owners (in this example the carrier, bell, light, and fender) can be reused when the commuter scenario is chosen.
- Additionally, consideration should be given to the assembly of modules, as the obsolescence of a part can render the whole module unusable. Modules should be configured in such a manner that all its parts are from the same strategic discipline so that they can be replaced or upgraded together when they become obsolete.
- The results of this tool can help Roetz to determine how many use cycles to aim for. For instance, while the Part Planning tool showed that the bicycle saddle could potentially last three generations, the MLPD tool places this part in customer intimacy, limiting the number of times it is *advisable* to reuse it.
- If the goal is to maximize the reuse of spare parts, commuters could be chosen as target group.

4.2 Step 6: Tracking performance

After having identified conceptual solutions in step 5, step 6 continues by analysing the solutions in more detail. Throughout the project, the technical, economic, and environmental performance of the solutions are monitored, to assess whether the project can move to the consecutive development stage. Potential circularity, value capture, and profitability can be assessed via more detailed analyses in the Circularity Calculator and Analytical tool (described in section 3.1). However, once more details become available on the lifecycle scenario of the solution and on the implementation costs, more detailed analytical tools are available to track performance. Within ResCoM the Mi:BoM Analyzer with Enhanced Eco Audit tool and the Multi-Method simulation tool were developed to track performance.

4.2.1 Granta ResCoM MI:BoM Analyzer: Enhanced EcoAudit

The ResCoM MI:BoM Analyzer enables the assessment of environmental, regulatory, and supply chain risks, and supports increased resource efficiency for products. After importing and editing a bill of materials (BoM), the tool instantly runs reports that apply an extensive database of materials, process, and environmental data to assess product risk and guide design decisions (figure 10). This includes newly-enhanced Eco Audit reports, which can assess environmental impacts and cost across multiple use cycles, providing detailed information on reverse logistics and estimating the break-even point for closed loop remanufacturing against linear production in terms of both environmental impacts and lifecycle cost.

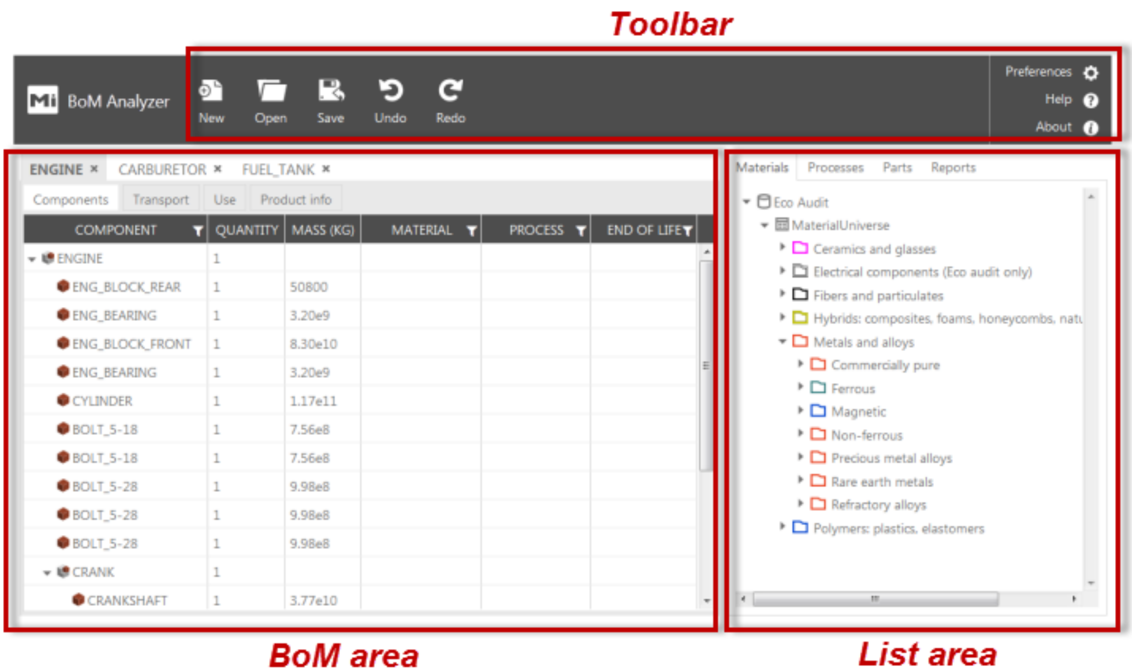
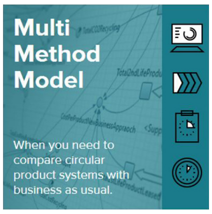


Figure 10: MI:BoM Analyzer—construct or edit a Bill of Materials and run any of a wide range of reports. In the list area you also have the option to select different processes and reports to run.

4.2.2 Multi-Method simulation tool



The Multi-Method simulation tool has been developed using system dynamics (SD) and agent based (AB) modelling techniques to assess economic and environmental performance of circular product systems from a system perspective. More than 120 variables are considered simultaneously in order to describe a typical circular product system, which deals with changes and effects of business models, product design and supply chain, addressing challenges including:

- Customer acceptance and expected demand of new business models
- Consideration and effects of product design alternatives
- Design of supply chain to respond to the needs of the new business models

The integration of the developed sub-models for business models, product design and supply chains give a comprehensive overall picture in order to understand the dynamics of circular product systems while making use of today's available computing-power. Figure 11 shows an overview of inputs and outputs used in the multi-Method simulation tool.

Combining these inputs, outputs and their feedback, the tool is capable of assessing the economic and environmental performance of circular systems as shown in figure 12.

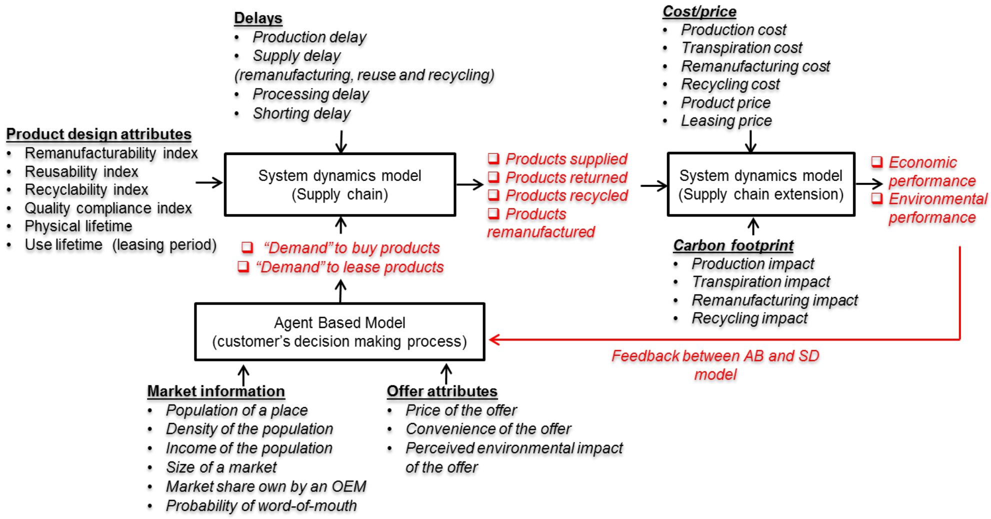


Figure 11: An overview of the inputs and outputs of the multi-method simulation tool.

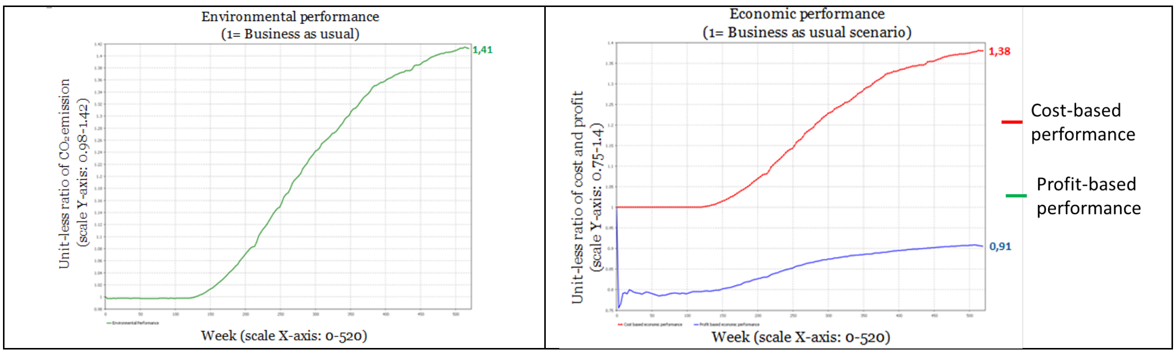


Figure 12: An example of economic and environmental performance graphs. (Performance ratio > 1: Environmental/economic performance of the circular product systems is better than the linear scenario. Performance ratio <1: Environmental/economic performance of the circular product systems is worse than the linear scenario)

5. Design definition (Stage 3)

5.1 Step 7: Detail design

As in traditional ‘linear’ product development, conceptual solutions are turned into production drawings. In this process, choices are made about the embodiment of the design, such as materials, fasteners, assembly steps and component interfaces. These are choices that may help, hinder or be neutral to circular ambitions such as increased recyclability, remanufacturability or repairability. The same tools used in the concept definition stage (**step 5:** ResCoM product design tools and **step 6**: Tracking performance tools) can now be used to check a partial solution, to compare alternatives, to track progress and to provide context to requirements.

6. Project implementation (Stage 4)

6.1 Step 8: Implementation

For the product manufacturing stage, a comprehensive circular strategy includes return logistics, with products or parts returning to the manufacturer for inspection and reutilisation. As a consequence, additional information must be stored to enable identification of the products and parts that come back after use. This identification is vital to ensure the quality of the multiple lifecycle products. In case of remanufacturing for instance, only compatible components should be recombined, in refurbishment cases only appropriate spare parts should be used for repairs,, and in recycling cases only components of the exact same material should be recycled together. While it is already commonplace to issue serial numbers to identify products of a specific production batch (allowing identification for servicing and discovery of production flaws), circular cases and especially remanufacture cases require more fine-grained identification.

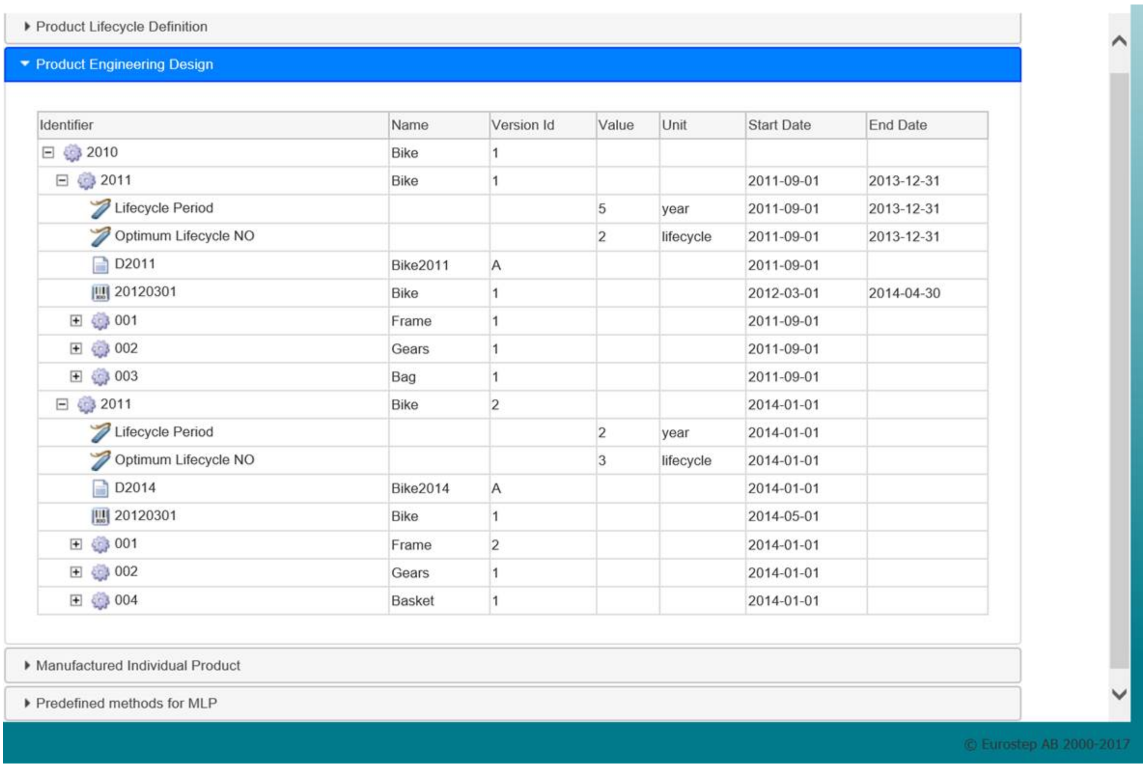
6.1.1 Product Multiple Lifecycle Management tool

The ResCoM Share-A-Space PMLM (Product Multiple Lifecycle Management) can identify individual products (not only batches) and individual components within the products (not only whole products), so that when a product comes back that has been remanufactured before, knowledge is present on how many use cycles each component has had and whether they are fit for another use, compatible with a new design version or in line with present-day regulations.

The PMLM tool is an enhanced product lifecycle management (PLM) tool that supports closed loop, multi life cycle products and supply chains in an integrated and traceable manner. The information managed includes production definition (multiple lifecycles), product design including material selection, usage and maintenance definition, business model definition and supply chain definition etc. (figure 13). From the well-structured product data, one can check:

- Processes linked to remanufacturing and closed loop supply chains
- Product changes traced during the multiple lifecycles
- Product evolution throughout the multiple lifecycles

The tracing system enables OEMs to maximize the return from products by going beyond the initial product sale and providing customers with value-added service throughout the product lifecycle.



Identifier	Name	Version Id	Value	Unit	Start Date	End Date
2010	Bike	1				
2011	Bike	1			2011-09-01	2013-12-31
Lifecycle Period			5	year	2011-09-01	2013-12-31
Optimum Lifecycle NO			2	lifecycle	2011-09-01	2013-12-31
D2011	Bike2011	A			2011-09-01	
20120301	Bike	1			2012-03-01	2014-04-30
001	Frame	1			2011-09-01	
002	Gears	1			2011-09-01	
003	Bag	1			2011-09-01	
2011	Bike	2			2014-01-01	
Lifecycle Period			2	year	2014-01-01	
Optimum Lifecycle NO			3	lifecycle	2014-01-01	
D2014	Bike2014	A			2014-01-01	
20120301	Bike	1			2014-05-01	
001	Frame	2			2014-01-01	
002	Gears	1			2014-01-01	
004	Basket	1			2014-01-01	

Figure 13: Impression of the Product Multiple Lifecycle Management tool for a bicycle.

7. Conclusions

The ResCoM design methodology, with the stepwise approach and tools set out in this report can provide practical assistance to companies in circular product development. Due to the current pioneering stage of the circular economy and circular product development, a company such as Roetz may embark upon a journey towards circular product development without really knowing where to start. It can be difficult to assess which barriers and enablers are present and to identify which solutions are economically and ecologically viable. By following the steps in this report and implementing the tools, companies can know where they need to pay attention to and discover circular product development avenues worth pursuing. The tools give detailed information at part level on what the consequences and performances indicators are, so that companies can make sound circular decisions on the basis thereof.

The tools described in this report, will become available via the ResCoM Platform www.rescoms.eu. The platform brings together the software applications and descriptive tools (Figure 14), allowing companies to see actual demos of the tools for the bicycle example case, and to get further access to the tools.

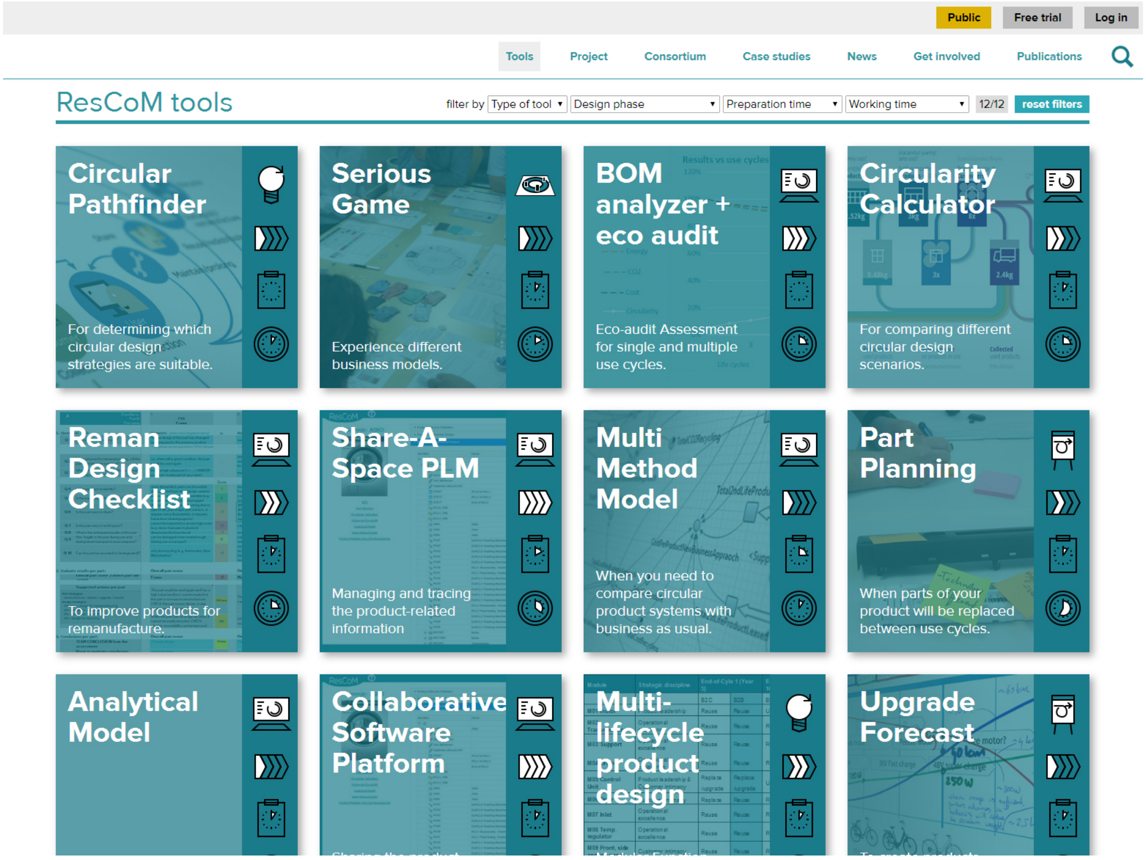


Figure 14: Impression of the ResCoM tool platform

Visit the website to access the ResCoM platform,
tools, and the final project deliverables.

www.rescoms.eu

2017