Circularity in Product Development - a case at SKF

Master's thesis in Programme - Product Development

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To implement circularity in the product development of a bearing manufacturing company

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Abstract

As we are facing environmental challenges globally, the traditional take-make-disposal liner model is no longer sustainable and society as a whole must evolve. Organizations and industries currently operate under such traditional liner model should particularly be at the forefront of the transformation. Circular economy, driven by product life extension, reuse, remanufacture, recycle, etc., is recognized as a sustainable economic system and has been an area of research to develop frameworks, methods and tools to support organizations in making the shift. SKF, a Swedish company which has a high vision of sustainability, has initiated a Circularity Program and determined to implement circular product development within the organization. Therefore, a master thesis project was kicked off to explore collaborative approaches to implement circularity in product development. A backcasting approach was taken in the project to establish goals, identify the gaps between the future and the present, and define key initiatives for the organization to make future planning. The project aims to develop a methodology, building upon existing theories and concepts related to sustainable and circular product development, to implement circularity in product development at the case company. Meanwhile, the project outcome could give inspirations to other manufacturing organizations on circularity implementation, as well as to academia on future researches in the area of circular product development.

Keywords: sustainable product development, circular economy, circular design, backcasting, circular value chain, value chain collaboration, circular collaboration, collaboration with stakeholders, circularity quantification, circularity indicator, circular assessment, circularity metric

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HUAN WANG, Gothenburg, Jun 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ASO	Application Specific Offer
CAT	Circularity Assessment Tool
CDR	Circular Design Rules
CE	Circular Economy
CEIP	CE Indicator Prototype
CET	Circular Economy Toolkit
COMO	Condition Monitoring
CPAT	Circular Product Assessment Tool
CPD	Circular Product Development
DSIP	Digital Sustainability Implementation Package
LCA	Life Cycle Assessment
MCI	Material Circularity Indicator
NMO	New Market Offer
PCM	Product-Level Circularity Metric
PD&E	Product Development & Engineering
PDP	Product Development Process
PSS	Product Service System
ReMan	Remanufacturing
SPD	Sustainable Product Development

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Introduction

Over the past 50 years, human activities have been geared towards meeting increasing demands, which has led to rapid and negative changes in ecosystems [1]. Side effects such as biodiversity loss, climate change, and desertification continue to occur, making ecosystems less capable to provide services to humans. However, there are many indications that human demands on ecosystems will continue to grow in the future. Mitigation actions to minimize negative impacts on all species on the planet and natural ecosystem to make the society sustainable are therefore essential.

1.1 Theory

The circular economy (CE) is recognized as a sustainable economic system which could make better use of resources and create less negative impact to our environment [2]. With the essence of CE - to maintain the product's functionality and value for as long as possible, it becomes crucial that how we could integrate and implement circular product design to minimize the use of virgin material, diminish the environmental impact, whilst ensuring that the quality and performance of the product meets the required standards for product development [3].

To support organizations' transition towards sustainability and circularity, SPD (Sustainable Product Development) and CE have been research areas in academia for decades. Methodology, frameworks, and tools have been developed to be applied in the industry [4]. The measuring of CE transition progress was explored [5], as well as the leverage point from product perspective [3].

However, it was found that organizations are facing tremendous challenges to make progress on circular product development due to the barriers in technological, financial, consumer behaviour and organizational collaborations [6]. Therefore, it is worthwhile to deep dive in industrial practical cases to explore how the methodology, frameworks, and tools could support the implementation of circular product development in the organization and what is needed for future improvements.

1.2 Company background

SKF, a Swedish company, was founded in 1907 and focusing on rotating equipment performance solutions. SKF's bearing products are well-known all over the world. SKF has a long history of working with industrial sustainability, including re-manufacturing of bearing, oil regeneration technology, carbon-neutral manufacturing, etc, aiming to reduce environmental impact. There is a strive to create engagement throughout the business, not only by implementing sustainability on a strategic level, but also by encouraging the ideas and grass root projects initiated by employees around the world. Circularity, as one of the main contributors in sustainable product development, has high priority in SKF to drive the development towards sustainability, and seven Circular Design Principles were published as a fundamental guideline to implement Circularity in the company. The seven Circular Design Principles are:

- **Circular Supply** - Where viable, recyclable materials can be used in production, packaging and transportation e.g. secondary material, renewable and bio-based materials. Focuses on using recyclable, renewable, and bio-based materials in production, packaging and transportation to minimize environmental impact.
- **Material Efficiency** - Improve the utilization of materials throughout the product's lifecycle to increase overall efficiency and reduce dependency on new resources. Emphasizes the efficient use of materials throughout the product's lifecycle to increase overall efficiency and reduce dependency on new resources.
- **Build to Last** - Design products for durability reducing the need for frequent replacements and maintenance. Emphasizes designing products for durability, reducing the need for frequent replacements and maintenance by tailoring longevity to specific applications and performance needs.
- **Maintainable & Repairable** - The product design considers how repair and maintenance services might extend the life of existing products in the market. Highlights the importance of designing products that are easy to maintain and repair thereby extending their operational life.
- **Remanufacturable / Refurbishable** - The product design considers how "a second lifecycle" might be enabled in order to perform industry-like reconditioning of the product. Promotes the ability to remanufacture or refurbish used products to like-new condition, lengthening their useful lives and reducing waste.
- **Recyclable / Upcyclable** - The product design considers the potential to collect, separate and recover materials of end-of-life products in order to recycle or reuse them. Advocates for the consideration of collection and recovery of materials from end-of-life products for reuse in new products.
- **Avoid & Return** - The product design considers how to minimize waste by designing products and systems that avoid creating waste in the first place or ensuring that any waste materials are returned to the supply chain for reuse. Emphasizes strategies for minimizing waste by designing products and systems that avoid creating waste in the first place or ensuring that any waste materials are returned to the supply chain for reuse.

When developing a new product for certain markets or specific customers, SKF follows business project management process - NMO (New Market Offer) or ASO (Application Specific Offer) to define the project organization, working packages, tasks and time plan. Under the working package of PD&E (Product Development & Engineering), which focuses on product design, the working package leader follows PDP (Product Development Process) to plan their work, see the example of NMO project management process including PDP as a sub-process managed by PD&E in Figure 1.1. However, it has shown from previous product development experience that current PDP could not fully cover the interpretation and fulfillment of sustainable and circular requirements, whereas there are more and more demands in this area from regulations, customers, and other stakeholders. Thus, transitions (rather than mere incremental changes) are needed to break through the boundaries and re-build the foundation of sustainable collaboration in the value chain. A company level program - Circularity was kicked off in 2024, and PD&E has put high priority on sustainability-circularity in their 2025 strategy.

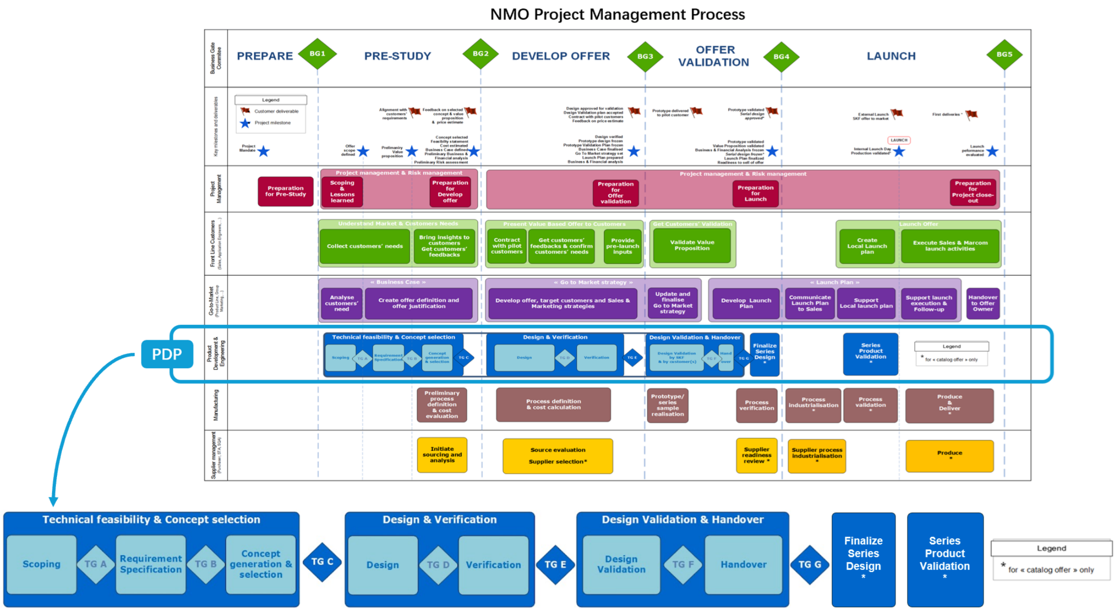


Figure 1.1: NMO process including PDP as a sub-process

As SKF is rooted in various segments of the industrial field, they have wide range of products, including hardware, software as well as IoT systems, and has typical waterfall product development processes which sequentially complete one stage before move on to the next, the outcome of this project could provide a reference to other manufacturing enterprises when it comes to circularity implementation. The combination of theory and practice in such a typical manufacturing company will in turn bring tangible insights to academic research and guidance for future research directions.

The project goal of SKF is to develop a methodology to realize Circular Product Development (CPD) during PDP. It aims to explore collaborative ways of working to integrate circularity in PDP and an approach to measure sustainability effects as a guidance for product development engineering team. SKF is expecting to enhance sustainable compliance, fulfil the relative requirements from stakeholders, and reach an advanced level of sustainability standard in the industry.

1.3 Research questions

The aim of this study is to address how SPD methods and tools could be leveraged in industrial practices to assist the case company implement circularity in PDP, what are the challenges of adopting SPD tools in the organization, and in addition, how SPD tools could be adapted and improved to support the case company achieving the CPD goals. Therefore, the following five research questions are constructed for the investigation:

- What methods and tools have been proposed in previous research to guide organizations in assessing sustainability effects on the environment during collaborative circular product development across the value chain?
- What methods and tools are particularly suitable in early phases for the case company to facilitate circular product development?
- How to make the methods and tools applicable in the context of circular product development at the case company?
- What are the key factors to implement circularity in the area of product development in the case company, and specifically in the early stages of the product development process?

2
Methods

In order to develop a methodology to implement CPD for the case company based on the state of art in SPD area with a rigorous approach, the research followed the development process [7, 8, 9], to: 1) define the problem by literature review and gap identification; 2) align the tangible goals and focus area of the project; 3) design and develop the methodology for circularity integration and evaluation; 4) use PDP projects for demonstration; 5) evaluate the methodology through observation, feedback and discussion; 6) loop back to step 3 to iterate and fine tune the methodology; when all above are done, 7) communicate the methodology at the case company and thesis report. See the process steps illustration in Figure 2.1.

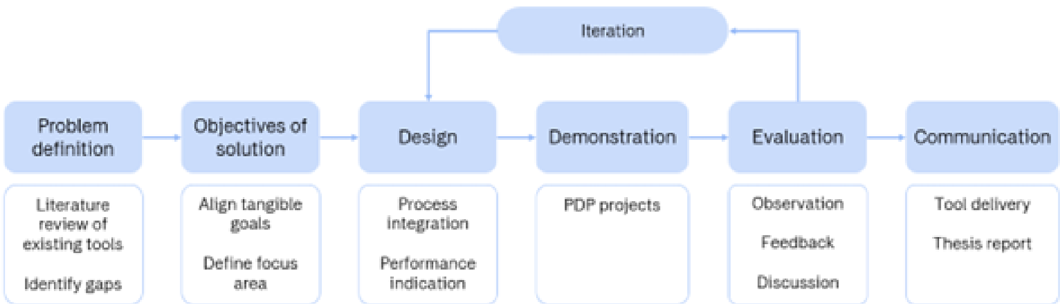


Figure 2.1: The process of research approach

The methods corresponding to research questions are summarized in Table 2.1:

2.1 Literature review

A clear understanding of the state of art could help to build a foundation of the needed knowledge for strategic planning and execution of this project. Therefore, literature reviews were conducted by searching the published papers and articles with relative keywords in Scopus, Google Scholar and Google, reading through the theories, and aspiring from the case studies.

As a starting point, to get an overall picture of SPD, CE and CPD, "sustainable product development, strategic sustainable development, circular economy, circular product development, circular design" were keywords used for literature searches in Scopus and Google Scholar. With the finding that the "backcasting" methodology

Table 2.1: methods corresponding to research questions

Research Questions	Methods
1. What methods and tools have been proposed in previous research to guide organizations in assessing sustainability effects on the environment during collaborative circular product development across the value chain?	Literature reviews
2. How can backcasting methodology support the case company to set up the goals and define initiatives for circularity implementation?	Workshop, Observation
3. What methods and tools are particularly adaptable in early phases for the case company to facilitate circular product development?	Literature reviews
4. How to make the methods and tools applicable in the context of circular product development at the case company?	Prototyping, Evaluation
5. What are the key factors to integrate and implement circularity in the area of product development in the case company, and specifically in the early stages of the product development process?	Evaluation, Communication

was frequently mentioned in the literature as a basis of the framework for strategic sustainable development [10], an in-depth review was conducted to explore how it could be applied in the organization to execute SPD strategies, and "method for sustainable product development, SPD workshop" were searched as key words to look for methods and tools could be used systematically applying this methodology. In addition, as collaboration was realized playing a key part in this area, "circular value chain, value chain collaboration, circular collaboration, collaboration with stakeholders" were derived for further literature search to gain insights of prerequisites and enablers for SPD, CE and CPD implementation in organizations.

In order to fulfill the case company's request for circular evaluation, additional literature searches with "circularity quantification, circularity indicator, circular assessment, circularity metric" were arranged in Google and Google Scholar to examine the tools that have been developed in this field. As the intention was to get inspiration from existing tools and to do customization to match the tool with SKF's product and circularity context, the literature searching and review of circular evaluation were focusing on the most famous and commonly used ones.

2.2 Interview

To learn about the practical experience of curcular product development, interviews were conducted in the case company with relative value chain stakeholders to:

- understand challenges and support needed from each perspective
- get lessons learned from previous transition experiences
- align the goals and way of working for coming activities

- get feedback of the thesis work

Six interviews were held in the beginning at SKF involving sustainability/circularity leaders as well as product development experts; see the interviewee details in Table 2.2. Eleven questions were prepared covering interviewee's role & responsibility, work relevance to circularity, challenges, and support needed. See interview questions in Appendix A. Every interview started from self-introduction of the interviewer to narrate the thesis project background and objectives, reason of the interview, and the coming activities in the following months. After interviewees got a better understanding of the project, they also briefly talked about their roles and responsibilities, as well as their cognition of circularity. In this process, the relevance of their job to this project was confirmed.

All six interviews were conducted one on one through Teams, and each took 45 to 60 minutes. Most interviews had video recorded with permission from interviewees and converted to transcripts; otherwise was noted down in text. Key messages were extracted from the records as inputs for further use in the workshop and circularity implementation methodology development.

Table 2.2: Position and responsibilities of interviewees

Position	**Responsibility**
Program manager	Leader of Circularity Program
Product and Service Sustainability Manager	Sustainability strategies and circular design rules
PD&E Architecture & Expert	EMEA PD&E strategies and priorities
PD&E Portfolio Manager	Circular design competence
PD&E Quality and Process	PDP process
PD&E Expert	Bearing designs

During demonstration phase, another round of interviews was conducted at the end of each case study to obtain user experience feedback of the methodology developed to integrate and evaluate circularity in product development. This feedback was used to iterate the tool and explore potential for future optimizations.

2.3 Observation and analysis

Observing the day-to-day work and analyzing documentations related to product development in the case company facilitated a practical understanding of existing circularity strategies & initiatives, organization set up, roles and responsibilities, process mechanism, working procedures and tools. It was also a practical way to collect expectations of PD&E's on additional effort required to implement circularity in their product development work. During the observation process, results were compared with the key factors of circularity implementation in product development at the same time, which could be used to understand the readiness and deficiencies of these key factors, so as to determine the areas should be focused on in the subsequent methodology development should focus on.

Observations were performed during PD&E working on PDP projects to see how tasks were planned and executed, and how they were in accordance with circular principles. There were also monitoring at workshops, to find how cross-functional teams were collaborating with each other, and how knowledgeable they were about circularity based on their reactions to SKF's circular design principles. At design and demonstration phase, key users' attitude, behaviors, and capabilities of trying out the methodology, as well as their feedback were captured as input for future planning of circularity implementation.

Company's strategies and initiatives regarding circularity were examined to confirm if action owners and plans were in place. PD&E's working procedure, which is PDP, was scrutinized to see if it provided instructions and tools to PD&E to execute circular product design.

2.4 Workshop

To build a co-creative environment, open dialogue is an effective way to bring multiple actors together. Thus, two workshops were arranged to enhance the alignment, collect input, and pave the way for further collaboration in the value chain.

2.4.1 Circularity Self-Assessment workshop

Before action taking, it is crucial to understand the objectives and current maturity of circular product development at the case company [11]. Therefore, a workshop was conducted with nine colleagues, involving key stakeholders from sustainability, PDE and Circularity Program in the case company. With participants from both online and on-site, the workshop was hold in a conference room with Teams set up for remote connections. To make the workshop efficient and effective, it was prepared with goal & scope, agenda, materials & tools [12].

2.4.1.1 Goal & scope

The purpose of the workshop was to clarify the end goal, identify gaps between the present and the future, and adjust the scope and prioritization of the thesis project.

The workshop followed backcasting A-B-C-D procedures [13], which was learned from literature review and dilated in the result session, focusing on step A and B to get circularity goals aligned and gaps identified in the first place. See the backcasting procedure and scope of the workshop in Figure 2.2.

Step B and C would need to take the result from the self-assessment workshop, and proceed with more discussions with cross-functional teams in details, therefore were not included in this workshop.

2.4.1.2 Agenda

A structured agenda with topics, activities, working groups and allocated time was attached in the workshop invitation to all participants. See the agenda of the workshop in Figure 2.3.

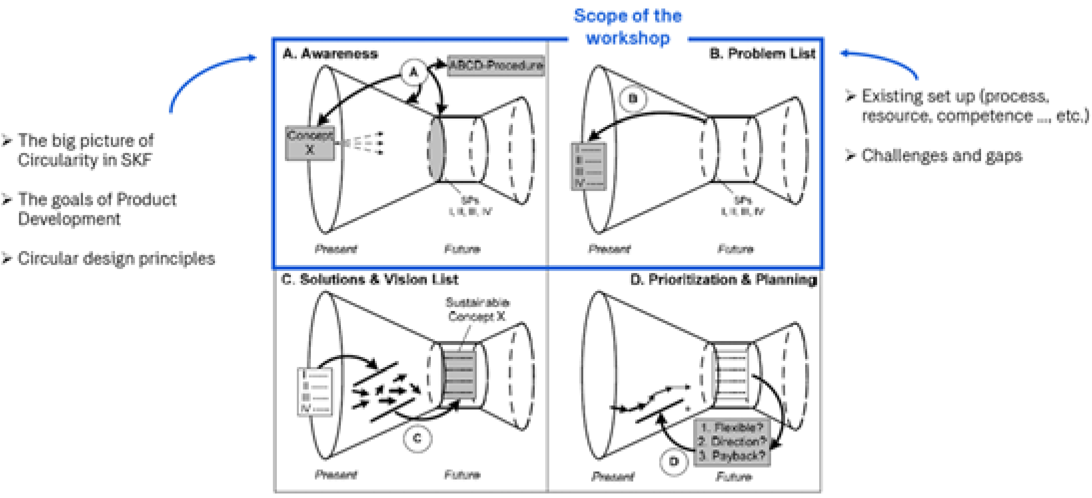


Figure 2.2: Scope of the workshop [13]

Topic	Owner	Duration
Workshop opening	D.W	08:30 – 08:40
Introduction of circularity program	L.S	08:40 – 08:50
Introduction of PDE priorities	G.P	08:50 – 09:00
Introduction of circular design principles	M.B	09:00 – 09:10
Group work instruction	D.W	09:10 – 09:20
Group working (3 groups)	Groups	09:20 – 10:30
15 minutes break		
Present the result and discuss • Focus on the weak parts (red & orange) with examples • Align and finalize the result	Groups	10:45 – 11:45
Summary of the assessment & wrap up for the workshop	D.W	11:45 – 11:55

Figure 2.3: The agenda of the workshop

2.4.1.3 Handout of Circular Design Principles

Considering the seven Circular Design Principles published in 2018 was not well known by participants and not yet integrated in their daily work, the detail explanations of each principle were prepared in hard copy for on-site participants and digital version for online participants. See example of the handout in Figure 2.4.

Circular Design Principle 5: Remanufacturable/Refurbishable

Promotes the ability to remanufacture or refurbish used products to like-new condition, lengthening their useful lives and reducing waste.

Principle: The product design considers how "a second lifecycle" might be enabled in order to perform industry-like reconditioning of the product.

Rationale: Remanufacturing or refurbishing involves returning used products to like-new condition. This principle focuses on enabling remanufacturing or refurbishment processes to recondition products to their original performance standards.

Thought Starters:

a) What processes are required when remanufacturing or refurbishing the product?
b) What quality assurance processes need to be in place to ensure remanufactured products meet performance standards?

Relevant Circularity Targets: 50% of our share of production recoverable for re-use by 2025, 25% of production volume recovered and re-used by 2030

Clean Assessment question: To what extent do you believe your project can contribute to maximize reuse of products and components and eventually enable recycling without downgrading? -> Reman will grow

Figure 2.4: The example of handout used in the workshop

2.4.1.4 Self-Assessment workshop tools

In order to conduct the assessment in a systematic way, and to obtain a visualized outcome, an assessment tools was built to be used in the working session. The tool was a combination of **SAM4SIP** [11] and **Overall Sustainability Fingerprint** [14] from DSIP, and associated with SKF's seven circular design principles.

SAM4SIP: a self-assessment tool could help to gain insight on how the company currently performs in relation to eight elements (backcasting, commitment, early PDP, decision support, roles, competence, procurement, social aspects) for sustainability integration and implementation [11]. It is used for high level assessment covering a wide scope of the company. To use the tool in such a smaller scale of the thesis project, six out of eight elements were restructured and grouped into three categories - organization alignment, process facilitation, and resource readiness. Each category was further subdivided, resulting in a total of eight elements as key dimensions for self-assessment. The other two - procurement and social aspects were not considered in the Self-Assessment workshop due to their broad scope and limited influence by PDE team. Procurement is highly relevant to product development and has always been involved in PDP early phases in the case company. However, circularity is a complex subject for procurement team to address from strategic planning to implementation, and it involves more than just product development. Therefore, it was decided not to discuss Procurement in this workshop, but to focus more on the scope of PDE in relation to circular product development. Social aspects were excluded as the guiding questions of this session in the tool were very general, not highly related to product development, and SKF has been always undertaking social responsibilities with good reputation, thus it was not necessary to be included in the workshop. See the illustration of the tool adaptation from DSIP - SAM4SIP in Figure 2.5.

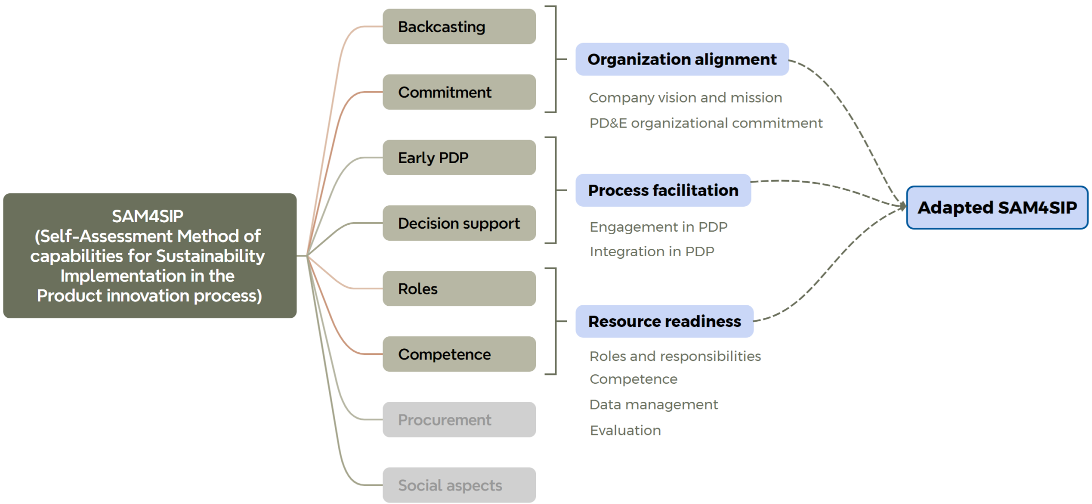


Figure 2.5: An adapted version of the DSIP tool - SAM4SIP

Overall Sustainability Fingerprint: another tool in DSIP, which could be used to make comparison among different solutions by assessing sustainability level for each life cycle phase and identifying sustainability hotspots to make improvements [14]. Templates in the tool show the level of sustainability compliance with a qualitative scale where level 9 (green) is compliant with a sustainable solution and level 1 (red) is lowest level of sustainability compliance. The result is automatically displayed in a spider chart, which, combined with the colour scale, makes hotspots clearly visible. Given that the aim of the workshop was to assess the level of circular compliance of the case company, guided by their seven fundamental circular design principles, and to identify gaps for further prioritization on improvement opportunities, the Overall Sustainability Fingerprint tool was reshaped to assess current status of each circular design principle, rather than different sustainability solutions.

With a merge of adapted SAM4SIP and Overall Sustainability Fingerprint, and seven SKF circular design principles integrated, an self-assessment working sheet (see example in Appendix B) was structured to be used by the participants in the workshop. Figure 2.6 illustrated how the assessment in the workshop was organized with above combination.

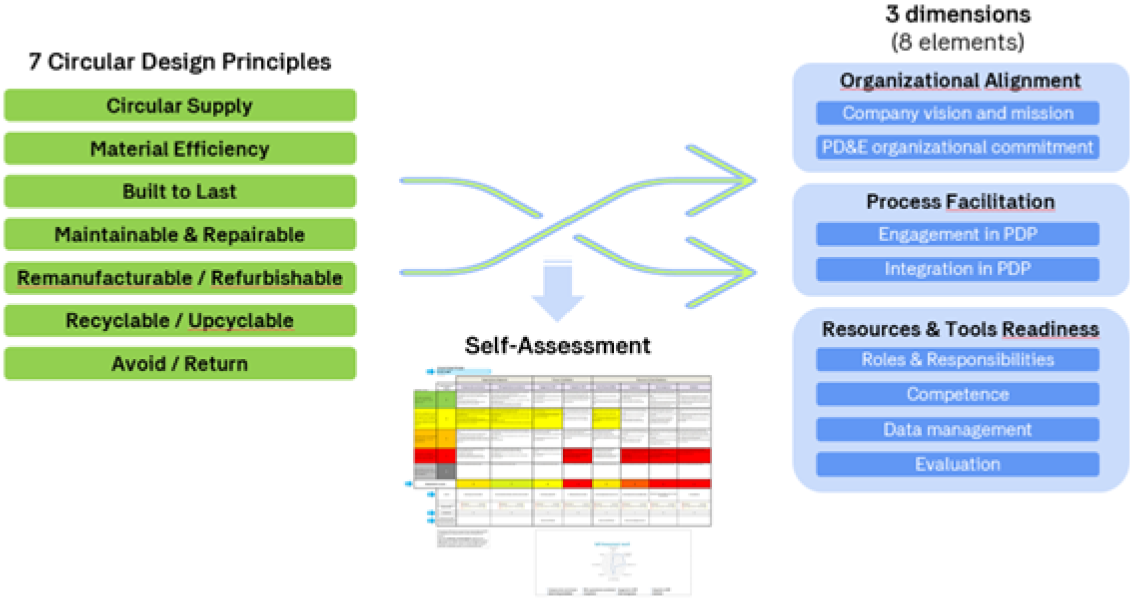


Figure 2.6: A Self-Assessment tool combined with DSIP tools and SKF Circular Design Principles

2.4.1.5 Assessment procedure

The participants of the workshop were divided to three groups with a mixture of their functions, and each group took two or three circular design principles to give scores based on the fulfillment of criterion given from the eight elements, see groups in Figure 2.7. Continued with a discussion session, in which all groups presented their assessments and adjusted the results until a final alignment was reached. See assessment working procedure in Figure 2.8.

A follow-up discussion was facilitated, taking into account the workshop result, PDE influence, as well as resource availability, to decide on the priorities and focus area of the thesis project.

Group	NAME	Department	Circular design principles
1 (online)	G.P	PD&E	Circular Inflows • Circular Supply • Material Efficiency
	K.P	PD&E	
	S.M	Sustainability	
2	G.B	PD&E	Product Use Extension • Built to Last • Maintainable & Repairable • Remanufacturable / Refurbishable
	M.B	Sustainability	
	L.S	Circularity	
3	P.J	PDE – Strategic Portfolio Manager	Circular Outflows • Recyclable / Upcyclable • Avoid / Return
	M.O	Sustainability	
Facilitator	D.W	Chalmers	
Observer	A.K	PD&E	

Figure 2.7: Groups divided for assessment

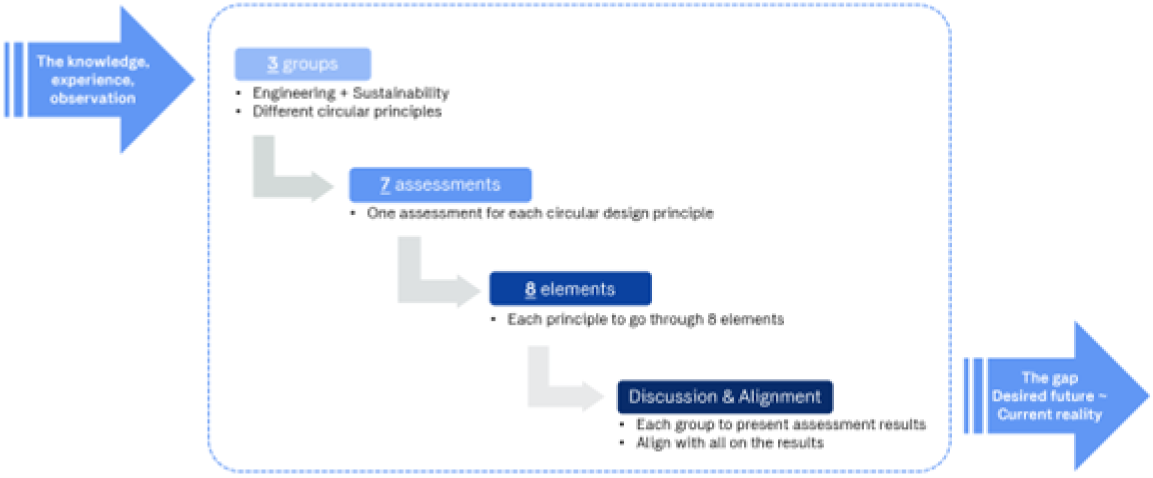


Figure 2.8: Procedure of the assessment working session

2.4.2 Design for ReMan workshop

Another workshop - Design for ReMan was conducted to work with cross-functional teams in operational level to deep dive into one particular Circular Design Principle - Remanufacruable / Refurbishable. It involved ReMan factory, PDE and COMO (condition monitoring) team, aiming to find the opportunities of bearing design improvements to better enhance bearing remanufacruability and promote ReMan business growth.

Since all participants of this workshop are located in Gothenburg, the workshop was conducted on-site at SKF ReMan factory. With the smaller scale and very focused topics, the workshop was arranged with two sessions, problem identification and solution discussion.

2.4.2.1 Problem identification

A line tour in ReMan factory was taken with all participants in the first place, to observe the main process flow of bearing remanufacturing, and understand the PD&E related parts during operations. See ReMan main process in Figure 2.9.

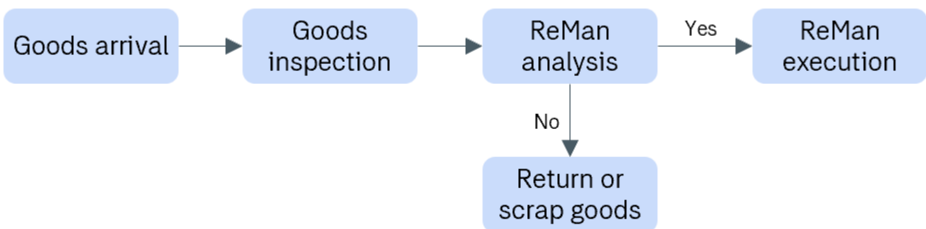


Figure 2.9: Main process of ReMan

Following that, participants did more observation and discussion focusing on the PD&E related parts, to get more insight of pain points and the related root causes.

2.4.2.2 Solution discussion

After the line tour, all participants sat together and discussed about the potential improvement to solve those pain points that ReMan factory had been suffering and the leverage points of ReMan business model. A summary of the key points that PDE could put effort on to ensure and improve bearing remanufacturability were generated as an input for further evaluation tool development to implement ReMan (as one of the Circular Design Principles) in product development.

2.5 Methodology design

There are six key elements to implement circularity in the organization: 1) high-level strategies of circularity; 2) guidelines of design for circularity; 3) trade-off management; 4) stakeholder engagement and value chain collaborations; 5) cross-functional team set up and competence readiness; 6) evaluation of product circularity performance [15]. The current situation of the case company was understood from interviews, observations and analysis, and then compared with these six key elements to find out the missing part that should be addressed from the thesis project, see the comparison in Figure 2.10.

Key elements for circularity implementation	Description	SKF's readiness	Comment
Circularity strategies and selection	High level circularity strategies and circular design principles are defined	Yes	Seven circular design principles are published
	Circularity strategies are selected at early stage for competitive positioning and guiding product development	No	No process to support circularity strategy selection
Circular design guidelines	Concrete design rules to implement Design for X (DfX) principles (eg. design for remanufacturing)	Ongoing	The owner of design rules will update DfX principles once the input is clarified
	Circular design concept has intangible (PSS - production service system) dimension included	No	Business model is not in place to support PSS
Trade-off management	Weighting system is created to manage conflicts between product circular features and other KPIs	No	Trade-off should be managed under business project management scope
Stakeholder engagement and value chain collaboration	Key stakeholders are identified and governance is established	No	No governance established in the process
	The way of working is created for collaborations in the value chain	No	No value chain collaborative working instruction created in the process
Cross-functional team set up and competence readines	Cross-functional team in terms of human resource and data system are in place	Ongoing	Competence build-up for circularity is another initiative, which was assigned to PD&E portfolio manager
	The competence of cross-functional teams are built up to execute circularity tasks	Ongoing	
Product circularity performance evaluation	Measuring system for early stage screening and late stage verifying of enviromental impact	No	No measuring system to guide decision-making

Figure 2.10: The comparison between key elements of circularity implementation and SKF's readiness

In SKF, circular strategies and principles were defined years ago, circular design rules are going to be updated by the design rules owner when DfX inputs are clarified, and cross-functional competence build-up is managed under other circular initiatives. Therefore, the missing parts as highlighted in red from the comparison are mainly in four aspects: 1) operational process; 2) circular business model; 3) trade-off management; 4) circularity evaluation.

Although these four aspects are equally important, the contribution and influence could be provided from organizations to them varies. Business and controlling hold the main responsibility of the business model, and trade-off management is another broad issue to be addressed at the business project level, while PD&E, the initiator of this thesis project, owns the responsibility of product development process and the evaluation of the technical performance of the product. Thus, the design of the methodology to implement circularity in PDP was mainly approached from two aspects: operational process and circularity evaluation.

Circularity factors need to be incorporated into the workflow to ensure the adherence during the product development process, while circularity performance and effectiveness must be evaluated to provide guidance at the practical level and support decision-making throughout the process. Given that the case company's product development process has been running successfully for decades, and used as working instruction at PD&E's project execution. It could enable a quick adoption if circularity is integrated into the existing PDP workflow. However, the tool design of the circularity evaluation needed to start from scratch, as there was no such tool existing in the case company. References of tools could be found from literature review, but it was necessary to adapt the tool to the specific characteristics of the case company's products and manufacturing processes.

2.5.1 Circularity integration

PDP, as the key process PD&E and other cross-functional teams follow to develop products in SKF, was examined to see where and how it should have circularity elements reflected to guide PD&E's work. The PDP process contains seven phases with project deliverables required for each phase, as well as gating reviews to decide if the project meet the criterion to pass the gate and move to next phase. Deliverables and gate review check points at each phase were scrutinized line by line, and circularity elements were added where relevant. See brief description of SKF's PDP phases in Table 2.3.

Table 2.3: PDP process of the case company

PDP phase	**Description**
Scoping	Define the project goals & scope and get alignment with key stakeholders.
Requirement Specification	Define system boundaries according to external & internal input(s) and derive measurable requirements accordingly.
Concept generation	Define and select concepts in alignment with external & internal key stakeholders.
Design	Transform the concept(s) into product design details and perform cross-functional design review to get the design approved.
Verification	Verify and complete the design for validation.
Design validation	Validate the design to ensure external & internal requirements are met and perform design review for design finalization.
Handover	Release and communicate the technical product documentation to production.

Pugh matrix, an existing tool in PDP supporting PDE to filter concept(s) at early design phases, has Compliance Sustainability as one of the criterion to judge the fulfillment of each design concept from legal / safety / environmental compliance and sustainability rating perspectives. Under sustainability rating, circularity should be taken into account, and the corresponding assessment tool should be provided to PDE to obtain circularity indications.

2.5.2 Circularity evaluation

To follow the workflow and implement circularity in product development, it is crucial for PD&E to have appropriate evaluation tool to measure the progress and give indication of how circularity is implemented in the product design and later phases [16].

To begin with, principles were established as a foundation to derive relevant and measurable factors. In the case company, there were seven Circular Design Principles (as mentioned in section 1.2) published in 2018 and still valid today as the baseline for circularity implementation. Therefore, the seven principles were chosen as the fundamental standards to further develop a tool to measure circularity performance. In the next step, reference tools learned from literature review of circularity evaluation were summarized in a table with their core characteristics listed. Meanwhile, key users of the evaluation tool in the case company were identified, and their needs were collected and rated in terms of importance. These needs were converted into functional features and then used in a Pugh Matrix to compare with the characteristics of the reference tools in order to screen out the most adaptable ones that could be used as references for the evaluation tool design. Subsequently, the selected tools were tested with real product cases to further confirm their adaptation to the case company's context and then the way to design the evaluation tool was decided. At last, an excel based tool to assess and compare design concepts' circularity performance through guiding questions was built upon above, and it was named **CPAT** (Circular Product Assessment Tool) .

2.6 Demonstration and Evaluation

To answer the last research question, assessing the effectiveness of the developed methodology is crucial. Therefore, a demonstration and evaluation of the circularity implementation methodology within real PDP projects were arranged to clarify their potential, boundaries, and limitations.

2.6.1 Demonstration

The demonstrations of the method to integrate circularity in the product development process were conducted with two experts and one product design engineer in SKF PD&E team. Real project cases were taken into the method and walked through the PDP process to check the applicability.

In terms of the circularity evaluation tool, demonstrations were managed with eight product design engineers through Teams 1-on-1 meetings, and each engineer took one of their ongoing PDP project cases to go through the CPAT tool within one hour. The session started with a background introduction of the PDP project, to assess if the purpose of the product design was relevant to circularity or other aspects (e.g. cost reduction, CO2 emissions reduction, etc.). Following that, the product concepts were described in order to obtain a better understanding of the concept comparison in later assessment session. Each PDP project case had two or three product concepts with differences on component design, material selection or manufacturing process. Every product concept was walked through the guiding questions in the assessment tool and put a score under each guiding question according to the applicable answer. Once the guiding questions were all finished, a final score would be automatically calculated and showed up in the tool, the lower score means more circular product.

2.6.2 Evaluation

Demonstration results were evaluated to investigate the validity of the methodology and the prerequisites of applying it.

The results of the circularity integration demonstration triggered further discussion of key stakeholders, who should be involved in the process, and their roles and responsibilities. The output of CPAT demonstrations was examined to see if the different levels of circularity could be reflected by the tool. At last, a pattern was summarized as the condition of using the assessment tool.

Findings during demonstrations also triggered several iterations of the methodology to better fit with product development scenarios in the case company. The outcome from the evaluation could support and guide the further development of tools for the circularity implementation in the case company, as well as bring insights to academia for future research.

2.7 Communication

The developed methodology were reviewed by PDP owner to gain the alignment on the purpose, the validity and future plans. It was also introduced to Engineer Sharing Hub, which was conducted in PD&E organization globally through Teams conference, to bring awareness to the team of the coming activities to implement circularity in product development.

The thesis project was presented to management team members in PD&E and Group Sustainability at SKF, to recognize the approaches taken to design the methodology to integrate and evaluate circularity during product development, the validity of the methodology, as well as to align on future plans to complete and final release the upgraded PDP and the CPAT to support the circularity implementation through out PDP phases.

2.8 Constraints

The positive contributions from circular economy include economic, environmental, and social perspectives [17]. To get a holistic view of the impact from circularity implementation, it is necessary to measure these three aspects and manage the conflicts between them. However, the project was initiated from SKF's PD&E department with a focus on circularity implementation in the product design. Therefore, the study excluded trade-offs between circular design and other project performance indicators (such as capital investment, product cost, resource, and time), and it also excluded the topic of circular business model which is a key enabler of circularity but is managed by business and controlling in the case company.

3

Results

This chapter presents the result in seven sections. Section 1 focuses on existing methods and tools proposed from previous research supporting organizations on collaborative circular product development in the value chain, and the selection of them. Section 2 to 4 cover the approaches taken to collect the input of methodology development for implementing circularity. Finally, section 5 and 6 exhibit how the developed methodology was designed and the effectiveness was verified.

3.1 Literature review

3.1.1 Frameworks for collaborative circular product development

While more and more companies are aware of CE is an effective approach towards sustainability, the implementation of circular solutions is facing complex barriers from cultural, technical, and institutional perspective [18]. Collaboration is a necessity between organizations to achieve CE, as it enables interactions and integrations of knowledge and resource, as well as inspires co-creation.

A number of studies have investigated the frameworks for circular collaboration, and the key factors of the framework are: 1) circular proposition; 2) people engagement; 3) objective alignment; 4) governance mechanism; 5) circular model [19]. The second factor is extremely crucial as internal and external stakeholders holds diverse propositions and therefore play a key role in the collaboration. The stakeholders are normally identified as internal cross-functional teams (eg. marketing & sales, technical research & development, business development, purchasing and supply chain, production), external customers and suppliers, as well as academia, consulting and NGOs. See the circular collaborative framework with key stakeholders' engagement illustration in Figure 3.1.

It could be seen from the framework that circular activities should start from the beginning of the project and value chain partners should be involved in early phases. Therefore, when designing the methodology to implement circularity in the case company, the circularity elements need to be integrated in SKF's PDP from the outset, as well as the engagement from value chain.

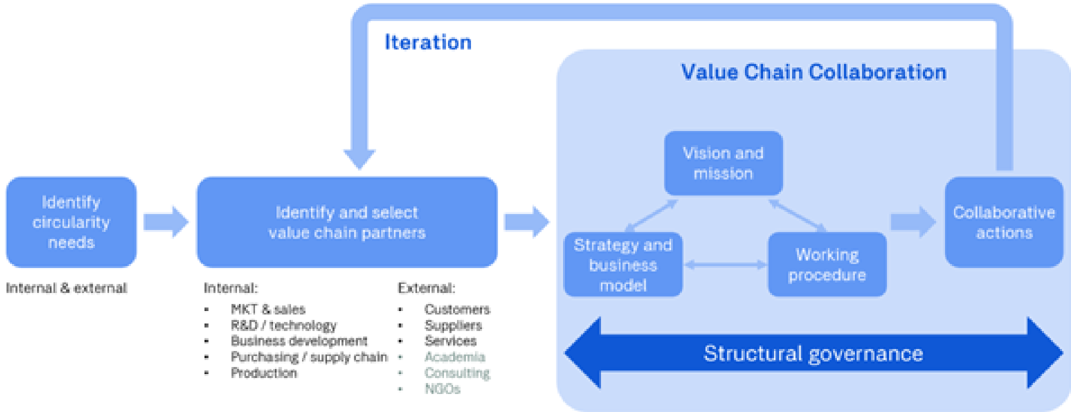


Figure 3.1: Circular collaborative framework in the value chain (building on the model proposed by Brown et al., 2021)

3.1.2 SPD and CE methodologies

There are method and tools developed to support organizations implement SPD from strategic level to practical actions.

Backcasting, an approach could be used to make strategic planning of complex problems. It encourages stepping outside of existing paradigms and aligning on a shared goal between value chain actors in a systematic way [20]. With the well-defined end-goal, the risk of over/under emphasizing problems could be reduced [13]. An A-B-C-D methodology was presented in Figure 3.2 to:

- A - have organizational awareness and alignment on the desired future
- B - look at current status to identify the problematic gaps
- C - find potential opportunities to fill the gaps
- D - prioritize the actions and make detailed plannings

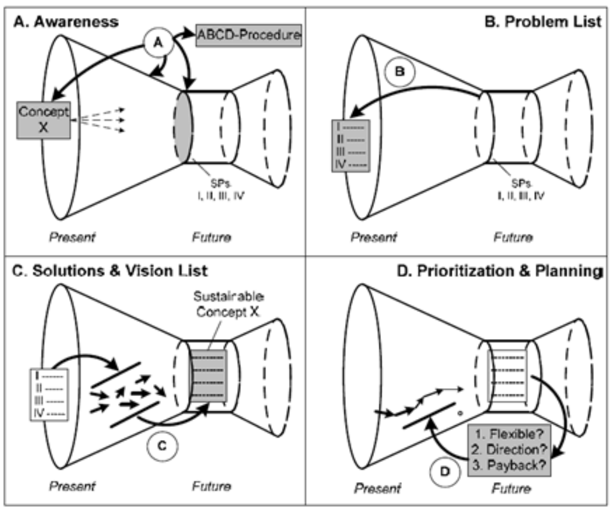


Figure 3.2: Backcasting A-B-C-D procedure [13]

DSIP (Digital Sustainability Implementation Package), led by Professor. Sophie. I. Hallstedt from Chalmers University has compiled a set of tools for SPD into a digital package [21], with the aim to include Circular and Data Driven Collaborative Design Framework to build a base for circular solutions with actors in the value chain. The tools from this platform could be adapted to fit with the context of case company and used for workshop, assessment and analysis. See DSIP platform and the summary of tools in Figure 3.3 and 3.4. SPD workshop method [10] showed the logic to manage a backcasting workshop, which inspired the conduction of Circularity Self-Assessment Workshop. SAM4SIP [11] and Overall Sustainability Fingerprint [14], as introduced in section 2.4.1.4, were found particularly useful to align the goal, realize the present, and identify the gaps at early stage of sustainable product development.

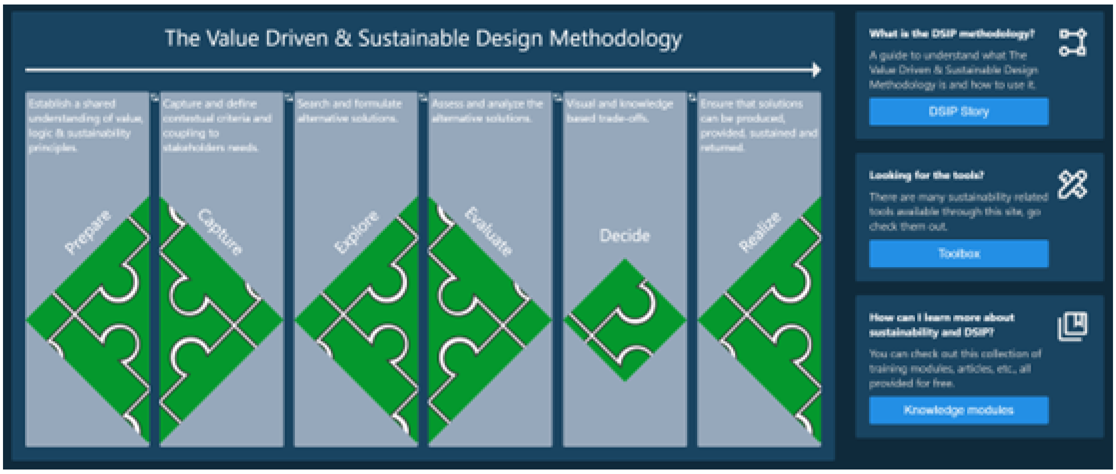


Figure 3.3: DSIP knowledge platform [21]

Circular economy strategies - 9RS, a set of "R-behaviors" which supports the shift to a circular economy [5], see Table 3.1. It created the R-behaviors in a general way which was applicable to manufacturing industries. Organizations could take it as a reference to derive their own circular design principles, taking product characters and business models into account.

3.1.3 Tools to measure product circularity

To ensure the value chain circular collaborations are towards the aligned goal, it is necessary to build a measurement system to give guidance to the circular activities as well as evaluate the circular performance [22]. Many tools have been developed and often used to support organizations from different perspectives, and the frequently mentioned and commonly used tools were listed below:

- MCI (Material Circularity Indicator): A product level metric focusing on material flow and utility factor [23]. It requires many data collections including use and recycling phase which might be difficult to get in product early design phase.
- CDR (Circular Design Rules): An online tool gives overall assessment from Material, Component, and Service aspects. Guiding questions of each aspect

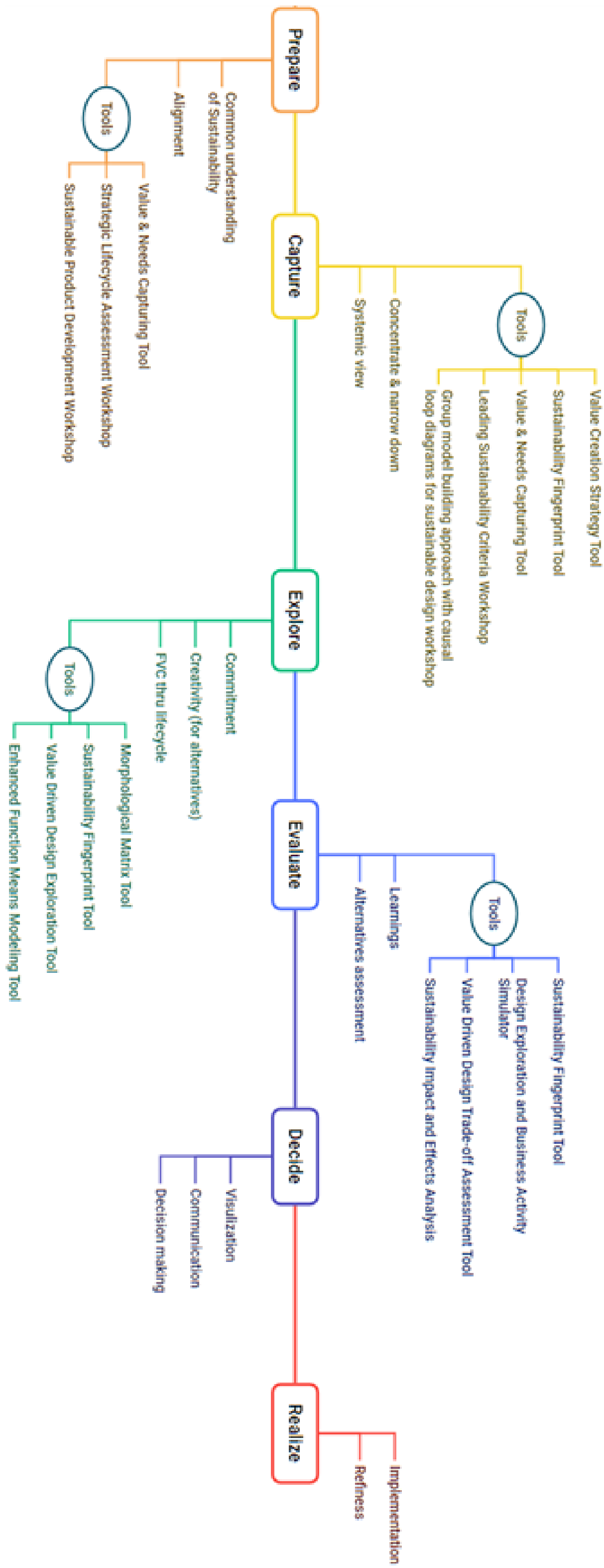


Figure 3.4: DSIP tools through out project phases

Table 3.1: Circular economy strategies [5]

R	**Strategy**	Description
R0	Refuse	Make product redundant by abandoning its function or by offering the same function by a radically different product.
R1	Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market).
R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
R3	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function.
R4	Repair	Repair and maintenance of defective product so it can be used with its original function.
R5	Refurbish	Restore an old product and bring it up to date.
R6	Remanufacturing	Use parts of a discarded product in a new product with the same function.
R7	Repurpose	Use discarded product or its parts in a new product with a different function.
R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality.
R9	Recover	Incineration of materials with energy recovery.

are given to users and a recyclate percentage is calculated after all questions are answered [24]. It could be used to compare the different design concepts but not open for customization for diverse user context.

- CET (Circular Economy Toolkit): An online tool aids organization to find potential improvements through product full lifecycle [25]. The guiding questions in the tool are not editable, and information from full lifecycle is required to answer those guiding questions. The result from CET shows potential circular improvement directions but not visualizes circularity comparison across product designs.
- CEIP (CE Indicator Prototype): A tool built in MS Excel with guiding questions grouped by product lifecycle stage [22]. Answers are pre-set for users to choose from, and score is automatically calculated based on the selected answers. The result is visualized in a spider diagram indicating the circular strength and weakness of each product lifecycle stage.
- CAT (Circularity Assessment Tool): An excel-based assessment tool to evaluate how circular the product concepts are based on defined circular guidelines [26]. The tool is editable, and it gives good visualization of concepts circular performance ranking.
- PCM (Product-Level Circularity Metric): A cost-based ratio calculation of circulated parts value to the total product value [27]. It takes activity cost into consideration and supports decision making from financial standpoint.
- LCA (Life Cycle Assessment): A method to holistically assess how much environmental impact the product brings in its lifecycle [28]. It provides quantified data for decision making but has high demand on data collection which might be unrealistic in early product design phase.

The characteristics of each tool were summarized in Table 3.2, which was used for tools screening later on.

Characteristics of circularity evaluation tools					
Tools	Sustainability expertise is needed	Utility data is required	Editable for company context	Local file	Free of charge
MCI	Yes	Yes	No	Yes	Yes
CDR	No	No	No	No	Yes
CET	No	Yes	No	No	Yes
CEIP	Yes	Yes	Yes	Yes	Yes
CAT	No	No	Yes	Yes	Yes
PCM	No	No	Yes	Yes	Yes
LCA	Yes	Yes	Yes	No	No

Table 3.2: Characteristics of circularity evaluation tools

The advantages of frameworks and tools are significant, but to make them adapt to the company's context is a necessity, and there are also many challenges to apply them in practices due to lack of:

- Resource competence – Many of the tools need data collection associated with sustainability/circularity factors that may not be known by people who are making the circular efforts.
- Data accuracy – The data collected especially at early design phases may not be accurate and might mislead the decision of circular approaches.
- Trade-offs management – Circular indicators may be in contrast with each other or have conflicts with economic targets, therefore it is difficult to manage the trade-offs and make decision.

3.2 Interview

During the initial interviews, the pain points were consistently mentioned by different interviewees that although circularity has been included at a strategic level for many years, it has not been put into practice. One of the interviewees from engineering team said "The strategy of circularity has been made for years, but there's no rules or guidance to our design work. Another fact is we were mostly requested to design for low cost, is sales working on circular business model as well?" The statement reveals the lack of circular design support and value chain collaborations towards circularity. Insight from different angle could been seen during interview, "If we could have the process and tool to guide or inspire product design engineers to make a circular product, we could proactively offer our customer a more circular and sustainable product and create value beyond their expectations." said another interviewee from management team. There were common voices talking about the absence of decision making support and engineering competence as well, "We're lacking quantitative knowledge on the topic of circularity, and this always makes it hard for us to decide which direction to go", "Our process need to be upgraded with circular design elements and engineering competence needs to be enhanced to facilitate the circular product development", "Other cross-functional teams should be engaged as well, otherwise it's not achievable" said other interviewees. When talking about key challenges of circular approaches, most of the interviewees were in line with the need to measure circularity performance in order to guide product design and support decision making throughout the product development process. They were hoping to see the thesis project could create a methodology to get these challenges addressed, but preferably the methodology is based on existing system architectures or requires minimal effort to adopt. See summary of interviews in Table 3.3.

At the demonstration stage, interviews were conducted at the end of each case study to collect users' feedback of the developed methodology and needed improvement. Regarding the method of circularity integration, it was recognized that SKF's PDP is the most effective matrix to integrate circularity elements, "Every product design engineer follows PDP checklist to do their project, circularity tasks should definitely be there, but the roles and responsibilities, as well as governance should also be defined in the document." said the PDP owner. In terms of using CPAT to evaluate circularity in early design phase, product design engineers perceived the tool was user-friendly and helpful to inspire them towards circular design, "I was not aware that lifting holes could benefit ReMan, now I felt I should learn more about how ReMan is conducted for my product, then I may have better ideas to do the design" said one of the product design engineers. They also raised concerns about the tool with one version covering all different types of bearing. In SKF, there are more than twenty types of bearing product with different features and functions, plus more products other than bearings. With the future work to complete the CPAT for all circular design principles, it needs to verify if one generic working sheet is able to capture sufficient circular design details to compare different bearing design concepts, as well as to clarify if more working sheets should be developed to assess the circularity of other products (eg. seals and lubrications).

Table 3.3: Summary of interviews

Position	**Responsibility**	Challenges
Program manager	Leader of Circularity Program	To quantify circularity effects or indicators for decision making
Product and Service Sustainability Manager	Circular design rules	Implementation of circular design rules
PD&E Architecture & Expert	EMEA PD&E strategies and priorities	To implement circular design in practice
PD&E Portfolio Manager	PDP process, circular design competence build up	Process to integrate circularity in product development Circular design assessment Full value chain awareness and collaboration
PD&E Expert	Project leader of Circular Design of Bearings	Process and tools to work in practice Full value chain collaboration (business model, supply base)

3.3 Observation and analysis

The existing PD&E's working procedure - PDP was reviewed and found not to be well considered for circularity through out the process. There was no check point at the project scoping phase to identify circular requirements from external and internal stakeholders. In the later phases of product development, circularity was seldom mentioned as well. The PDP checklist, which defines deliverables of each project phase and project gating requirements, was discovered not including circularity deliverable as one of the gatekeepers. Sustainability was mentioned at some point, but the reference documentation is a general guidance that could not be used to measure the circular performance. Meanwhile, product design engineers were found following PDP checklist for project task planning and execution. Since circularity was not embodied in PDP checklist, there was no design work planned for such purpose.

In addition, design rule was found as another important document which PE&E follows to design the product according to established principles. There were seven circular design principles published in SKF years ago, and a plan was in place to create design rules accordingly. However, it depends on the interpretation of the circular design principles, which needs to be addressed further on.

In PD&E's previous working experiences, there were both tangible - concrete product and intangible - product service system (PSS) developed to fulfill business needs. However, PSS offers were not successful due to the lack of support from a circular business model to bring internal and external stakeholders to agreements.

In ReMan factory, some types of bearing disassembly have been suffering for a long time from the bearing design, but there was no direct dialogue between ReMan factory and PD&E team for improvements. There are also potentials that condition monitoring (COMO) system could benefit ReMan business, but no collaboration was bringing these two teams together for co-creation. In short, the voice of ReMan team was not delivered outside of ReMan factory.

However, the wide awareness of circularity strategy in the case company makes the journey promising. It was also encouraging to see management team is trying to work proactively to get ready for the circular product design instead of waiting for the circular requirement from downstream, and the competence build-up plan was already in placed and assigned to PD&E portfolio manager to enhance the comprehension and capabilities of circular product development in PD&E organization. Many cross-functional teams are also actively embracing circularity implementation, and willing to strengthen collaboration across the value chain.

3.4 Workshop

3.4.1 Self-Assessment of circularity in product development

The workshop was processed according to the agenda and completed on time with expected results. However, some findings during the workshop could be an inspiration for future improvements:

- Some participants were not familiar with the seven circular design principles, therefore extra time was spent for them to read the explanations of each principle in order to have correct understandings before moving to assessment session.
- The guiding questions in the assessment tool were easy to follow, but participants had different understandings based on their experience and competence.
- The time needed to finish the assessment for three groups respectively varied due to the different level of understanding about circular design principles and company present status.
- In the final presentation and discussion session, participants were easily aligned with each other without debates or arguments.

The self-assessment resulted in a total score of each circular design principles. Due to the scores were unevenly distributed, natural-breaks classification [29] was used to group the seven principles to: 1 - having big gaps; 2 - having medium gaps; 3 - having small gaps, as shown in Figure 3.5. The result was also visualized to seven spider charts showing the areas where gaps are, see the spider charts in Figure 3.6.

Principle	Score
Circular Supply	19
Material Efficiency	26
Built to Last	66
Maintainable & Repairable	36
Remanufacturable / Refurbishable	25
Recyclable / Upcyclable	15
Avoid / Return	38

Group	Principle
1 - big gaps (score range: 15–25)	Circular Supply
	Remanufacturable / Refurbishable
	Recyclable / Upcyclable
2 - medium gaps (range: 26–38)	Material Efficiency
	Maintainable & Repairable
	Avoid / Return
3 - small gaps (range: 66)	Built to Last

Figure 3.5: Scoring group of the seven circular design principles

Two main gaps were identified from the spider charts:

- PDP facilitation and Resources & Tools readiness;
- Value chain collaborations for some circular design principles (eg. circular supply, remanufacturable/refurbishable, etc).

To implement circularity according to the case company's given guideline, effort should be put on the identified gaps of each circular design principle. However, with limited time and resource of the thesis project, as well as considering influence from PD&E, gaps between present and future, and the available demonstration resource, **Remanufacturable/Refurbishable** was prioritized as the focus area in the thesis project to continue the development of method and tools. See the prioritization in Figure 3.7

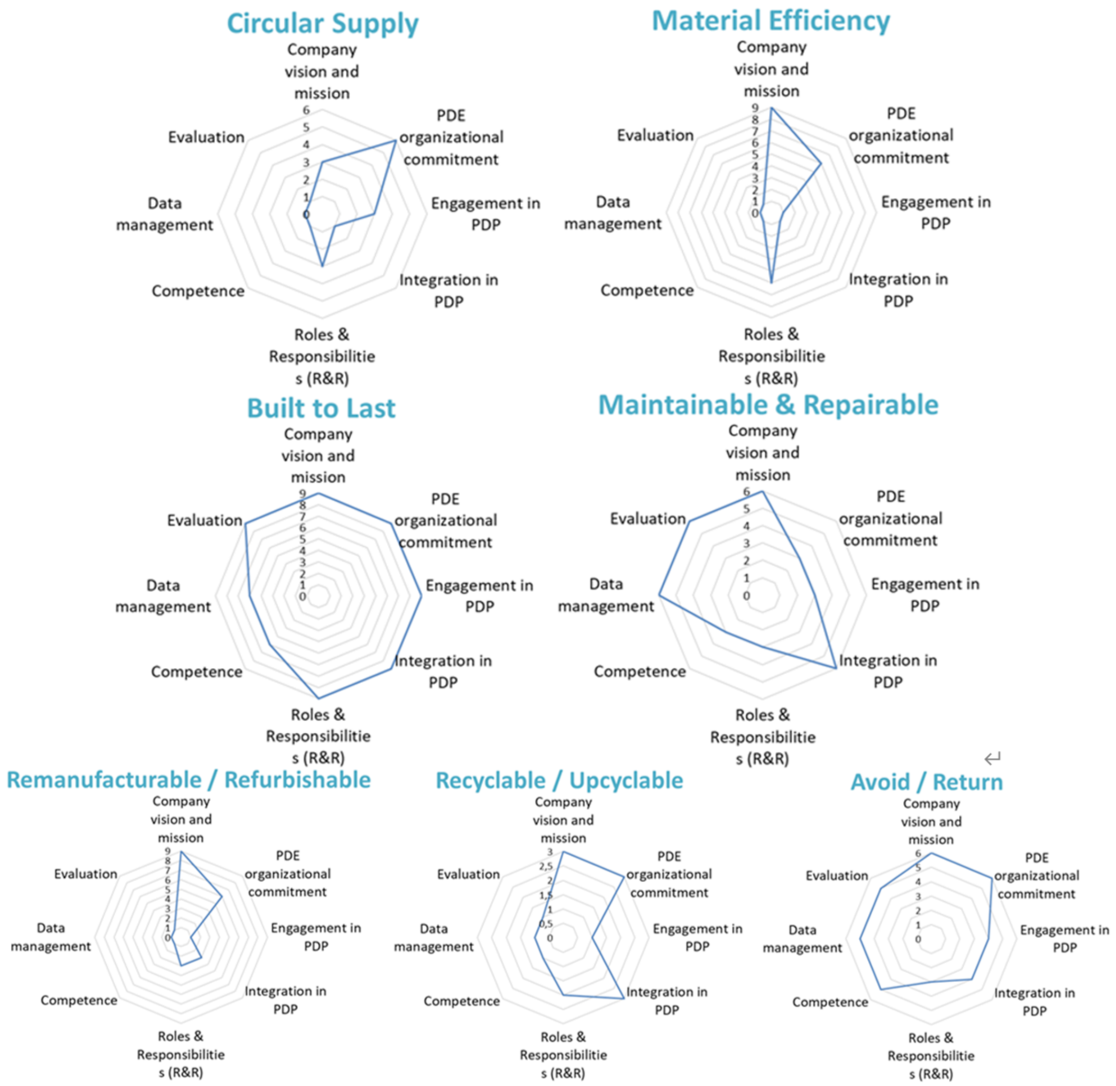


Figure 3.6: Result of the Self-Assessment Workshop

Circular design principles	Gaps 3 - not having major gaps 1 - having big gaps	PD&E influence 3 - vert limited influence from PD&E 1 - strong influence from PD&E	Demonstration 3 - hard to demonstrate (need extra works to build demonstration enviroment) 1 - easy to demonstrate with existing products	Resource 3 - need extra coordination among cross-functional teams 1 - could be handled with available resource in PD&E	Scoring
Circular supplies	1	2	3	3	9
Material Efficiency	2	3	3	3	11
Built to Last	3	1	1	1	6
Maintainable & Repairable	2	1	1	2	6
Remanufacturable/Refurbishable	1	1	1	1	4
Recyclable/Upcyclable	1	1	3	3	8
Avoid/Return	2	2	3	3	10

Figure 3.7: Prioritization of project focus area

3.4.2 Design for ReMan

In the Design for ReMan workshop, painpoints related to PD&E were marked in the process flow and the locations where these painpoints occured were identified. See the pain points in Figure 3.8.

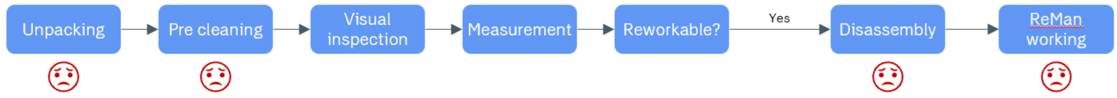


Figure 3.8: ReMan pain points

Following further technical discussions, a list of improvement opportunities was derived including both product design and value chain readiness perspectives. Every pain point was investigated, in terms of where it happened, how it could be improved and who the owner of improvement actions should be. The actions related to PD&E were the key inputs for the development of circularity evaluation tool at the later stage. Due to the confidentiality of the data, details of this list could not be presented in this report.

3.5 Methodology design

The development of the methodology to implement circularity was mainly from two aspects, circularity integration and evaluation. Circularity factors need to be integrated into working process, so it could be followed during product development. Circular performance and effects must be visualized with indicators to give guidance on a practical level and support decision-making throughout the process.

To develop a tangible approach for implementing circularity in product development, a methodology was designed for circularity integration and evaluation based on the case company's existing product development procedure, ongoing circular strategies and key initiatives. The existing circular product development frameworks or tools in academia or industry could be taken as reference, but adaptation was a necessity to tailor the approach to the case company's product and manufacturing characteristics.

3.5.1 Circularity integration

3.5.1.1 PDP framework in the case company

The existing overall PDP process in SKF has seven phases: Scoping, Requirement Specification , Concept generation & selection, Design, Verification, Design Validation, and Handover. The objective and content of each phase was examined and found that should be updated to put circularity consideration from beginning of PDP in order to make a thorough design under an aligned circular target. See the relevance to circularity of each phase in Table 3.4.

Table 3.4: The relevance of PDP phases to Circularity

PDP Phase	**Relevance to Circularity**
Scoping	A filtering to select the applicable circular design principle(s) as circular strategy of the project.
Requirement Specification	To identify circular requirement from external and internal stakeholders.
Concept generation & selection	To pre-evaluate and rank circular performance of each concept as a supporting reference for concept selection.
Design	To implement the circular design.
Verification	To assess circular performance of the design.
Design validation	To finalize the circular design rules of the product.
Handover	To implement and document the circular solution for product industrialization.

The current PDP had material compliance and sustainability performance featured throughout the Product Development Process, see Figure 3.9. However, the engagement to circularity from this process was insufficient, therefore a new PDP with circularity full integration was developed as showed in Figure 3.10.

Figure 3.9: Existing PDP with sustainability featured throughout the process

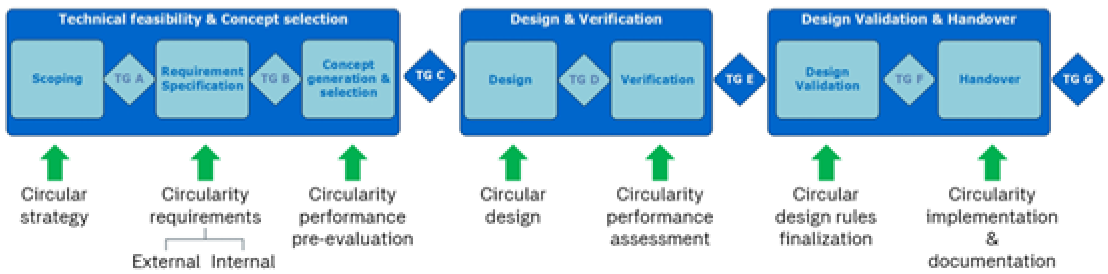


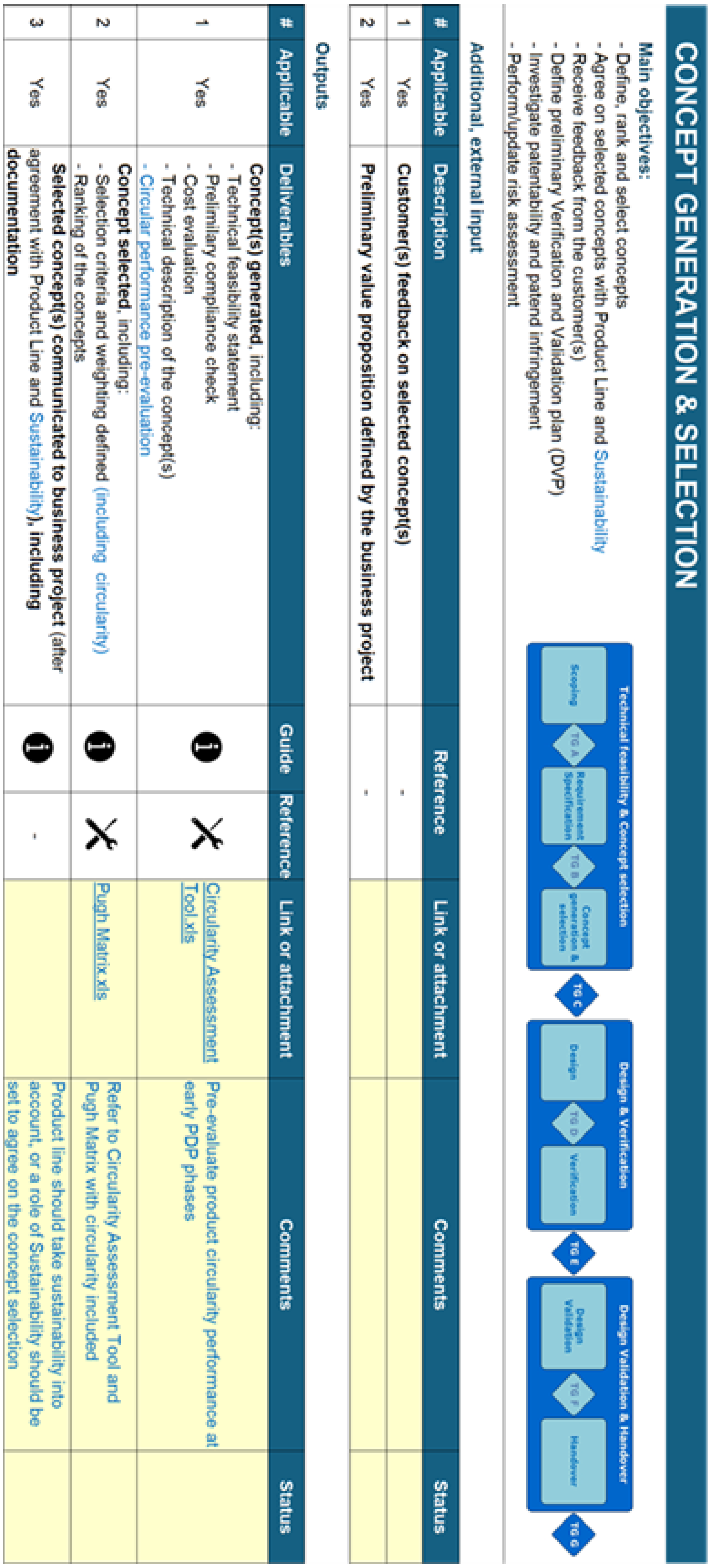
Figure 3.10: Proposed PDP with circularity integrated

3.5.1.2 PDP gating

As the PDP requires gate reviews to ensure needed actions were taken before the project moves to the next phase, the PDP checklist, where key deliverables of each phase as well as check points at each gating are listed, was the key document used to guide the design work in PD&E. There were technical and cost considerations, but not circularity. It should be improved to include circularity elements to safeguard PD&E has taken circular approaches during PDP execution when applicable. In addition, tools should be added to support the circular appraches. See example of circularity integrated PDP checklist of phase deliverables in Figure 3.11, and PDP gating questions in Figure 3.12, the added circularity elements were shown in blue. The engagement from cross-functional teams was discussed to have a role acting in PDP to execute and govern the PDP checklist in the case company.

3.5.1.3 Pugh Matrix

As the most effective and commonly used tool for PD&E to rank and select concepts, Pugh Matrix should have circularity included in the session of Compliance



CONCEPT GENERATION & SELECTION

Main objectives:
- Define, rank and select concepts
- Agree on selected concepts with Product Line and Sustainability
- Receive feedback from the customer(s)
- Define preliminary Verification and Validation plan (DVP)
- Investigate patentability and patend infringement
- Perform/update risk assessment

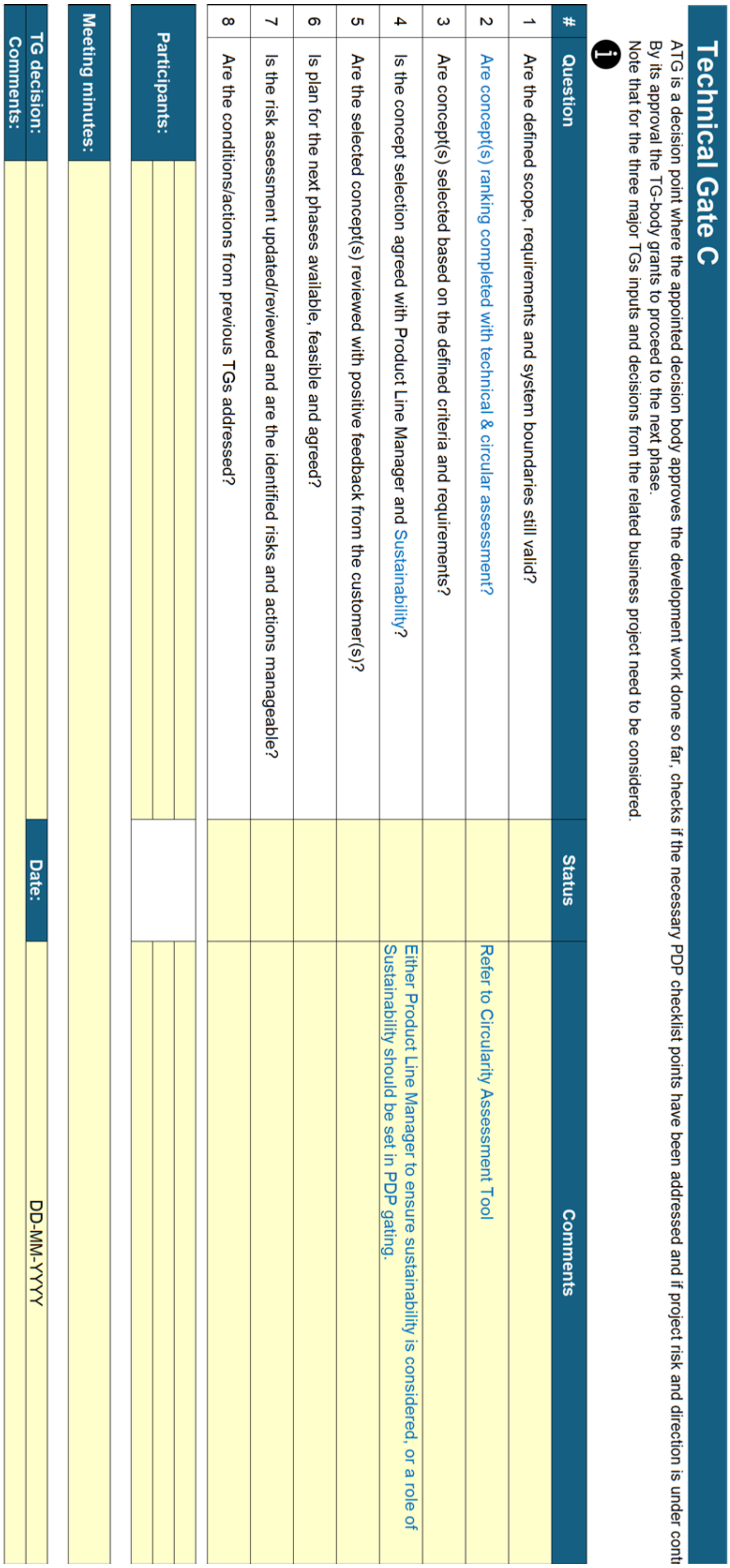
Additional, external input

#	Applicable	Description	Reference	Link or attachment	Comments	Status
1	Yes	**Customer(s) feedback on selected concept(s)**	-			
2	Yes	**Preliminary value proposition defined by the business project**	-			

Outputs

#	Applicable	Deliverables	Guide	Reference	Link or attachment	Comments	Status
1	Yes	**Concept(s) generated**, including: - Technical feasibility statement - Preliminary compliance check - Cost evaluation - Technical description of the concept(s) - Circular performance pre-evaluation			Circularity Assessment Tool.xls	Pre-evaluate product circularity performance at early PDP phases	
2	Yes	**Concept selected**, including: - Selection criteria and weighting defined (including circularity) - Ranking of the concepts			Pugh Matrix.xls	Refer to Circularity Assessment Tool and Pugh Matrix with circularity included	
3	Yes	**Selected concept(s) communicated to business project** (after agreement with Product Line and Sustainability), **including documentation**		-		Product line should take sustainability into account, or a role of Sustainability should be set to agree on the concept selection	

Figure 3.11: PDP phase deliverables with circularity integrated



Technical Gate C

ATG is a decision point where the appointed decision body approves the development work done so far, checks if the necessary PDP checklist points have been addressed and if project risk and direction is under cont
By its approval the TG-body grants to proceed to the next phase.
Note that for the three major TGs inputs and decisions from the related business project need to be considered.

#	Question	Status	Comments
1	Are the defined scope, requirements and system boundaries still valid?		
2	Are concept(s) ranking completed with technical & circular assessment?		Refer to Circularity Assessment Tool
3	Are concept(s) selected based on the defined criteria and requirements?		
4	Is the concept selection agreed with Product Line Manager and Sustainability?		Either Product Line Manager to ensure sustainability is considered, or a role of Sustainability should be set in PDP gating.
5	Are the selected concept(s) reviewed with positive feedback from the customer(s)?		
6	Is plan for the next phases available, feasible and agreed?		
7	Is the risk assessment updated/reviewed and are the identified risks and actions manageable?		
8	Are the conditions/actions from previous TGs addressed?		

Participants:			
Meeting minutes:			
TG decision:		Date:	DD-MM-YYYY
Comments:			

Figure 3.12: PDP gating questions with circularity integrated

& Sustainability. Sustainability rating, as the given compliance criteria, should be supported with measurement tool with reference link documented in Pugh Matix. See proposal of circularity to be added in Pugh Matix in Figure 3.13.

3.5.2 Circularity evaluation

To develop the measuring system for circularity evaluation, key users of the evaluation tool were identified in the first place:

- PD&E, who follows PDP process and design principles & standards to design the product
- Other cross-functional team members (manufacturing, purchasing, ..., etc), who are engaged to support on product industrialization
- Project governing group, who oversees the process and make decisions at project gating and conflicts

After that, key stakeholders' needs of the circularity indication tool were recognized through interviews and observations as inputs of the evaluation tool design. See the summary of key stakeholders' needs with importance level in Table 3.5.

Table 3.5: Key stakeholders' needs

Key stakeholder	**Need**	**Importance**
PD&E and other cross-functional teams engaged in PDP	Standards to follow for circular product development	High
	Guidance of circular product design and other circularity activities	High
	Working environment for cross-functional team collaboration	High
	Extra support if the tool requires competences they don't have	Medium
Management team	Quick implementation of the tool	High
	Support on decision making at conflicts and project gating	High
	Working efficiency and effectiveness	Medium

Based on the collected key stakeholders' needs, the features of the tool were defined as follows:

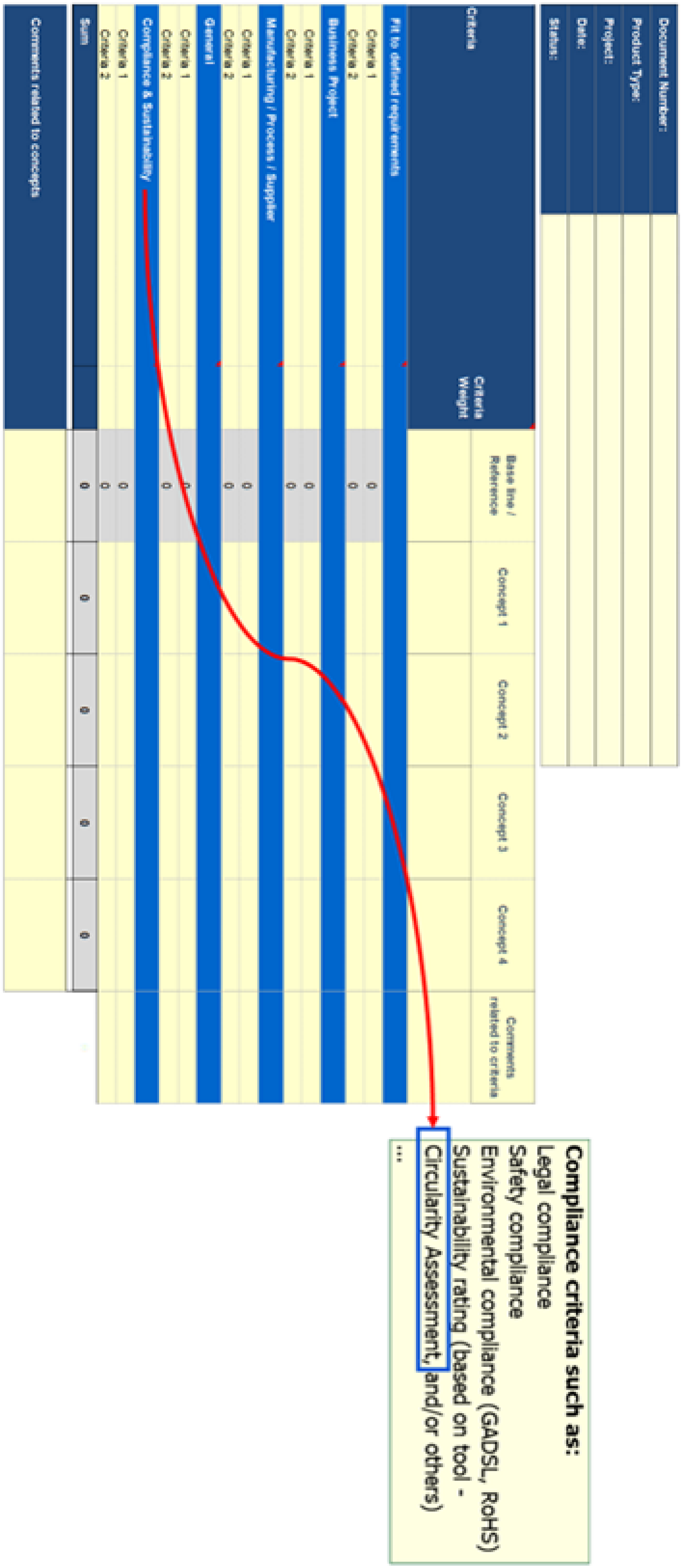


Figure 3.13: Circularity to be added in Pugh Matix

- Practicable in early product development phases without detailed product design;
- Containing value chain collaborations;
- Understandable without learning additional sustainability/circularity expertise;
- Providing measurements to guide the design work and decision making
- User-friendly and easy to be adopted.

To take reference from existing evaluation tools for further development adapting to the case company's context, a Pugh Matrix was performed to eliminate the unsuitable tools with the defined features, see the elimination process and outcome in Table 3.6.

Pugh Matrix						
Tools	In Engineering language	Editable to fit with SKF's context	Suitable for early design phases	No extra cost/authorization needed	Summary	Decision
MCI	Datum	Datum	Datum	Datum	0	Kill
CDR	1	0	1	0	2	Develop
CET	0	0	0	0	0	Kill
CEIP	0	1	0	0	1	Kill
CAT	0	1	1	0	2	Develop
PCM	1	1	1	0	3	Develop
LCA	0	1	0	0	1	Kill

Table 3.6: Pugh matrix

As a result, CDR (Circular Design Rules), CAT (Circularity Assessment Tool), and

PCM (Product-Level Circularity Metric) were selected for further investigation - testing with SKF's main product and analyzing the results. The try outs were summarized as follows:

- CDR [24] - An online tool that provides guiding questions from three perspectives (materials, components, and services). It was tested with two different bearing designs but resulted in same recycle rate because the guiding questions are not detailed enough to capture the impact from different bearing designs on circularity. The guiding questions are applicable for bearing products or most manufacturing products in a general way, but it could not be modified to reflect further more design details since it is not an open tool for adaptation. See CDR test results of product A and B in Figure 3.14.

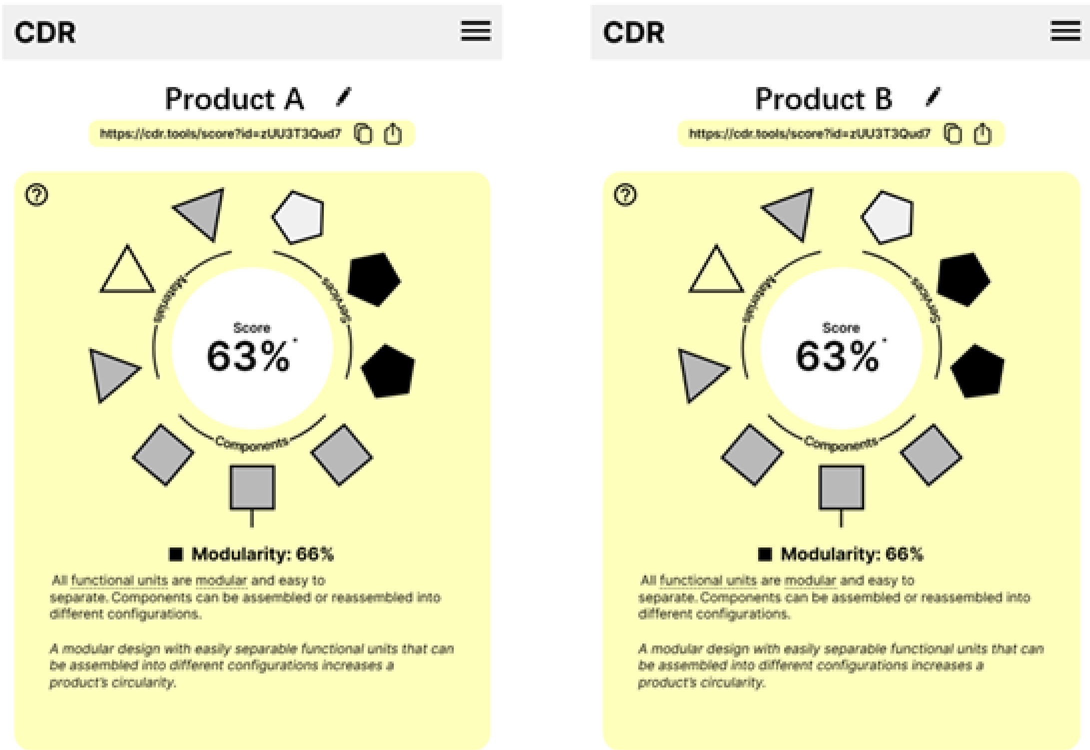


Figure 3.14: Test result of CDR

- CAT [26] - An excel based editable tool, which conducts assessment according to design guidelines. It has good visualization for concepts ranking, but the given guidelines are in general and not fully relevant with SKF's bearing products. However, there is possibility to modify the tool to reflect SKF's circular design principles and then to try it out with different bearing designs to see the validity. See try out example of CAT in Figure 3.15

- PCM [27] - A method that uses simple equations to calculate circularity ratio by components value/weight and gives quantitative results for different bearing designs. The equations were easy to understand and could be calculated by estimated component cost/weight at early design phases. Taking example from three different product concepts A/B/C, the calculation results showed

State your selected circularity goals: make a remanufacturable bearing

General design guidelines	Improtance to developing the product Really important (3) Moderately important (2) Slightly important (1) Not important (0)			Level of fulfillment Yes completely (1) Somehow but can be improved (3) No and it has to be (5)			Circularity Potential Scores 15: Vital and imperative 10 and 9: Improvement are necessary 6 and 5: Potential circularity improvements 3, 2 and 1: No change required 0: Not a concern		
	Concept A	Concept B	Concept C	Concept A	Concept B	Concept C	Concept A	Concept B	Concept C
Focus mainly on functionality and quality performance	2	2	2	1	3	3	2	6	6
Think about activity supports in the operational stage	2	2	2	1	1	1	2	2	2
Focus to fulfill the customer's requirements and value creation	3	3	3	1	1	1	3	3	3
Try to use digitalization, ICT and IoT solutions	1	1	1	1	1	1	1	1	1
Make it easy to inspect the product and components	3	3	3	1	1	1	3	3	3
Make it easy to clean the product and components	3	3	3	1	1	1	3	3	3
Make exchanging of faulty components easily accessible	3	3	3	1	3	3	3	9	9
Make it easy to dismantle the product nondestructively	3	3	3	1	1	1	3	3	3
Think about boundary management	0	0	0				0	0	0
Think about incumbent configuration	0	0	0				0	0	0
Think about complementary capabilities	0	0	0				0	0	0
Design using renewable materials	3	3	3	1	3	3	3	9	9
Design using recyclable and secondary (recycled) materials	3	3	3	1	1	1	3	3	3
Consider toxicity and other environmental aspects of materials	3	3	3	1	1	1	3	3	3
Favor cleaner production, processes, machines and equipment	2	2	2	1	1	1	2	2	2
Treat production (pre-consumer) wastes appropriately	3	3	3	1	1	1	3	3	3
Design for reduced energy consumption and usage of renewable energy	2	2	2	3	3	3	6	6	6
Design standardized components across different products and models	1	1	1	1	1	1	1	1	1
Design standardized tools required across different products and models	0	0	0				0	0	0
Use durable and robust components and materials	2	2	2	1	1	1	2	2	2
Design in modular construction	3	3	3	1	1	1	3	3	3
Provide manuals and documentation	2	2	2	1	1	1	2	2	2
Make spare parts and exchanging components easily available	2	2	2	1	1	1	2	2	2
Consider timeless design, emotional attachment and compatibility	0	0	0				0	0	0
Investigate current and upcoming laws and regulations	3	3	3	1	1	1	3	3	3
Use joints and connectors that can be easily opened and closed multiple times	0	0	0				0	0	0
Minimize the number of different incompatible or dissimilar materials	1	1	1	3	3	3	3	3	3
Make it easy to identify the materials and relevant information	2	2	2	3	3	3	6	6	6
Total Circularity potential Score with inclusion of the effect (the smaller the better)							**62**	**78**	**78**

Concept A is more circular

Figure 3.15: Example of CAT

concept A has higher circularity ratio if the calculation was based on weight, but it resulted in a different ratio when calculated by value. The reason was because concept C has component 4 valued much higher than the component in Concept A and B, see Figure 3.16. Therefore, depends on product type and strategy, different calculation method should be considered.

Full ReMan
Half ReMan
Zero Reman

Unit: kg	Concept A	Concept B	Concept C
Component 1	3	3	3.5
Component 2	2.5	2.5	3
Component 3	0.5	0.5	0.3
Component 4	5	5	2.5
ReMan ratio by weight	**77%**	**50%**	**62%**

Unit: Sek	Concept A	Concept B	Concept C
Component 1	30	30	35
Component 2	25	25	30
Component 3	5	5	3
Component 4	100	100	75
ReMan ratio by value	**69%**	**50%**	**76%**

Figure 3.16: Example of PCM calculation method

Based on above findings, it was decided to eliminate CDR but further develop and customize CAT to match it with SKF's circular design principles and its main users' needs, and to integrate PCM into CAT to obtain a holistic assessment tool.

Considering the adherence to the fundamental principles established at the outset, and linking the circularity assessment with business input and value chain partners' engagement, the tool was built with following steps:

- Replace General design guidelines with SKF Circular Design Principles
- Add filtering of circular design principles to align with business/product strategies
- Set the scoring from product design and value chain readiness perspectives
- Design guiding questions according to the outcome from discussions with cross-functional teams
- Integrate circularity ratio calculations (introduced by the New Product-Level Circularity Metric) in the guiding question

The draft version of the tool was created and reviewed by key users and updated based on their feedback before proceeding with demonstration. Lastly, a tool called CPAT (Circular Product Assessment Tool), referencing from CAT [26], was finalized after several iterations of guiding questions based on discussions with key stakeholders from PD&E, ReMan and COMO team. See illustration of the tool customization in Figure 3.17.

3.6 Demonstration and evaluation

To verify the validity of the customized tool, eight try out sessions were arranged with PD&E from different product lines to go through guiding questions using their ongoing or finished PDP projects. Seven out of the eight cases were from bearing product projects, and the other one was related to only component development.

It took 15 to 30 minutes of each try out to finish all guiding questions under ReMan session, and more time was needed if the PD&E had insufficient knowledge about ReMan. Less than 3 minutes was spent on each question except the one regarding Remanufactured/refurbished ratio, which took longest time to clarify and discuss how it should be calculated.

Out of the eight cases, four cases received different scores for different design concepts, which indicated the circularity level of design concepts as expected. In the other four project cases, the different design concepts in each did not result in different scores from the guiding questions to distinguish the degree of circularity. See the summary of demonstration results in Table 3.7. A pattern could be found from the try out results that the assessment tool would be valid for bearing products (not specific component), which are relevant with ReMan.

3.7 Communication

In the Engineering Sharing Hub, the PDP integrated with circularity was introduced to PD&Es from different regions, and the CPAT was show cased with one project example. The PD&Es appreciated the guidance could be given from the PDP process and evaluation tool to implement circular product design in their daily work.

The developed methodology as well as try out results were reviewed with key stakeholders in the case company. They endorsed the rationale of the approaches taken to develop the methodology and found the demonstration results promising as expected.

It was decided at the management level that same steps should be taken to get circularity integrated in each phase of PDP, and to have guiding questions set up for the rest Circular Design Principles in the Circularity Assessment Tool to give indications of product designs' circularity performance as a whole.

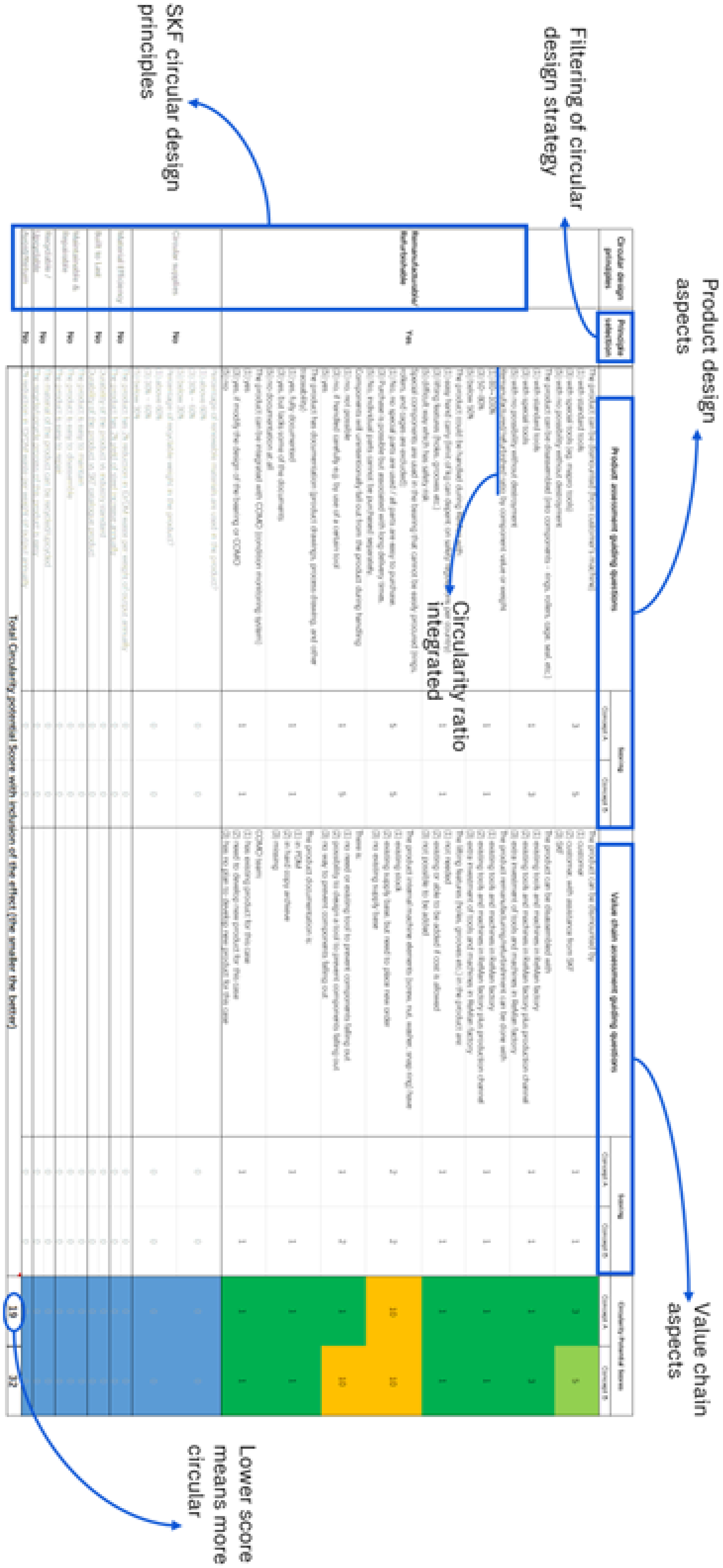


Figure 3.17: Customized Circularity Assessment Tool

Table 3.7: Try out results of the Circularity Assessment Tool

Product type	**Product Name**	**Product relevance with ReMan**	**The tool shows valid result**	**Reason of invalid result (from ReMan perspective)**
Bearing	A	Yes	Yes	NA
Bearing	B	No	No	Small and low value product, no ReMan needs, design is not aiming for ReMan.
Bearing	C	Yes	Yes	NA
Bearing	D	No	No	Smaller component in the new design for cost reduction, but no improvement for ReMan
Bearing	E	No	No	Manufacturing process changes for CO2 reduction, but no improvement for ReMan
Bearing	F	Yes	Yes	NA
Bearing	G	Yes	Yes	NA
Ball	H	Yes	No	Specific component, not applicable for the questions regarding bearing design

4 Discussion

The thesis project developed a methodology for implementing circularity in product development at a bearing manufacturing company. It showcased how the method and tools developed in the research area of circular product development could be adapted to aid organizations on related activities, and the key factors required for circularity implementation. Although the project was scaled down due to time and resource constraints, the effectiveness of the developed methodology was verified and laid the foundation for expanding the coverage of circularity implementation in the future at the case company. The project results could also provide a reference for the manufacturing industry, especially hardware-related companies, to plan their journey of circularity.

4.1 The adaptation of methods and tools from previous research

The conduction of the thesis project has taken many references from previous research. Many of the methods and tools found from the literature review were inspiring, but could not be directly adopted in the project.

In the initial phase of the project, backcasting was a useful methodology to bring all key stakeholders together to align on the goals and identify the gaps between present and future for prioritized action planning. To apply the backcasting methodology, a workshop was organized to carry out a self-assessment of circularity at the case company, and tools were selected to facilitate the workshop. Two particular tools were found from DSIP that had the potential for such self-assessment, but the existing settings of the tools were either in a larger scope or for a different purpose of assessment. Therefore, recompiling of these tools was crucial, otherwise the expected self-assessment results would not be achieved.

Similarly, the tools referenced for circularity evaluation were not fully fitting with the context of implementing circularity in SKF. Some of the tools have circular design guidelines that are not in accordance with SKF's circular design principles. Some of the guiding questions that facilitate the evaluation in the tool were in a general level and could not capture the differences between different bearing designs to produce an evaluation result that supports concept selection. Some well-known tools, such as MCI and LCA, support holistic assessment over the product life cycle, but have difficulty to be adopted without product data from utility and required expertise, so they were not adaptable for the circularity performance evaluation at product development early stage in PD&E organization.

All these practices demonstrated that it is essential to filter and adapt existing tools in the context of the case company to make them applicable.

4.2 The application of the methodology to implement circularity in product development

A practical methodology was developed from the study to implement circularity in product development. It could be summarized as following: 1) confirm the basic principles of circularity in the case company; 2) use backcasting procedure to align the goals, realize the present, identify the gaps, find solutions, and plan for actions; 3) integrate circularity activities into the case company's product development process with key stakeholder and governance defined; 4) provide tools and references to support the activities related to circularity. This methodology could be referenced by other manufacturing organizations, but the adaptation to their own context is the key to make the methodology applicable. See the illustration of the methodology in Figure 4.1.

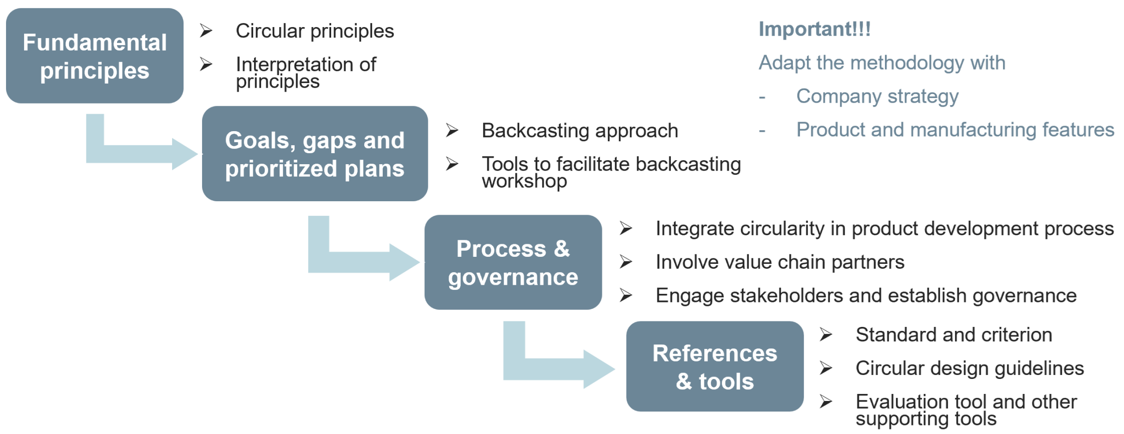


Figure 4.1: The methodology of implementing circularity in product development

The key factors to implement circularity in product development were investigated in the context of the case company during the project and found necessary to ensure the readiness of the following aspects, and it is extremely important to have the first four aspects ready in the early stages of the product development process.

- Organizational strategies and top-down commitment
- Stakeholder engagement and value chain working procedure
- Circular design rules and circular business model
- Product circularity performance evaluation

- Resource and competence
- Trade-off management

4.3 Limitation

With limited time and resources given to the thesis project, the development of the methodology to implement circularity was carried out based on the existing foundation of SKF within a lean scope, instead of full participation of the process and value chain partners. Furthermore, the development of the circularity assessment tool could be conducted with a more holistic consideration.

4.3.1 Circular design principles

At SKF, seven circular design principles have existed for many years, providing a foundation to the thesis project to develop the methodology of circularity implementation. Therefore, no effort was taken on circular design principle set up in this project. However, it might be worthwhile to re-visit the 9RS circular economy strategies and see if the seven circular design principles needs to be updated. In addition, other manufacturing organizations, especially SMEs (Small and Medium-sized Enterprises), might not have circular design principles defined yet. In this case, the baseline establishment should be the first step for implementing circularity, and 9RS could be a good reference at the starting point.

4.3.2 Value chain involvement

As emphasized in Section 3.1.1, value chain collaboration is extremely important to achieve success in circularity. To ensure collaboration happens during product development, it is crucial to identify who the value chain partners are, when and where they should be involved. However, due to the limitation of time and resource, only stakeholders have direct influence to the project were involved in interviews, observations and workshops. Meanwhile, the project focused on only one circular design principle - remanufacturable / refurbishable, which led to the engagement of PD&E, ReMan, and COMO team. In fact, procurement also plays a role in ReMan to support material supply, and there is potential that PD&E could work with buyers to optimize component design or selection. Nevertheless, procurement was not involved for the purpose of reducing project complexity.

There should be more internal and even external value chain partners (eg. suppliers and customers) to be sorted out according to all circular aspects in a thorough way, and working procedures across them should be established to guide their collaborations.

4.3.3 The coverage of methodology development

It was stated in Section 3.5.1 that each phase of PDP should have circularity element integrated to guide PD&E's work throughout the process. However, the focus was only put on Technical feasibility & Concept selection phase in the thesis project. To ensure the integration of circularity in the whole PDP, similar approach should be taken to reflect circularity elements in the rest phases, and more reference tools might be needed, in particular the circularity performance verification tools at later phase of PDP.

Moreover, the CPAT, which was proved that could support PD&E on comparing design concepts from circularity perspective, had equipped for circular design principle - Remanufacturable/refurbishable only. During demonstration, when the PDP project was not relevant to ReMan, the tool could not tell a comparable result for different concepts. To give a comprehensive judgment for concept selection, the other six principles should also be filled with guiding questions to obtain a complete assessment tool.

Additionally, it was argued in Section 2.5 that circular business model and trade-off management were excluded in the methodology design due to the limited influence from PD&E for these two key factors for implementing circularity in product development. However, PD&E's work has strong connection with the circular business model and trade-off management. The circular business model need to go hand-in-hand with circular product design to define the go-to-market strategy and capture the value of circular business [30]. Trade-offs should be managed based on a comprehensive understanding of the environmental and economic potential of design alternatives, in order to avoid misguided decisions [17]. Even if PD&E is not the owner of these two factors, it is necessary for PD&E to contribute in their establishment.

4.3.4 The Circular Product Assessment Tool

The development of the circular product assessment tool aimed to enable its application at an early stage of product development, thus excluding reference tools that require full life cycle data. However, this may lack consideration and lead to misleading decisions during product development. MCI, LCA and other tools might be worth considering even if only partial product life cycle data is available for applying the tool. In academia, it might also be worth studying how simplified models of these tools could be developed to support PD&E in adopting them for product circularity evaluation at early stage of design.

In terms of the CPAT working sheet, seven SKF's circular design principles were attached prior to the assessment working sheet. The intention was to provide CPAT users a basic understanding of the seven circular design principles. However, it was not clear enough to eliminate misunderstandings or confusions. Concrete examples should be provided, and the alignment among cross-functional teams is crucial before implementing the tool. In addition, the guiding questions in the assessment working sheet was designed in the context of bearing product, and demonstrated with seven different types of bearing. More verification is needed to check the validity for all types of bearing product, and it should be discussed with key stakeholders about the coverage of other products (eg. lubrication, seals,... etc.) for circularity implementation.

4.4 The value of implementing circularity in product development

There is no doubt to say that circular product design is a key enabler of Circular Economy which benefits the business and our environment. It extends product lifespan and unlocks new business model [3]. In the particular study - Design for ReMan at SKF, it showcased how circular product design could improve working efficiency and effectiveness, and bring more opportunities to ReMan businesses.

Further more, the implementation of circularity in product development promotes opportunities for circular collaborations in the value chain. In the traditional product development process, which applies to most hardware related manufacturing companies, product design inputs are normally from customers and business project team who generate requirements fit for the business and application needs. PD&E, as the input receiver, designs the product according to the requirements. Such traditional approaches could lead to missing potential opportunities for circular collaborations if the project initiator lacks knowledge or a sense of circularity. Instead of putting unrealistic expectation to downstream value chain partners, it is more pragmatic to take proactive thinking and action from PD&E, who would be supported by product development process with relevant tools, to make circular proposals and enable circular co-creation with value chain partners.

However, it is worth mentioning again that the value chain collaboration is the key to ensure that the circular economy is achievable [18]. A systematic process for developing circular products could help facilitate value chain partners building the circular product together in a good way, and the well-designed circular product needs to work with the circular business model under the aligned goal along the value chain to maximize the benefit for all partners and the whole society.

4.5 Recommendations for future research

The top-down determination to implement circularity in product development at SKF was obviously to see from company vision and mission, organization strategies and individual awareness. However, circularity is not achievable with mindset only, a systematic approach is essential to put ideas into actions in order to make progress towards circularity. Therefore, following the step C and D of backcasting methodology, a roadmap should be derived from the organization strategies to key initiatives with prioritized action plans. See example of PD&E circularity roadmap proposal in Figure 4.2.

Furthermore, as mentioned in Section 4.3.3, PD&E should realize how product design is in relation to circular business model and trade-off management and work together with the owner of these two key factors to enhance the readiness of implementing circularity in product development.

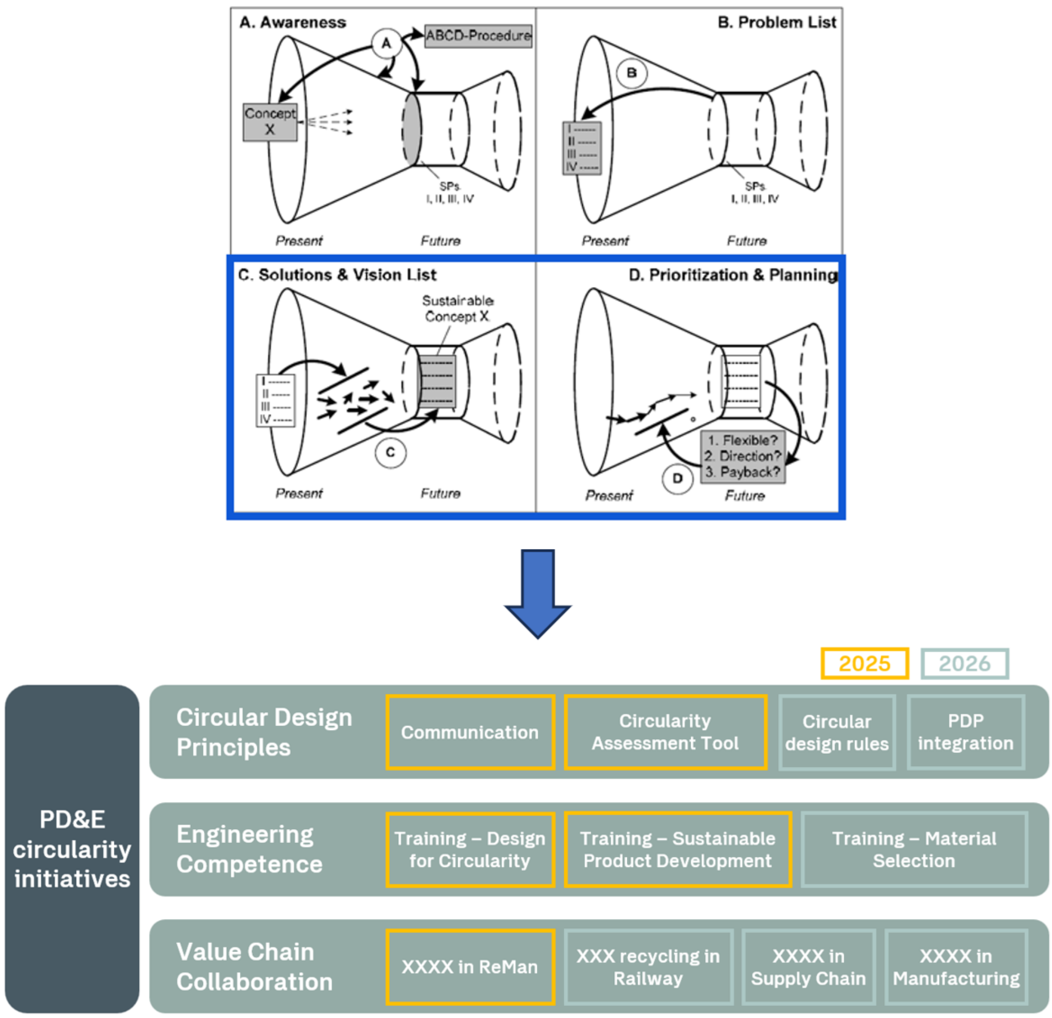


Figure 4.2: Example of PD&E circularity roadmap

5
Conclusion

The thesis project developed and demonstrated a practical methodology to implement circularity in product development at a bearing manufacturing company. By adapting existing methods and tools from previous research with the company's context, an updated PDP framework with circularity integrated and a Circular Product Assessment Tool (CPAT) were developed to guide the engineering teams to apply circularity in their product development work.

Although the full integration of circularity across all PDP stages was not completed and the CPAT needs further refinement to cover a broader scope of circular design principles and product categories, the methodology was validated by real product cases and shown to be effective to support decision making particularly at early stage.

The modular structure of the methodology makes it adaptable for other manufacturing contexts to build their own approaches towards circularity by tailoring it with their organizational goals, product characteristics, and circularity strategies. This positions the methodology as a transferable solution for other companies dedicated to circular product development.

As implicated from the key factors of implementing circularity in product development, future efforts should focus on the engagement of value chain partners to achieve a comprehensive and thorough implementation. In addition, expanding the CPAT to be used in PDP later phases to verify and validate product performance from circularity perspective will enhance the robustness of the tool. The involvement from academia could support the further development of the tool that better measure the performance and manage trade-offs.

Circular product development is an imperative but challenging topic, with high complexity and enormous obstacles along the value chain. However, it is encouraging to see that many companies are already committed and working toward the goal. The organizational behaviors are shifting from creating a vision to taking actions, which will make the journey even more promising. With the firm determination of organizations, it is critical to start action taking in working practices. As the saying goes, a journey of a thousand miles begins with a single step.

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A

Appendix 1

Interview with ________________

1. Could you give an overall introduction of your work in product development engineering team?
2. As you're leading the PDP project ___________________, could you give an introduction of this project? The scope and goals, major activities, and where we are right now.
3. What's already in the plan in terms of process / framework / template / working mechanism / … set up to support this PDP project?
4. Does this project involve value chain actors to collaborate and co-create?
5. What do you see as needed competence in the value chain (not limited in PDE) to achieve the project goal? And in a wider scope - circularity in product development?
6. What do you see as the main challenges so far?
7. Are those challenges addressed with action owner and plan?
8. What support is needed in the short and long term?
9. What do you see from the master thesis project that can benefit your work?
10. In what way do you see we can work together for circularity implementation in product development?
11. Who else to talk to? Should we involve colleagues from manufacturing or supply base for future discussion and workshop?

Figure A.1: Interview questions

B

Appendix 2

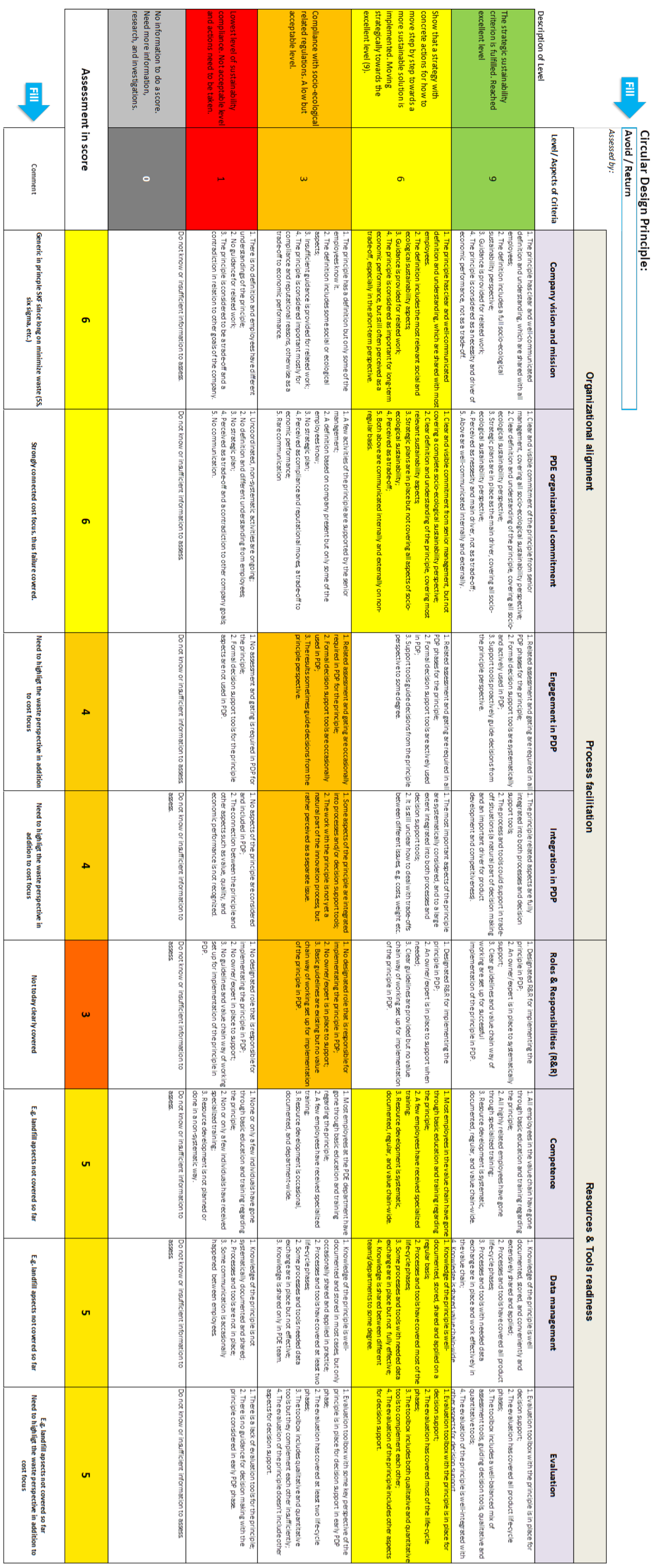

Figure B.1: The working sheet of Self-Assessment Workshop

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