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Applying the building blocks framework for circular economy progress in heavy-duty vehicle manufacturing

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Abstract. Heavy-Duty and Off-Road (HDOR) machines have a significant circularity potential. However, the implementation of Circular Economy (CE) in this sector, particularly regarding the End-of-Life (EoL) treatment, is still in its infancy. The present paper proposes a methodology to help a good-producing company initiate its CE transition. It encompasses two main steps: (1) an interview consultation strategy and (2) a classification of the resulting information into the CE building blocks framework, adapted from the Ellen MacArthur Foundation (EMF). The latter aims to identify situations to be improved and CE improvement avenues to be adopted. This methodology, applied to an HDOR manufacturer case study, proves to be highly effective in terms of the scope and complementarity of the CE improvement avenues while being easy to use. In this paper, two recommendations are formulated for improving the heavy machinery sector: proper dismantling and identifying in-use and EoL machines. The authors identify challenges for each of these areas of interest to address to shift towards CE in the heavy machinery sector.

Keywords: Circularity, heavy machine, end-of-life, industrial diagnosis.

1 Introduction

Circular Economy (CE) is an economic system that, at each stage of the product life cycle, tends to improve the efficiency of resource usage and lower the environmental impacts while contributing to the well-being of individuals (ADEME, 2015). It aims to slow resource loops through design for long-life and product-life extension or to close them through recycling (Bocken et al., 2016).

Contrary to other sectors, such as the automotive one, the CE in the Heavy-Duty and Off-Road (HDOR) sector is still in its infancy. The HDOR sector encompasses on-road vehicles weighing more than 3,5 tons and off-road mobile machinery, including trucks, buses, tractors, construction and mining machinery (Saidani et al., 2018). Around 20 million of them are in use in Europe (ICCT, 2016; Weiland, 2014), and approximately one million reach their End-of-Life (EoL) each year (Weiland, 2014). This represents an EoL tonnage comparable to the automotive

sector (Saidani et al., 2018). These mainly steel-composed EoL HDOR machines constitute a high potential deposit for proper recycling and remanufacturing activities. However, contrary to light vehicles, this potential is not fully exploited yet (Saidani et al. (2018). HDOR machines are currently not subject to specific EoL regulations (Saidani et al., 2018). The EoL treatment activity needs to be better organized (Saidani et al., 2018), and the literature on CE in the HDOR sector is still recent and needs to be expanded (see section 2.1). HDOR companies are keen to develop their CE strategy further but still need help finding ways to improve it. Among the different methods and tools companies use to picture the current situation, internal diagnosis is recognized as an effective one (Fouqué, 2021). Hence, they can support companies in identifying where and how they can improve the circularity of their activities (Gentric et al., 2023). In this regard, we propose to address the following research question:

How can a good-producing company, still in its infancy concerning CE and with limited resources, effectively use a single internal diagnosis to categorize potential ways of improving its circularity performance?

In this paper, an interview consultation strategy is proposed and conducted. Then, the CE building blocks framework (EMF, 2013) is adapted to classify information from the internal diagnosis in order to identify situations to be improved and CE improvement avenues. The study includes a use case from a French HDOR manufacturer that assembles and sells machines used by the construction, agricultural, and industrial sectors worldwide. This company and its subsidiaries are already involved in some CE-related activities on a modest scale in relation to the scale of waste. This approach includes the second-hand and reconditioned equipment business and the remanufacturing of spare parts.

The paper first discusses the state of the art on CE in the HDOR sector (sections 2.1 to 2.3), with a particular focus on the lack of information related to in-use and EoL machines (section 2.2) and on EoL regulations and HDOR dismantling (section 2.3). Then, the state of the art on classifying actions to move toward CE is discussed (section 2.4). The research methodology is then described, from the interview consultation strategy (section 3.1) to the classification of the information into the CE building blocks framework (EMF, 2013) (section 3.2). Next, results are presented, including a classification of CE improvement avenues compared with other frameworks (section 4.1) and a set of challenges to address to move significantly towards CE in the heavy machinery sector (section 4.2). Finally, limits and future works are discussed (section 5).

2 Literature Review

2.1 Circularity in the HDOR sector

Few papers focus on CE in the HDOR sector compared to the automotive sector. A comparison between these sectors regarding circularity was conducted by Saidani et al. (2018). They outlined the differences in organization and regulations between these industries and displayed current best practices and barriers in both sectors. Xiao et al. (2018) focused on the emerging remanufacturing of HDOR in China. They compared three scenarios from an economic and environmental point of view. The distance traveled between the remanufacturing factory and the local dealers was found to be a

significant criterion, making local remanufacturing the best option compared to a central remanufacturing factory or manufacturing a new machine. Schmitt et al. (2021) sought to find a balance between lean manufacturing and circularity considering product, process and system levels in an HDOR industrial case study. Saidani et al. (2020) studied the dismantling of heavy machines through a pilot industrial case study. They described and improved the HDOR dismantling process and identified the best recovery option for each component from an economic and circular point of view. Shekarian et al. (2023) focused on Sustainable Supply Chain Management (SSCM). They interviewed four industrialists and proposed a framework to identify hotspots and improve the SSCM. However, circularity is seen as one aspect of sustainability among others, and the results show that it is a minor concern for those surveyed.

According to Saidani et al. (2018), apart from a few companies (i.e., Caterpillar, DAF and Volvo trucks) with ambitious approaches to CE, the HDOR sector is underdeveloped when it comes to CE. Among the exceptions, Caterpillar is probably the most well-known for its CE approach. Its remanufacturing activity is recognized as particularly developed even out of the HDOR sector (EMF, 2013; Saidani et al., 2018; Stahel, 2016). In summary, CE is still in its infancy for most of the HDOR sector, and the academic interest is still recent. The following subsections discuss (1) the lack of data as a challenge to be tackled and (2) the EoL regulations and treatment.

2.2 Lack of data on the use and EoL of HDOR machines

Saidani et al. (2020, 2018), Schmitt et al. (2021) and Xiao et al. (2018) attested to the lack of information concerning the use or the EoL of HDOR machines and considered it as a barrier to CE. Saidani et al. (2020) recommended an investigation into the location of used and EoL machines to ensure a proper collection. Saidani et al. (2018) explained that the numerous uncertainties about the quantity, location, quality, and condition of EoL HDOR machines and used spare parts are challenging to close the loop. Schmitt et al. (2021) studied an HDOR company that loses track of its products a few years after selling them. They considered it a “crucial gap” for CE by significantly reducing the likelihood of the product being returned.

This issue is not specific to the HDOR sector. Indeed, EoL automotive location in Thailand is unknown (Mangmeechai, 2022). EoL knowledge in the railway sector is also affected by several uncertainties due to a lack of precise statistics (Delogu et al., 2017).

To contribute to filling this gap, Mangmeechai (2022) estimated the number and the location of EoL vehicles by exploiting car registration and deregistration data. However, these methods need precise data and suffer some limitations. The main one is that a car registration or deregistration location may differ from its EoL location. Another promising solution is the use of digital technologies. It is proposed to fill the gap in most articles from the previous sub-section (Saidani et al., 2020, 2018; Schmitt et al., 2021; Xiao et al., 2018).

The lack of data concerning the use and EoL of HDOR machines is a concerning gap for circularity. The nature of the information to collect to improve circularity and how are also gaps to fulfill.

2.3 EoL regulations and dismantling

Europe, China and Japan have some EoL regulations for the automotive industry (Mangmeechai, 2022). However, other countries like Thailand or the USA may not have such regulations (Mangmeechai, 2022). One of the most binding ones is the European Union (EU) directive 2000/53/CE (2000), which could be strengthened soon (EU Proposal, 2023). This directive forces automakers to take responsibility for EoL vehicles. Notably, it requires that at least 85% of the car's mass be reused or recycled, and it has to reach a 95% recovery rate, including energy recovery. Unfortunately, even in Europe, only automobiles are subject to such regulations. Trains (Delogu et al., 2017), some light vehicles like scooters and motorcycles (Berzi et al., 2016), and HDOR machines (Saidani et al., 2018) are not affected yet. The considerable environmental and economic potentials of EoL activity in the HDOR sector (Saidani et al., 2018), along with the possibility of a future EoL regulation, make the study of HDOR dismantling particularly challenging.

Saidani et al. (2020) highlighted that the dismantling activity in the HDOR sector is poorly developed and controlled. In order to help transform this situation, Saidani et al. (2020) studied the dismantling of heavy machines through a pilot industrial case study. They described and improved the HDOR dismantling process and identified the best recovery option for each component from an economic and circular point of view. Notably, dismantling matches the targets (Directive 2000/53/CE, 2000), and the profits vastly exceed the dismantling costs (Saidani et al., 2020). However, this paper did not include the buy-back price of the machine in the costs, making the overall profitability uncertain. Also, they dismantled solely two similar machines, limiting the generalization of the results for other HDOR types, conditions, or market values.

2.4 Classification of actions to move toward CE

Sections 2.1, 2.2, and 2.3 highlight some of the main issues related to the CE transition in the HDOR sector. To identify avenues for CE improvements, the authors dedicate this section to presenting the existing CE frameworks and selecting one as the basis for an internal diagnosis. In the remainder of this section, the authors use the term framework to refer to explicit frameworks acknowledged by their authors (Bocken et al., 2016; EMF, 2013; Geissdoerfer et al., 2020) but also materials that could be presented under the form of a proper framework such as a list of CE strategies (Salvador et al., 2021; Reike et al., 2018).

As shown in Table 1, these frameworks can be distinguished by CE strategies and CE building blocks coverage. CE building blocks concept is borrowed from EMF (2013) and represents significant areas on which to act to implement CE strategies successfully.

Geissdoerfer et al. (2020) proposed a framework to identify and classify CE business model strategies. It combines the value logic framework from Richardson (2008) with four different circular strategies: slowing, extending, intensifying, and dematerializing. Yet, this framework is limited to the consideration of the business models.

Table 1. Comparison of the identified frameworks to identify avenues for CE improvements.

Framework	Number of CE strategies	CE building blocks coverage	Interrelation of building blocks
Geissdoerfer et al. (2020)	4	BM	No
Bocken et al. (2016)	2 major strategies, 11 sub-strategies	BM, PD	Yes
EMF (2013)	Not considered explicitly	BM, PD, RC, CC	Yes
Reike et al. (2018)	10	PD, PU (includes BM and RC)	Yes
Salvador et al. (2021)	16	PD, BM, RC, CC, but as CE strategies	No

Legend: PD - Product Design, BM - Business Models, RC - Reverse Cycles, CC - Cross-cycle and Cross-sector collaboration, PU - Produce and Use

Bocken et al. (2016) proposed a framework encompassing two major strategies for circularity, slowing and closing the loop, and eleven sub-strategies. Bocken et al. (2016) did not only consider the business model aspects but also the design characteristics. The Ellen MacArthur Foundation (EMF, 2013) presented four CE building blocks in its framework: Product Design (PD), Business Model (BM), Reverse Cycle skills (RC), Cross cycle and Cross sector collaboration (CC). The CE building blocks framework (EMF, 2013) aims to identify situations with a potential for circular improvement and associate actions to exploit this potential in an industrial context. However, this framework does not explicitly acknowledge CE strategies. Reike et al. (2018) proposed a hierarchy of 10 CE strategies. They considered two interrelated life cycles forming a second dimension with the CE strategies: “Product concept and Design” and “Produce and Use”. Compared with EMF (2013), the first life cycle roughly corresponds to the PD block, while the second encompasses the BM and RC blocks without distinction. Salvador et al. (2021) identified 16 CE strategies, encompassing R strategies but also enablers for other strategies such as design, reverse logistics, or collaborative aspects. However, they considered these strategies separately rather than multiple aspects of the same strategy.

These frameworks share common characteristics: they can help industrialists identify CE improvement avenues and are relatively easy to use. They also share important limitations: they are insufficient to tell if an action must be taken, when, at what scale, and with which economic, environmental, or circular impacts. Apart from Reike et al. (2018), they barely consider the stakeholders’ role, while the relationship between them is a critical aspect of sustainability (Monastyrnaya et al., 2017). The work from Reike et al. (2018) is a notable exception, considering who owns the product and distinguishing the role of customers and businesses for each CE strategy. Other frameworks consider more ecosystemic views like the one in Monastyrnaya et al. (2017), which adapts the Business Model Canvas (Osterwalder and Pigneur, 2010) to better include the different stakeholders’ roles.

Bocken et al. (2016) argued that: “design and business model strategies need to be implemented in conjunction” as shown in Table 1; some frameworks extend this approach by considering even more CE building blocks (EMF, 2013; Salvador et al.,

2021). We argue that considering a wide range of building blocks is desirable to identify relevant and various CE improvement avenues. However, according to Hopkinson et al. (2020): “configuring one block in isolation could realize value opportunities but could also lead to value leakage and lost opportunity”, leading to the necessity of considering them complementarily. In this regard, the EMF (2013) framework appears to be the most suitable for identifying relevant and complementary CE improvement avenues.

The EMF (2013) framework has already been used by Saidani et al. (2018) to represent the best practices and challenges in the HDOR and automotive sectors. Hopkinson et al. (2020) also used this framework to illustrate real-world circular practices from three case studies, including data from publicly available reports and input from company executives. To the best of the authors’ knowledge, the CE building blocks framework (EMF, 2013) has not yet been used in an in-depth industrial diagnosis context to identify multiple avenues for CE improvement.

3 Methodology

The main objective of this work is to provide a method for a good-producing company, still in its infancy CE transition, to establish a comprehensive and pertinent roadmap of CE improvement avenues. To do so, this paper proposes a two-step methodology to prepare the assessment, sizing and implementation of actions afterward. It comprises (1) a series of interviews to collect data and (2) a classification of this information into the CE building blocks framework (EMF, 2013).

3.1 Interview consultation strategy

The main objective of the interview consultation is to provide data concerning (i) the industrial context, (ii) barriers and CE improvement avenues, and (iii) existing CE actions.

In order to establish a relevant CE action plan for an HDOR manufacturer, the authors assert that comprehensiveness in terms of topics and activities is essential. The data collection phase involves interviewing numerous stakeholders from different company areas.

Three waves of interviews were achieved. Wave one started by interviewing the most obviously CE-related persons in the company: CSR members, people explicitly involved in CE-related activities, and possibly people identified as having a potential influence on CE, like the design managers. For each interview, several possibilities emerge: more confidential CE initiatives are identified in other parts of the company, some causes or effects of situations to be improved are identified, and other people who could influence CE are recommended. In all cases, the interviewer asked the interviewees for interesting people to interview. Alternatively, if some new CE-related topics emerged during an interview, the interviewer identified who is in charge of these topics. All the interviewees identified as relevant constituted the following round of interviews. Progressively, the following waves allowed us to ascend or descend a ladder in the causality chain and, therefore, identify several levels

on which to act and get closer to root issues. It also allows for identifying relevant interviews in other companies' departments, resulting in increasingly broader topics being covered. The third wave can help interview people the company does not consider CE-related, whereas they can influence barriers or enablers for CE strategies.

The borders of the waves are blurred. Some interviews of a wave can start before the ending of the previous one. Some topics tackled in an interview could be raised during the same wave if the interviewee was already identified as relevant to another topic.

An example of an interview chain: the spare parts interview showed that component diversity threatens component remanufacturing. The reasons for that diversity were discussed with a designer. He identified the frequent machine generation renewal as part of this problem, recommending diverse marketing managers' interviews. One of the marketing managers identified the users' willingness to change as being responsible, and other managers considered the shifts in engine regulation to be one of the leading causes. The continuation of this interview chain could be done either by interviewing machine users or regulatory experts.

Some other relevant interviews could have been conducted, but the amount of information from the 44 interviews was considered enough to attest to the method's reliability.

To be in the best condition to explore and dig into new topics, the interview conditions are:

- One-hour meetings are a constraint from the company's agenda and have been deemed sufficient in most cases to cover the subject.
- One interviewee at a time to avoid peer or hierarchy pressure and let every interviewee detail his/her thoughts.
- Only company members because of accessibility constraints and to limit the scope of the study.
- Face-to-face meetings are used to streamline interaction, as respondents appreciate the effort.
- Taking notes instead of recording to limit the interviewee's stress.

The goal is to help the interviewees tell what they know about their activity, which could concern CE, and to identify new, interesting, and unexpected information. Consequently, the authors choose to conduct the interviews as follows:

1. Presentation of the interviewer's role and settling common ground on what CE is, with guidelines and examples according to the interviewee's role.
2. The interviewer explains why he/she thinks the interviewee is relevant, who recommended the interviewee, and the topics to discuss.
3. The interviewer tells the interviewee that he/she is searching for avenues for improvement and barriers for CE and not to hesitate to discuss other topics than the original one as long as it appears relevant from a CE point of view.
4. The interviewee presents himself/herself and his/her current or past activities. This provides industrial context to the interviewer and can lead to identifying situations that need improvement or already done CE actions.
5. The interviewee gives explanations, concerns, identified barriers, and improvement avenues on the introducing topic or on other topics he/she has

evaluated as interesting for the interviewer based on his/her CE understanding and the elements provided by the interviewer in steps 1 and 6.

6. This step occurs during steps 4 and 5. The interviewer asks precisions on topics, contradicts with other interviewees' declarations, asks for future interviewee recommendations, explains CE concepts, and refocuses the discussion.

The next step is transforming the information gathered into a synthetic, consolidated set of CE improvement avenues.

3.2 Classification of the information, adaption of the CE building block

The authors state that comprehensiveness regarding CE building blocks is important to establish a relevant and broad CE industrial action plan. After collecting information, a framework is needed to classify information and identify actions on a broad scope of key CE activities.

In subsection 2.4, the EMF building blocks framework (EMF, 2013) is identified as suitable for the present study. It is noteworthy that, so far, it has not been identified to classify and exploit information from an in-depth diagnosis context. This building blocks framework aims to aid industrialists in identifying potential CE improvement avenues on four interrelated key axes: design and production, business models, cascades/reverse cycle skills, cross-cycle and cross-sector collaboration. This framework is adapted in Table 2.

Data collated from the interviews is classified following a decision tree illustrated in Figure 1. The process detailed below enables transforming the collated data into valuable information for a CE industrial action plan:

1. A situation is identified as improvable from a CE perspective in the interview notes or the literature.
2. For one of the building blocks: Search for solutions to improve the situation in interview notes or the literature. Alternatively, the authors can propose their ideas for improvement.
3. Identify relevant context elements and helpful information in interview data or literature.
- A. Are steps 2 and 3 done for all the building blocks? Yes, go to B. No, go to step 4.
4. Repeat steps 2 and 3 for another building block.
- B. Do some of the newly identified CE improvement avenues or done actions cause relevant situations to be improved? No, End. Yes, go back to step 1 with the new situation(s) to be improved.

Alternatively:

5. An action is identified in the interview or the literature as relevant to improve CE. Do B and step 6.
6. Identify the initial situation the action aims to improve. Go back to step 1.

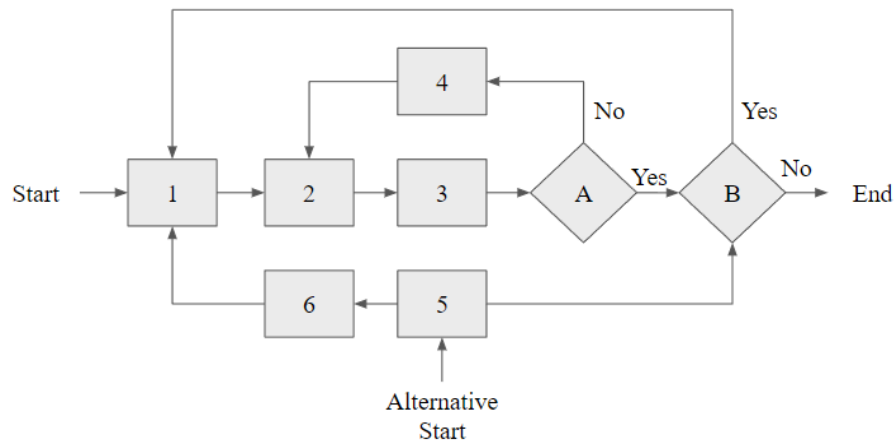


Fig. 1. Data classification following the designed decision tree.

At each step, fill the framework with the relevant data. Repeat the process as long as you identify situations to be improved or actions to improve CE in the company.

4 Results

4.1 Identified CE improvement avenues for the case study company

In this section, results from applying the first two steps described in section 3 allow for establishing a set of CE improvement avenues. Such results are obtained from implementing the proposed methodology to a good-producing company in the HDOR sector. Around 200 potential CE improvement avenues, corresponding to 70 various situations, are identified, as derived from the interviews. The four CE building blocks (PD, BM, RC, CC) are fairly represented, with 56 CE improvement avenues for the production-design block, 50 for the business model one, 45 for the reverse cycle block, and 46 for the cross-cycle and cross-sector one. Some CE improvement avenues from each building block are depicted in Table 2. Employees from diverse parts of the company were interviewed, resulting in a wide range of identified topics; a sample of the identified situations is depicted in Table 3.

Among 70 identified situations to be improved, 16 have improvement avenues in two or more CE building blocks. These CE improvement avenues could either synergize or compete. An example of synergizing CE improvement avenues is to equip main components with sensors and connectivity to predict the breaks (PD) and to propose a proactive buy-back of specific components before the break (BM). Conjointly, these improvement avenues could help ease remanufacturing. In contrast, to answer the “Management of lithium batteries EoL is uncertain” issue, the proposed improvement avenues from different building blocks compete against each other. PD solutions are mainly alternatives to lithium-ion batteries (lead-acid batteries, hydrogen, biofuel, plugged-in) to avoid the problem. At the same time, CC

improvement avenues target an improvement in the management of the EoL lithium-ion batteries via reconditioning or stocking them until an improvement of the recycling channels occurs.

Table 2. CE building blocks framework (EMF, 2013), HDOR case study.

	From... (initial situation)	To... (improvement avenues)	Sources
Product design	Counterweights cannot be reused on other machine models	Rethink the machine design order Modular counterweights	Design / Eco-design
Business models	Customer concerns about the quality of remanufactured components	Labels to assess a certain remanufacturing quality for the remanufacturing partners Systematized discarded components recover	Spare parts / Used subsidiary
Cascading / Reverse cycle skills	Not enough components to remanufacture	Dismantling machines to recover components to remanufacture	Used subsidiary / Schmitt et al. (2021)
Cross-cycle and cross-sector collaboration	Difficulties in finding machines for reconditioning or recycling	Collaboration with insurance to recover rugged machines	Dismantling company

Table 3. Examples of initial situations to be improved and related building blocks identified.

Initial situation (From...)	PD	BM	RC	CC
Difficulties in finding machines for reconditioning or recycling		X	X	X
Lack of standardization	X			X
Shortage of qualified technicians to recondition machines			X	
Components are not designed for remanufacture	X			
Management of lithium batteries EoL is uncertain	X			X
Machines' real lifetime is unknown				X
Lack of information on the becoming of machines			X	
Machine connectivity does not remain for the entire machine's lifetime	X	X		
Conspicuous consumption of some customers pushes for more frequent machine generation renewal	X	X	X	X
Components to remanufacture are sometimes recovered in lousy condition, complicating the remanufacture	X	X		

Legend: PD - Product Design, BM - Business Models, RC - Reverse Cycles, CC - Cross-cycle and Cross-sector collaboration

4.2 Future research questions to be addressed

Building upon the insights from the conducted literature analysis and the internal diagnosis, the present section discusses two main areas of interest to support CE transition in the HDOR sector. Moreover, future research perspectives are highlighted to address the current gaps, as identified in section 2.

The first area of interest identified as particularly relevant is the dismantling of HDOR machines. The dismantling activity in the HDOR sector is currently poorly developed (Saidani et al., 2020) and not regulated (Saidani et al., 2018). However, the industrial diagnosis and the literature show there is an interest for HDOR industrialists in developing machine dismantling. Among these interests, there is notably the anticipation of extended regulations from the automotive sector similar to Directive 2000/53/CE (2000) and the possibility of a new revenue source by exploiting a currently unorganized activity. In addition, by providing steel to be recycled to the steel industry, HDOR companies could benefit from a stable supply of recycled steel to address the current unsatisfied demand in terms of recycled steel for new machines, fostering the CE in the HDOR sector.

The literature review in subsection 2.3 highlighted gaps concerning the lack of studies about HDOR dismantling and a lack of understanding concerning the drivers of these dismantling performances related to machines and market characteristics.

To develop and improve the HDOR dismantling activity, industrialists need a better understanding of the economic and circular performances, the main drivers, and how to act on them.

From this consideration and the literature gaps, the following research questions appear and could be further explored: What are the economic and circular performances of HDOR dismantling? Which machines and market criteria drive these performances, and how? What are the levers to improve the circularity and profitability of HDOR dismantling?

The second area of interest is the identification of HDOR machines during and at the end of their lifetime. The literature review from subsection 2.2 reveals a critical gap concerning the lack of information on in-use and EoL HDOR machines. While this gap is well identified in the literature, the type of information to collect in order to fill this gap needs to be more exhaustively described.

These gaps are also observed in the company where the case study is conducted. Indeed, traceability on products is easily lost, making it hard to collect pertinent data for circularity improvement. The company under study has connected machines for several years, providing useful information. However, the information collected is not exploited from a CE perspective, is limited in quantity, is difficult to interpret due to the diversity of data types and quality, and, above all, the connectivity is often lost after a few years of the machine's use.

From this gap analysis, some research questions can be highlighted: What information should be collected to manage the EoL of the HDOR machines properly? How to collect or estimate this information? What do the HDOR machines become after selling?

Answering these research questions could lead to significant progress for CE in the HDOR sector by facilitating the collection of used and EoL products,

identifying and addressing new markets with CE services or products, and giving insights to improve from a CE perspective: design, business models, and reverse cycles. In particular, this information could feed into a decision-making model to determine the best time to take back each machine and which recovery option(s) to use.

5 Discussion and conclusion

5.1 Results comparison with other methods

The framework used in the present paper allows for a broad consideration of CE building blocks compared to other presented CE frameworks. Bocken et al. (2016) considered design, business model, and partially cross-sector collaboration through industrial symbiosis. Reverse cycle aspects, including collection systems and treatment/extraction technologies (EMF, 2013), cross cycles, and cross-sector collaboration aspects like regulatory or pooling of means, are not explicitly considered. However, they represent over a third of the CE improvement avenues identified to improve CE in case study companies. Geissdoerfer et al. (2020) focus solely on the business model aspects. Even if solutions of the three other CE building blocks are evoked as potential actions, they are not detailed. Reverse supply chain, durable/repairable product design, and “slow and close the loop” capabilities or collaborations are examples of value creation and delivery into that framework. In contrast, they are considered major parts of some building blocks in the EMF framework (EMF, 2013). In consequence, around three-quarters of the potential CE improvement avenues identified in this case study may not have been identified using the framework of Geissdoerfer et al. (2020).

Therefore, the breadth of major areas on which to act, as offered by the CE building blocks, is key to establishing a relevant action plan. However, what the CE building blocks framework gains in breadth and multi-perspective solutions is lost in detail and structure. Bocken et al. (2016) and Geissdoerfer et al. (2020) proposed sub-classifications per CE strategies. Geissdoerfer et al. (2020) subdivide the business models into three interrelated aspects: the value proposition, creation and delivery, and capture. Although adapting the CE building blocks to add these aspects is possible, careful care is required to keep the framework easy to use.

5.2 Identified limitations and future perspectives

While the present work provides valuable insights to improve CE, some limitations can be highlighted. Notably, the interview strategy could be more extensive in some aspects. The main one is the absence of stakeholders’ interviews from outside the company, whereas their insights would be of paramount importance in establishing a relevant CE industrial strategy. The manufacturer-centric view of the present work is a limitation because CE and sustainability could gain to embrace a more ecosystemic point of view (Geissdoerfer et al., 2020; Monastyrnaya et al., 2017).

There are also limitations to the framework part. As explicitly mentioned in subsection 4.1, the simplicity and exhaustiveness of the CE building blocks framework came at the cost of less detail and structure about CE strategies than other

CE frameworks. CE strategies such as the one from Bocken et al. (2016) and Reike et al. (2018) are considered to identify situations to be improved and CE improvement avenues. However, they are not explicitly considered as a part of the framework.

Fouqué (2021) argues that an industrial diagnosis should meet three important requirements: reliability, speed and accessibility. Extending the scope of the research to external stakeholders and adding complexity to the framework may constitute interesting future research to improve the reliability of the results. However, it could come at the expense of the two other criteria.

Concerning the validation of the model, the literature about CE in the HDOR sector offers few comparisons to attest to the relevance and originality of the results found. The case study company is too small to have a distinct group of experts from the diagnosed one to attest to or criticize results. An assessment and prioritization model could also be a solution to better validate the relevance of the proposed method. More than classification and assessing the quality of actions, there is a need to properly monitor and simulate the impact of potential actions in a company to improve CE. The Circular Digital Cockpit (Yannou et al., 2024) is a promising tool to address this concern.

To go further, the research question from section 4.2 could be addressed by:

- Identifying relevant machines and market characteristics and studying their variations on HDOR dismantling economic and circular performances.
- Identifying information to collect from in-use and EoL HDOR to improve CE.
- Identifying and testing methods to obtain that information, giving a clear view of the becoming of in-use and EoL HDOR machines.

5.3 Conclusion

This article proposes a cost-effective approach to identify CE improvement avenues within a large company that has not yet reached CE maturity. We opted for a structured method, including an internal consultation of CE-related players and a classification of the information via the CE building blocks (EMF, 2013). Results are a broad scope of situations to be improved and CE improvement avenues brought by the internal players themselves. The proposed methodology offers broad coverage of the company's activities, contributing to industrialists' adoption of CE strategies while being comprehensive, relatively fast to apply, and easy to use. Other large companies could use this model at the beginning of their CE transition to mobilize internal intelligence and quickly find broad and sector-specific CE improvement avenues.

To help the HDOR industry progress significantly in CE, we also identify and discuss challenges of particular importance for the sector. These challenges concern two areas of interest: the lack of data on the use and EoL of HDOR machines and the lack of regulation and understanding concerning the EoL treatment. We propose research questions for both areas of interest to address the need to move significantly toward CE in the HDOR sector.

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