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Multi-tool methodology to evaluate action levers to close the loop on critical materials – Application to precious metals used in catalytic converters

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ABSTRACT

Implementing circular economy (CE) practices can lead to both environmental savings and competitive advantages for companies. While transitioning from a linear production system to a closed-loop system is not straightforward, adequate methodology and tools can support industrialists in this sustainable shift. This paper proposes a multi-tool approach to systematically identify, classify, and assess the contribution of influence parameters and action levers to close the loop on products and key materials. Industrial ecology and model-based engineering tools are combined to ensure a systemic analysis and evaluation. The developed multi-tool approach combines, in a stepwise methodology, material flow analysis, fuzzy cognitive mapping, structural analysis, and system dynamics, to model and qualify the impact of potential and promising CE strategies. To illustrate each step of this multi-tool methodology, a case study is carried out on a real-world industrial product: a catalytic converter, which contains a non-negligible amount of platinum, considered as a critical raw material by the European Commission. New insights to close the loop on platinum from catalytic converters are thus provided and discussed. Notably, the connections between key action levers to close the loop on platinum are identified and highlighted, including regulations to limit the number of exports, mandatory recycling and reuse rate, end-users behaviors, based on regulatory constraints and financial motivations, and platinum price fluctuation. These findings could help to generate and fine-tune an ad hoc system dynamics model to evaluate the impact of key action levers through more specific scenarios. For instance, the broader implication of this multi-tool methodology could support an original equipment manufacturer in the evaluation of potential CE strategies, through the simulation of selected action levers on the circularity and sustainability performance of their value chain. Ultimately, it could provide quantitative insights to relevant prospective questions, such as, what if a take-back scheme is proposed to augment the collection rate by a given percentage, or what if the design is modified for easy disassembly.

1. Introduction

1.1. Context and motivations

Closing-the-loop on critical raw materials is essential for the European Union (EU) economy from an economic and strategic perspective (Hofmann et al., 2018; Ferro and Bonollo, 2019). Critical raw materials, including precious group metals, are defined by the European Commission (2017) as "raw materials of high importance to the EU economy and of high risk associated with their supply". Particularly, among these precious group metals, the interest of recovering platinum from catalytic converters in the EU arises for several reasons, namely: (i) economic, catalytic converter being a high added-value component due to the non-negligible presence of platinum that costs around $30,000 per kilogram; (ii) environmental, due to the low platinum concentration in mines (below ten grams per metric ton) which leads to large consumption of energy to extract and refine primary platinum; (iii) social, ore mining conditions are being increasingly harsh for workers in mines; and, (iv) geostrategic, more than 90% of platinum reserves being located in South Africa and Russia (Pryshlakivsky and Searcy, 2020; Saidani et al., 2019, Rasmussen et al., 2019). Furthermore, platinum supply is critical for the global green transition due both to its current primary use in autocatalysts and its increasing use in emerging and renewable energy technologies such as fuel cells.

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Currently, platinum contained in catalytic converters accounts for the most primary use and possess the highest platinum stock. On this basis, augmenting the end-of-life collection and recycling rates in the EU is of utmost importance to address potential future supply risks (Rasmussen et al., 2019). Even if some marginal channels exist, the collection rate of platinum from catalytic converters in Europe is still low and estimated at around 50% (Hagelüken et al., 2016). As for now, while several issues need to be tackled to close the loop on platinum have been outlined in the literature, there is a lack of operational improvement solutions and simulations to assess "what if" scenarios (Franco, 2019; Saidani, 2018), and thus evaluate quantitatively the impact of various *a priori* relevant reconfigurations in the design, value chain, business model, or policy related to autocatalysts.

1.2. Research gaps and objectives

With this background, the overarching objective of the present research work is to evaluate the impact key action levers to further close the loop on catalytic converters not only from automotive vehicles but also from heavy-duty and off-road vehicles that contain more platinum. To do so, system dynamics appears to be an effective and practical tool to visualize the interaction among various factors in a product recovery management system, as well as to run "what if" simulations, e.g., to assess end-of-life product recovery scenarios under different situations (Alamerew and Brissaud, 2018). Indeed, a system dynamics model might be particularly useful to manufacturers, service providers, and collection parties seeking to test or evaluate the performance of circular economy (CE) strategies and the viability of self- or third-party imposed collection targets (Franco, 2019). Yet, in addition to the complexity of system dynamics models and the significant amount of quality data required (Franco, 2019), there are some methodological challenges to build a complete and relevant model, as well as to validate the soundness of it. For instance, it is necessary to identify the most important factors and determine the dependencies of factors among themselves (Manjunatheshwara and Vinodh, 2018). In this light, the operational objectives of this work are twofold, (i) to construct a methodology that aims at assessing the impact of different action levers to achieve a more circular economy, (ii) to experiment with the proposed approach through a significant industrial case study from a manufacturer willing to know how close the loop of their product containing precious raw materials.

In this paper, an integrated four-step multi-tool approach is proposed to identify and assess key action levers to close the loop on materials. This study notably links together industrial ecology and model-based engineering tools such as material flow analysis, fuzzy cognitive mapping, matrix-based structural analysis, and system dynamics. It provides thus new methodological and practical insights to close the loop on products and materials in the light of the current transition towards a sustainable CE. The proposed approach is illustrated through a case study on platinum, which is considered as a critical raw material for the European Union. The first steps of the multi-tool methodology developed in this paper aim to identify systematically, assess, and select key and relevant action levers variables to support building the system dynamics model. Material flow modeling is first used to map out the value chain and to highlight hotspots and key areas of improvement. Fuzzy cognitive mapping, combined with structural analysis, are then deployed to identify, rank, and select the most promising action levers. Methods of prospective are also expected to be used so as to define relevant and realistic scenarios, before running the system dynamics simulations. In addition to the methodological contribution, this research work aims to provide industrial practitioners and/or policymakers with new qualitative and quantitative insights on how to close the loop on platinum in the EU, through the evaluation of different actions levers (in design, business models, financial incentives, etc.) that would contribute in maintaining the platinum contained in catalytic converters in the EU for secondary use and therefore securing future supply. In the next sections, the main sources of inspiration to design this multi-tool methodology are described (section 2); then, the proposed methodology is explained in detail and illustrated through a case study (section 3); next, the results for each step of the multi-tool methodology are analyzed and interpreted (section 4); and, finally, promising lines for future research to reach a sound and sustainable circular economy are discussed (section 5).

2. Literature review

In this literature review section, the focus is made on the studies combining several methods and tools to tackle complex issues in the fields of sustainability and circular economy, as sources of inspiration for the proposed multi-tool methodology. Interestingly, some approaches combine methods and tools from the same field (e.g., industrial ecology tools such as material flow analysis and life cycle analysis) while others put together tools from industrial ecology, system engineering or value analysis in the same framework to come up with new valuable insights and methodologies.

2.1. Multi-tool approaches in the fields of sustainable design and circular economy

An integrated methodological framework for modeling and eventually designing sustainable and resilient systems has been proposed by Halog and Manik (2011), based on the capitalization of the complementary strengths of different methods, including: life cycle thinking methods such life cycle assessment, multiple criteria decision analysis, system dynamics, agent-based modeling, and geographic information systems. The authors indeed advanced that "sustainable development is a complex, multidimensional phenomenon, with a breadth and depth that cannot be fully covered by the current portfolio of reductionist-oriented tools" (Halog and Manik, 2011). More precisely, because the existing life cycle thinking and multiple criteria decision analysis methods are considered as steady-state methods providing snapshots of hotspots based on historical data, modeling and projecting the dynamic interrelationships of the key variables overtime is needed to make the results more useful for decision and policymakers. As such, Halog and Manik (2011) deployed both system dynamics and agent-based modeling tools to take into account the interconnections and thus create a dynamic computational sustainability assessment of the system investigated. Additionally, the use of geographic information systems can be explored to assist in spatial analysis. In all, different software packages and modeling tools can successfully complement each other to deliver richer insights for sustainable decision-making.

In this line, Idjis (2015) combined three modeling and simulation methods, namely: systemics for complex organizational systems' modelling, cognitive mapping, and system dynamics, to characterize the recovery network of vehicle batteries, by understanding its dynamics and identifying the key variables in these dynamics. More simply, Turner et al. (2016) combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making. Similarly, Pinto et al. (2019) combined system dynamics and life cycle assessment to test multiple changing variables and to provide a clear visualization of gate-to-cradle dynamics. The authors argued that such an approach "could potentially interest industrial decision-makers who would like to broaden the understanding of their operations as their goods and products integrate the economy as well as when they leave it". Eventually, research projects in industrial engineering can be led

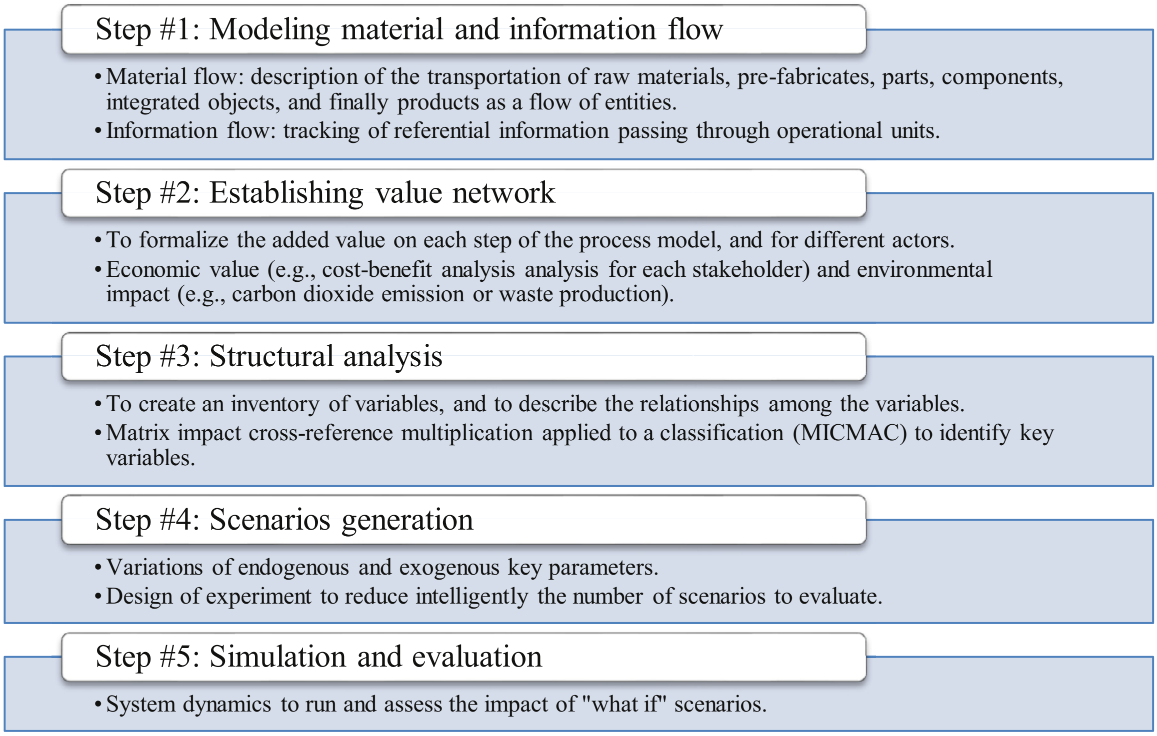


Fig. 1. Stepwise method to design a value chain from scratch, retrieved from Farel and Yannou (2013)

successfully through the deployment of a multi-methodology research approach. For instance, in his action-research project, Lamé (2017) assembled different research methods, including interviews, observations, soft systems methodology, discrete event simulation, and system dynamics, to frame and manage a transformation project in real-time.

Using this multi-methodology mindset is particularly valuable here because the CE requires systemic and lifecycle thinking. The arguments found in the literature in favor of multi-methodology approaches have emphasized the fact that it is actually necessary to deal effectively with the full richness of the real world where problem situations are inevitably highly complex and multi-dimensional (Mingers and Brocklesby, 1997). Therefore, we intend to challenge the assumption that the combination of *a priori* promising research methods could positively contribute in closing-the-loop of industrial systems and associated key materials. For instance, a system dynamics model that is usually seen as a model of reality, or as a detailed and dynamic cognitive map, could be interestingly combined with key industrial ecology tools such as systems analysis, material and energy flows, analogies to natural systems, and closed-loop systems (Garner and Keoleian, 1995).

2.2. Designing a sustainable recovery channel through a multi-tool process

Concretely, Farel and Yannou (2013) designed and proposed a multi-actor value chain using a multi-method approach, considering both technical and organizational issues. They argued the value chain system could exist if: (i) it is economically viable as a whole; (ii) it is profitable and interesting for all stakeholders; (iii) it could sustain to the external changes; and, (iv) it can be coordinated and managed. One of the main challenges is, therefore, to find ways or mechanisms to make the system and its value chain sustainable. On this basis, they proposed a multi-method approach to model, analyze, and evaluate a given industrial ecosystem, in order to generate future scenarios and provide evaluation criteria for decision-makers. As summarized in Fig. 1, it includes the following steps: (i) modeling material and information flow; (ii) establishing the value network; (iii) structural analysis; (iv) scenarios generation; and, (v) simulation and evaluation.

Note that the structural analysis conducted by Farel and Yannou (2013) to design a recovery chain for the glass from end-of-life vehicles, including three successive phases: (i) creating an inventory of variables; (ii) describing the relationships among the variables; and (iii) identifying the key variables. More recently, after identifying the factors that influence the sustainable development of information and communication technology products from literature and with experts input, Manjunatheshwara and Vinodh (2018) combined: (i) the total interpretive structural modeling methodology to establish factor dependencies, with (ii) a matrix-based analysis to categorize the factors based on their ability to influence other factors.

In the present case, even if we are not starting from scratch to improve the circularity performance of the platinum contained in catalytic converters, the combination of such methods and tools appears to be inspirational to model and assess the impact of different mechanisms or action levers in the (re)design of sustainable circular systems. In fact, we argue that using an appropriate combination of some of these approaches could contribute to (re-)shaping a value chain and industrial practices in a CE perspective, by providing industrial decision-makers and policymakers with well-founded analysis on the most promising ways to close the loop on their systems.

3. Methods

3.1. Proposed multi-tool methodology

The developed multi-tool approach consists of four steps, feeding each other, as illustrated in Fig. 2. Inspired by Farel and Yannou (2013), the first step is about modeling the current situation through material flow analysis to quantitatively describe the entire

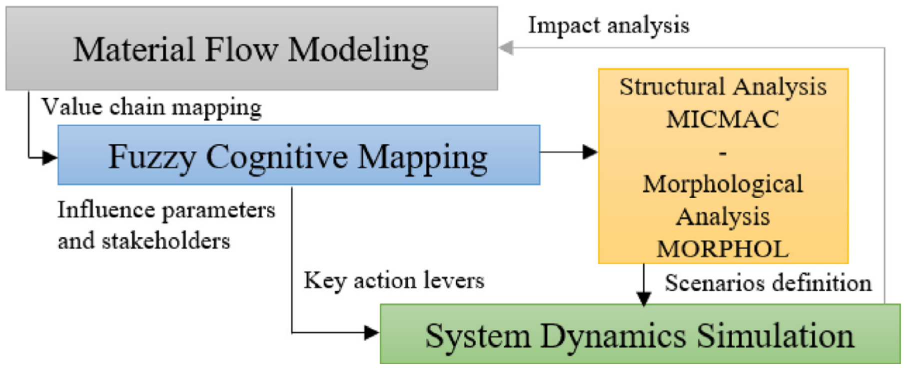


Fig. 2. Schematic illustration of the multi-tool methodology to close the loop on industrial components

value chain, to highlight areas of improvement, as well as to identify the economic and environmental value buckets. The second step consists of making a connected inventory of a comprehensive number of factors that could contribute in closing-the-loop and enhance the sustainability performance of the value chain. This step is supported by the use of fuzzy cognitive mapping to both identify and represent the connections between action levers. The third step deals with the evaluation, ranking, and selection of key action levers, through the use of engineering-based models and structural analysis. At the end of this stage, a presentation of the key outcomes is made to an industrial practitioner, acknowledged as an expert in this field, to have a first feedback and validation of the preliminary results. The last step consists of simulating the impact of different scenarios (i.e., diverse configurations of key variables selected in the previous step) through system dynamics, compared to the initial circularity and sustainability performance, as mapped out in the first step through material flow analysis. Each tool is briefly introduced in the next sub-sections (from 3.1.1. to 3.1.4), including related and relevant inspirational examples from the literature, before being applied to a case study (sub-sections 3.2. and from 4.1. to 4.4.).

3.1.1. Material flow analysis

Material flow analysis (MFA) is a tool that can be deployed to perform a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2003). MFA is one of the most acknowledged tools in the industrial ecology field to monitor material use and industrial processes, as well as to design closed-loop industrial systems (Takeyama et al. 2016) in a CE perspective. Brunner and Rechberger (2003) provide key guidelines to perform consistent, transparent, and reproducible MFA. In this research work, to identify and quantify the barriers preventing from achieving an enhanced CE of platinum contained in catalytic converters in Europe, an MFA was performed using STAN (subSTance flow ANalysis) software (Cencic and Rechberger, 2008) with the consideration of data uncertainties, as further detailed in Saidani et al. (2019) and in the present sub-section 4.1.

3.1.2. Fuzzy cognitive mapping

Fuzzy cognitive mapping (FCM) – also known as concept map, heuristic map, or causal graph – provides a nonlinear way to visualize and unfold the complexity of design problems. FCM appears to be a practical tool to model the relations between the elements of complex systems. In an FCM, the information is branched out in multiple directions providing designers and other stakeholders with a more holistic view of possible unforeseen connections. More precisely, FCM represents knowledge by defining three main characteristics of a system (Gray et al., 2013), namely: (i) the components of the system; (ii) the positive or negative relationships between the components; (iii) the degree of influence that one component can have on another, according to a semi-quantitative weighting. Indeed, an FCM utilizes fuzzy logic in the creation of a weighted and directed cognitive map. Additionally, once an FCM is developed, it can be deployed to test “what if” scenarios allowing users to evaluate several configurations of a given system (Papageorgiou and Salmeron, 2011). For instance, Gnoni et al. (2017) used a fuzzy cognitive map model to quantify the impacts on the social, economic, and environmental dimensions induced by the transition from an ownership-based to a product-as-a-service-based business model, considering both direct and reverse supply chain. Bertassini et al. (2021) recently deployed an FCM to represent and evaluate the relations between captured values from new circular business models and key stakeholders. On this basis, the authors “obtained a stakeholder classification applied to CE, identified a list of circular values these stakeholders could capture, and proposed a guide that drives the organizations toward identifying new opportunities and solutions for CE implementation” (Bertassini et al., 2021).

3.1.3. Structural analysis

The functional analysis system technique helps to list and represent the logical relationships between the functions of a project, product, process, or service, based on the questions “how” and “why” (SAVE International, 1999). The development of a Function Analysis System Technique (FAST) diagram is particularly relevant to stimulate creativity, to verify if, and to illustrate how a proposed solution achieves the needs of the project, as well as to identify unnecessary, duplicated or missing functions. In the present case, this system engineering-based formalism is used to build a comprehensive and well-structured list of influence parameters or action levers (considered as functions, according to the FAST formalism) that can contribute to achieving a CE of platinum contained in catalytic converters. Moreover, as recommended by Farel and Yannou (2013), it is essential from a practical point of view to identify the key variables, in order to set up relevant scenario generation and feasible simulations. The Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC) is a tool that structures the pooling of ideas (Godet, 2007). It allows the identification of the main variables that are both influential and dependent, that is to say, those that are essential to the evolution of the system.

3.1.4. Scenarios generation and system dynamics

While system dynamics (SD) has been first defined as a computer-aided approach to policy analysis and design (Forrester, 1961), it can also be applied to dynamic problems arising in complex social, managerial, economic, or ecological systems, characterized by interdependence, mutual interaction, information feedback, and circular causality behavior (Richardson, 2013). For instance, Sinha et al. (2014) adopted a dynamic system modeling

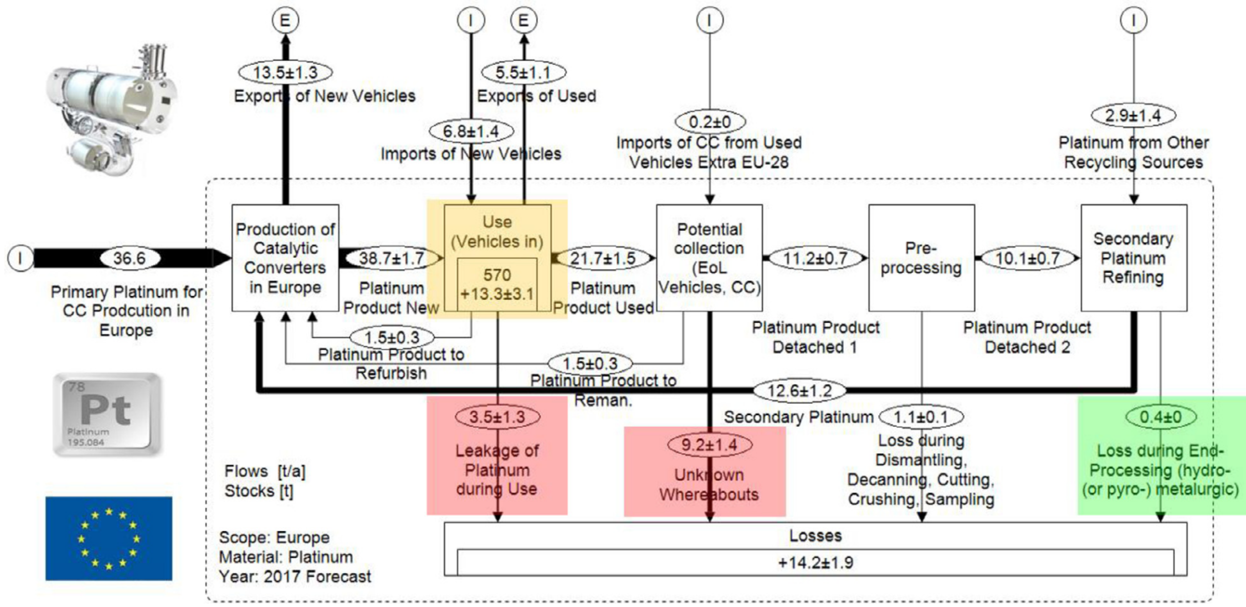


Fig. 3. Material flow analysis of platinum from catalytic converters, retrieved from Saidani et al. (2019)

approach to identify leverage points for closing the material flow loop and approaching a CE for a mobile phone product system. Rodrigues et al. (2017) proposed a causal loop diagram-based tool so that industrial decision-makers can assess the potential benefits of ecodesign by testing multiple scenarios and strategies. Idjis et al. (2017) opted for a system dynamics approach to model and optimize a recycling network of lithium batteries in the automotive industry. According to Idjis et al. (2017), it is useful for stakeholders and decision-makers to have access to simulated data, showing the situations of a system in a long-term perspective, following the various possible evolution of key variables. Idjis et al. (2017) also recommended that those situations, called scenarios, should be generated intelligently from the crossing of the dynamic evolution of key variables of the system. Rosa and Terzi (2018) applied a system dynamics simulation model to perform a real-time comparison of several scenarios for the end-of-life vehicles recovery chains of a European country, in order to identify recovery processes leading to an increase in profits for dismantlers and shredders. Still, in the automotive industry, Mohan and Amit (2021) used a SD model to quantify the feedback effects of competition in the end-of-life vehicle recycling market, discussing the effects of price fluctuation on end-of-life vehicles for dismantlers. Eventually, using a system dynamics simulation model, Franco (2019) analyzed the systemic effects of combining multiple product design and business model strategies for slowing and closing resource loops in a CE.

3.2. Case study

To experiment and illustrate each step of the developed multi-tool methodology concretely, a case study is conducted on a catalytic converter, which contains a non-negligible amount of platinum (Hagelüken et al., 2016), considered as one of the critical raw materials by the European Commission (2017). A catalytic converter is a key and mandatory component in motorized vehicles (e.g., cars, heavy-duty vehicles, and non-road mobile machinery), which converts toxic pollutants (exhaust gases produced from motor combustion) into less or non-toxic gases. There are mainly composed of three components: the canning in stainless steel, the substrate in cordierite, and the coating containing precious metals groups such as platinum, which is the essential element to realize the catalytic conversion and reduction. As emissions regulations are becoming increasingly strict not only in Europe and North America, but even in emerging countries, the quantity of precious metals in catalytic converters is likely to rise to meet future standards (European Commission, 2017). The present case study has been developed in close interaction with a large European manufacturer of construction equipment, which also designs and manufactures their own catalytic converter systems, as further described in the Ph.D. thesis manuscript of Saidani (2018). In addition to an extensive literature review to identify key influence parameters, drivers, and action levers to close the loop on platinum, inputs from a project manager of the team designing catalytic converters have notably been sought and used throughout this project. Particularly, this project manager, who recently heard about the promising benefits of implementing CE strategies, was interested in knowing how the catalytic converters they design and develop could be more circular to retain the value of precious metals in their business and thus benefit from associated economic profit and environmental savings.

4. Results and discussion

4.1. Material flow analysis and circularity indicators (application)

The outcomes resulting from this first step has been extensively presented and discussed in an independent research paper (Saidani el al., 2019), focusing on the complementary inputs from material flow analysis (MFA) and circularity indicators (Saidani et al., 2017) to close the loop on products and materials. In a nutshell, the additional contributions from MFA and circularity indicators provide a quantitative and localized identification of the improvement opportunities, as well as interesting value buckets not fully exploited yet, on the platinum value chain, as shown in Fig. 3. While approximately one-quarter of the losses are due to in-use dissipation, 65 % are attributed to insufficient collections and unregulated exports. For instance, the growing stockpile of platinum from catalytic converters in use urges for better collection mechanisms, and the leakage of platinum during the use phase (attrition of the catalytic converter) needs further attention. It also gives a reliable and up-to-date baseline to track and seek progress on the circularity performance of the platinum value chain. No-

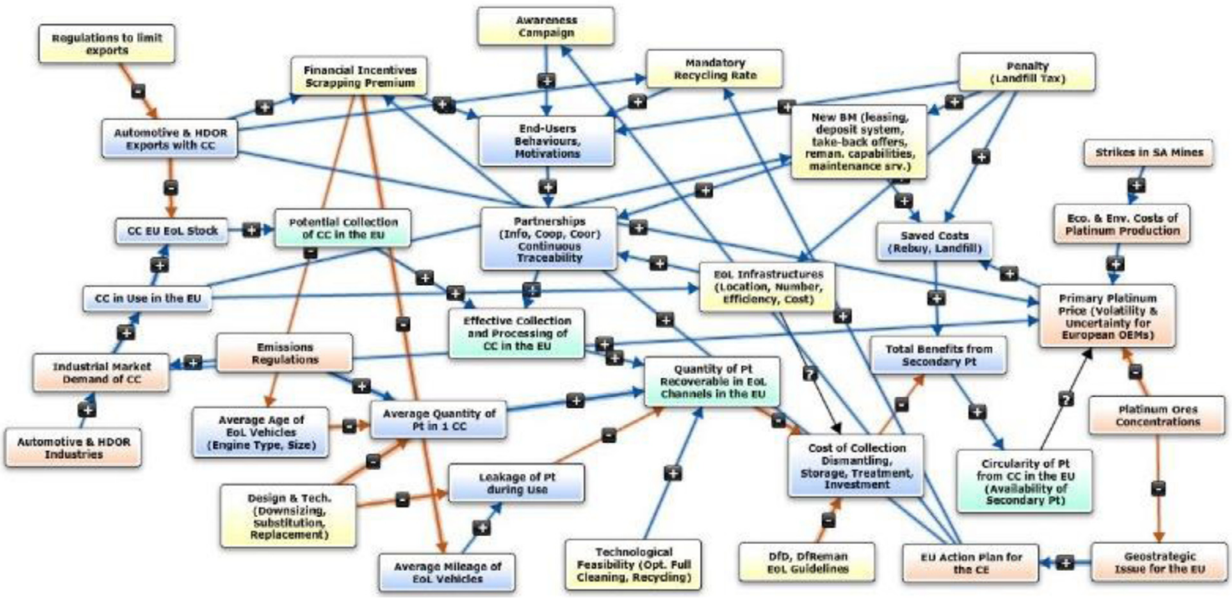


Fig. 4. Fuzzy cognitive mapping with action levers, drivers, and parameters to close the loop on platinum

tably, it has been found that halving the leakages of phase occurring during the usage and collection phases could lead to the environmental savings of approximately 250,000 tons of carbon dioxide equivalent. Thus, activating appropriate action levers to enhance the CE performance of platinum in Europe is of utmost importance in order to secure the future productions of new generations of catalytic converters, and other components demanding a sustainable supply of platinum such as the fuel cells.

4.2. Fuzzy cognitive mapping (application)

In the present case, using the web-based software Mental Modeler, developed by Gray et al. (2013), fuzzy cognitive mapping (FCM) is deployed to develop a semi-quantitative model of the different factors – identified through the combination of industrial data and an extensive literature survey (Saidani, 2018) – that could affect positively the circularity performance of the value chain of platinum used in catalytic converters. In fact, it enables the user to list and define a first visual relationship between these variables, as illustrated in Fig. 4, where: improvements areas are highlighted in green, action levers in yellow, influence variables in purple, and drivers in red. This FCM contains 35 components – including nine driver components, one receiver component, and 25 ordinary components – for 54 connections, has a density of 0.045, and a complexity score of 0.11. Metrics like complexity and density allow the comparison of one model with another by quantifying the structure of the FCM. These metrics are computed automatically by the software Mental Modeler, and the formulas are available in Gray et al. (2014). The density of an FCM is an index of connectivity, quantifying how dense or sparse the variables or action levers are connected. Here, a density of 0.045 shows a relatively low number of direct connections between the action levers. Similarly, a complexity score equals to 0.11 shows a relatively low complexity.

Note the FCM software used can also serve to run “what if” scenarios, but only to describe qualitatively or semi-quantitatively how the system might react under a range of possible changes. Each causal link can indeed be assigned with a polarity, either positive (+) or negative (-) to indicate how the variables evolve. Yet, before simulating such possible variations, this inventory of potential factors has to be augmented and enhanced by structural analysis, using both the Functional Analysis System Technique (FAST) to complete more rigorously the list of potential action levers, and the Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC) to select the key variables. Interestingly, we found that the use of an FCM is relevant as a first approach to map and model the interactions between several variables in a visual way. On the other hand, it becomes less practical when the number of variables or interactions increases significantly compared to the computation of a matrix such as the MICMAC, as illustrated in Fig. 5. As such, this FCM, coupled with a structural analysis-based model, will serve as creating a fine-tuned system dynamics model.

4.3. Structural analysis using Function Analysis System Technique and Matrix Impact Cross-reference Multiplication Applied to a Classification (application)

As introduced in sub-section 3.3, the Function Analysis System Technique (FAST) diagram of the present project in available in Appendix A. In all, the final list – combining findings from the application of both FCM and FAST – of potentially relevant actions levers, drivers, and influence variables inventoried is available in Appendix B. Note that this list of actions levers is also closely related to the value chain and the associated stakeholders, as mapped in the MFA.

Once all the variables have been identified, a direct influence matrix is filled out as depicted in Fig. 5, answering the following question for each square of the matrix: “is the variable X influencing the variable Y?”, in association with the following scoring system: “no” = 0; “potentially” = 1; “indirectly” = 2; and “directly” = 3. Then, the indirect classification is obtained by increasing the power of the matrix (four times in the present case, as recommended by Godet (2007), corresponding to the “number of iterations” in Table 1). It enables not only to confirm the importance of certain variables but also to uncover certain key variables which, because of their indirect actions, play an important role, not identifiable through direct classification. Based on the computation of the Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC), whose features are listed in Table 1, the dependence-influence chart, mapped out in Fig. 6, enables to identify the cluster of the least important variables (i.e., passive and/or inactive), and the cluster of

	1 : 1.1	2 : 1.2	3 : 1.3	4 : 1.4	5 : 2.1.1	6 : 2.1.2	7 : 2.1.3	8 : 2.2.1	9 : 2.2.2	10 : 2.3.1	11 : 2.3.2	12 : 2.3.3	13 : 2.3.4	14 : 2.4.1	15 : 2.4.2	16 : 2.4.3	17 : 3.1.1	18 : 3.2.1	19 : 3.2.2	20 : 3.2.3	21 : 3.2.4	22 : 3.2.5a	23 : 3.2.5b	24 : 3.2.5c	25 : 3.2.6a	26 : 3.2.6b	27 : 3.3.1	28 : 3.3.2	29 : 3.3.3	30 : 3.3.4	31 : 3.4.1	32 : 4.1.1	33 : 4.2.1	34 : 4.3.1	35 : 4.4.1	36 : 4.1.2	37 : 4.1.3	38 : 4.2.2	39 : 4.3.2	40 : 4.4.2
1 : 1.1	0	0	0	2	3	3	3	1	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	3	3	0	0	1	1	1	3	1	0	0	0	3	0	0	0
2 : 1.2	3	0	0	2	3	3	3	3	3	0	0	0	1	3	2	2	3	3	3	3	3	3	3	3	2	2	0	0	2	3	1	0	2	1	0	0	1	0	0	0
3 : 1.3	3	3	0	0	3	3	3	2	1	2	3	2	3	1	0	0	2	2	1	3	2	2	2	2	2	2	3	3	3	3	1	0	0	2	0	3	3	0	1	1
4 : 1.4	3	3	3	0	3	3	3	1	3	0	0	0	2	1	3	3	2	2	2	3	2	3	3	3	3	3	0	1	2	2	2	3	3	3	3	0	0	3	2	2
5 : 2.1.1	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	3	2	1	2	2	2	2	2	1	1	0	0	0	2	1	0	2	1	2	0	0	1	0	0
6 : 2.1.2	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	2	2	0	0	0	0	0	0	0	3	0	0	0	0	3	0	0	0
7 : 2.1.3	0	0	0	0	3	3	0	3	2	0	0	0	0	1	0	0	2	2	1	2	2	0	0	0	1	1	0	0	0	2	0	0	0	0	0	0	1	0	0	0
8 : 2.2.1	0	0	0	0	0	0	0	0	2	0	2	0	1	1	1	2	2	3	3	3	2	3	3	3	3	3	0	0	0	1	1	0	2	1	1	0	0	1	0	0
9 : 2.2.2	2	0	0	0	2	2	3	1	0	0	0	0	1	3	3	2	2	2	1	3	2	2	2	2	2	2	0	1	1	2	3	2	2	2	2	0	3	2	0	0
10 : 2.3.1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 : 2.3.2	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
12 : 2.3.3	0	0	0	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 : 2.3.4	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0
14 : 2.4.1	2	3	3	0	2	0	1	2	2	0	3	0	2	0	0	0	1	3	0	2	2	2	2	2	2	2	0	2	3	2	1	1	1	1	0	0	1	1	0	0
15 : 2.4.2	0	2	3	3	0	0	1	2	0	0	3	0	2	3	0	3	1	2	0	2	2	0	0	0	0	0	0	2	2	2	1	1	1	2	2	0	1	2	0	0
16 : 2.4.3	0	2	3	3	0	0	1	2	0	0	3	0	2	0	0	0	1	0	0	2	2	0	0	0	0	0	0	0	1	2	1	1	1	3	0	0	1	3	0	0
17 : 3.1.1	0	0	0	0	2	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	1	3	1	2	0	1	1	0	1
18 : 3.2.1	2	0	0	0	2	2	2	1	0	0	3	0	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	3	2	2	0	1	2	0	0
19 : 3.2.2	0	0	0	0	1	1	1	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	1	2	0	1	1	0	0
20 : 3.2.3	0	0	0	0	0	0	0	1	0	0	2	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	2	2	0	1	1	0	0
21 : 3.2.4	0	0	0	0	0	0	1	1	0	0	2	0	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	2	2	0	1	1	0	0
22 : 3.2.5a	1	0	0	0	2	2	3	2	1	0	2	0	1	0	2	2	2	1	0	2	1	0	0	0	1	1	0	0	3	2	2	1	0	2	1	0	1	1	0	0
23 : 3.2.5b	1	0	0	0	2	2	3	2	1	0	2	0	1	0	2	2	2	1	0	2	1	0	0	0	1	1	0	0	3	2	2	1	0	2	1	0	1	1	0	0
24 : 3.2.5c	1	0	0	0	2	2	3	2	1	0	2	0	1	0	2	2	2	1	0	2	1	0	0	0	1	1	0	0	3	2	2	1	0	2	1	0	1	1	0	0
25 : 3.2.6a	1	0	0	0	2	2	2	2	2	0	2	0	1	0	0	0	2	1	0	2	1	1	1	1	0	1	0	0	2	1	1	1	0	1	1	0	1	1	0	0
26 : 3.2.6b	0	0	0	0	2	2	2	2	2	0	2	0	1	0	0	0	2	1	0	2	1	1	1	1	1	0	0	0	2	1	1	1	0	1	1	0	1	1	0	0
27 : 3.3.1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	2	0	1	1	0	0
28 : 3.3.2	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	1	0	2	0	0	1	1	1	2	0	1	1	0	0
29 : 3.3.3	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	1	0	0	1	3	3	3	2	2	1	2	0	0	0	1	0	1	1	0	1	1	0	0
30 : 3.3.4	2	2	0	0	1	1	3	0	1	0	2	0	1	3	2	0	2	3	0	3	2	1	1	1	1	1	1	2	3	0	0	1	0	1	2	0	2	1	0	1
31 : 3.4.1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	2	1	1	1	2	0	0
32 : 4.1.1	0	0	0	3	1	1	1	0	0	0	1	0	1	0	0	0	1	1	0	1	0	1	1	1	0	0	0	0	0	0	1	0	1	1	1	3	3	1	0	0
33 : 4.2.1	0	0	0	0	1	1	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	0	1	2	2	2
34 : 4.3.1	0	0	0	3	0	0	0	0	1	0	0	0	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	2	0	1	3	1	3
35 : 4.4.1	0	0	2	3	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	2	1	3	3
36 : 4.1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
37 : 4.1.3	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	1	0	0	0	0	0	0	0	1	1	1	1	3	0	1	0	0
38 : 4.2.2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	2	3
39 : 4.3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	0	0
40 : 4.4.2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	0	0

Fig. 5. Matrix impact cross-reference multiplication applied to a classification (MICMAC)

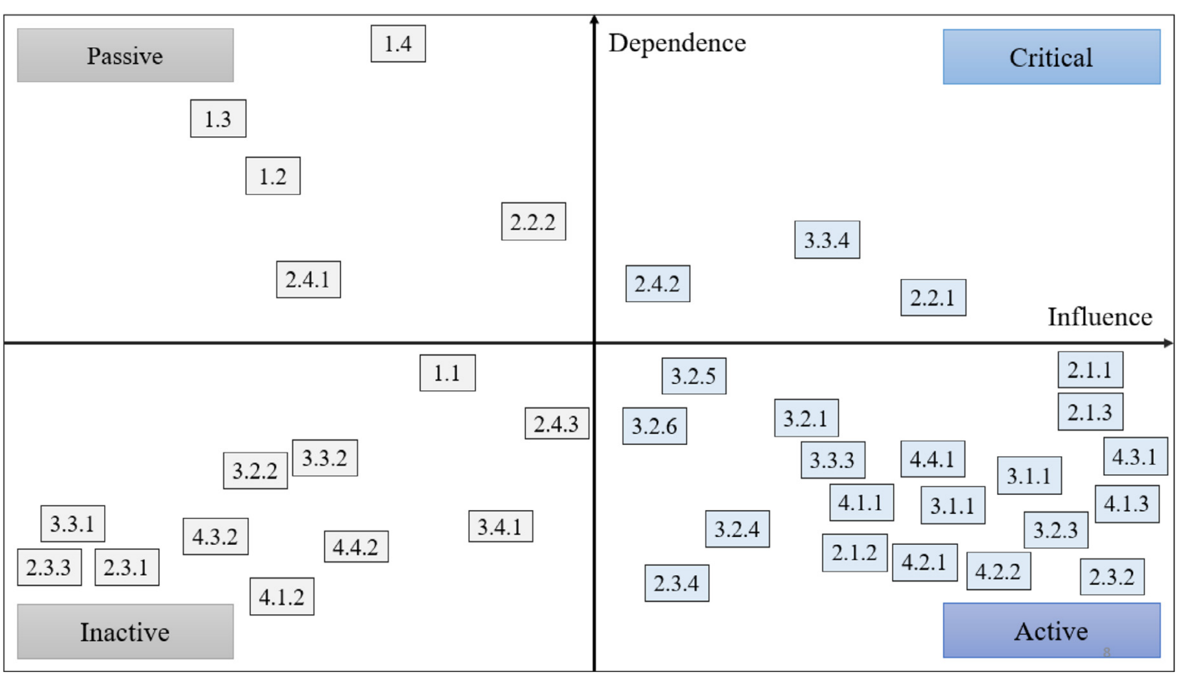


Fig. 6. Dependence-influence graph

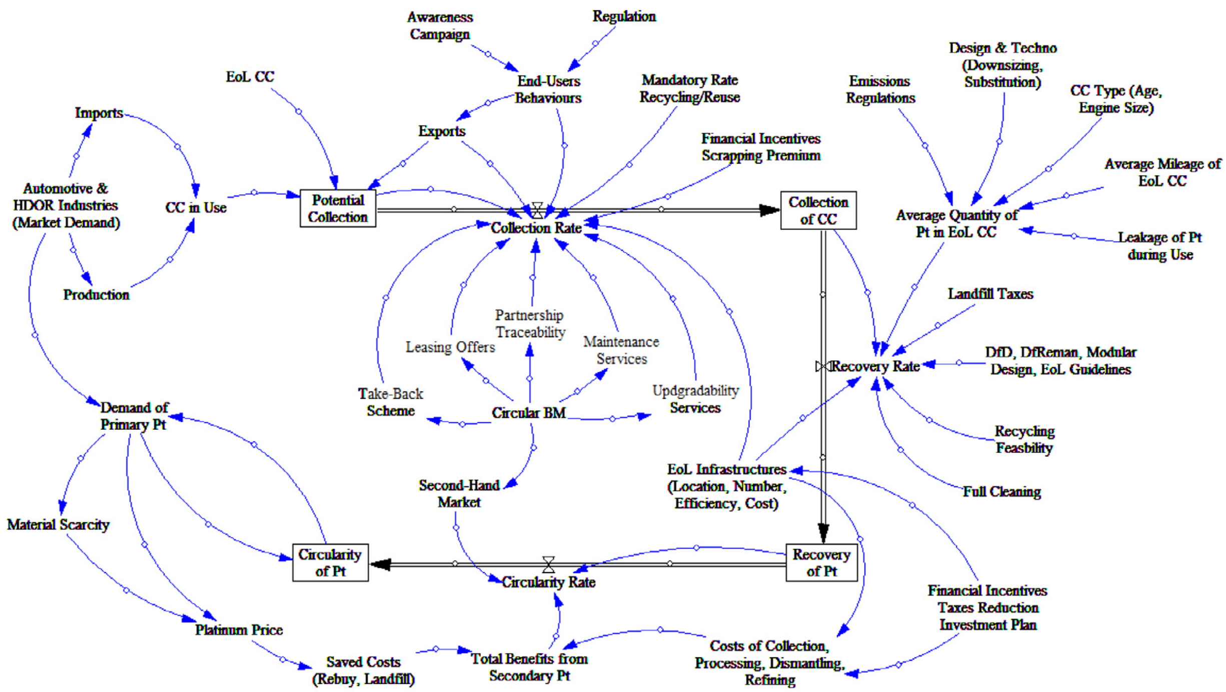


Figure 7. Overview of the system dynamics model

Fig. 7. Overview of the system dynamics model

Table 1
Characteristics of the MICMAC.

Indicator	Value
Matrix dimension	40
Number of iterations	4
Number of zero	958
Number of one	295
Number of two	217
Number of three	130
Total	642
Filling ratio	40.125%

the most important variables (i.e., active and/or critical), considered here as key variables. Note that after computing the matrix, this classification is performed automatically by the MICMAC software (freely downloadable here: http://en.laprospective.fr/methods-of-prospective/softwares/59-micmac.html), as illustrated in the “dependence-influence graph” of Fig. 6. In Table 1, the “Total” refers to the number of cells with a non-zero value, and the “Filling ratio” refers to their percentage to the full matrix (i.e., 642 divided by 40^2).

The least important variables include, for example: the average age or mileage of end-of-life vehicles in the EU, possible innovative design and/or technology such as downsizing of the catalytic converter, the evolution of emissions regulations, or an awareness campaign. The most important variables include, for example: regulations to limit the number of exports, mandatory recycling/reuse rate, end-of-life stock of catalytic converters in the EU, end-users behaviors, including constraints (regulatory) and motivations, or platinum price. These preliminary findings have been presented to an industry expert from a European original equipment manufacturer that designs and develops catalytic converters. According to him, the obtained classification makes sense, and he did not see any other important variables that would have been missed. The full list of variables, with their associated numbers, is available in Appendix B.

4.4. Scenarios generation and system dynamics simulations (perspective)

In the present study, deploying an SD simulation model appears to be particularly compatible and complementary to the MFA depicted in sub-section 4.1, as they both describe reality by means of stocks and flows (Inghels et al., 2016). In fact, the stocks (i.e., the levels) and the flows (i.e., the rates) that affect the MFA are also essential components of the system dynamics model. In this line, the quantitative results from the MFA model provide a relevant baseline to compare the evolution of stocks and flows through the simulation of scenarios in the system dynamics model. Fig. 7 provides a first overview of the complete system dynamics model, developed using Vensim software. In this Figure, the stocks are “level variables” that accumulate over time by inflows or depleted by outflows, and the flows are “rates” at which stocks change over time. Stocks are represented by boxes, flows by double-line arrows, and influence parameters or actions levers by simple-line arrows. The actual computation and simulation runs of this system dynamics model required more quantitative data, and is therefore left for future work, as further discussed in the Conclusions section.

5. Conclusions

The sustainable management of critical materials is of utmost importance for the European Union (European Commission, 2017). Scarcity of these key materials may indeed raise important environmental, economic, social, and geostrategic challenges for the European Union and for many industrial sectors. Circular economy represents a promising strategy for recovering these materials from second-hand or unwanted products and ensuring their stock availability. With this background, this paper proposed and tested a multi-tool methodology for systematically locating the importance of various parameters and the most relevant action levers for achieving circular management of these materials. The first steps of this multi-tool methodology have been illustrated and applied to one of the 27 critical raw materials inventoried by the European Commission (2017), namely, platinum. It has been found that the combination of material flow analysis, fuzzy-cognitive mapping, and structural analysis contributed here in classifying and selecting promising action levers to improve the circularity performance of platinum from catalytic converters.

These findings would help to build, fine-tune and validate an ad hoc system dynamics model to evaluate the impact of key action levers through more specific scenarios. Thus, it could support an original equipment manufacturer in the evaluation of potential CE strategies, through the simulation of selected action levers on the circularity and sustainability performance of their products and materials within a specific value chain, mapped and analyzed through material flow analysis. For instance, it could provide quantitative insights to the relevant prospective questions, such as, what if a take-back scheme is proposed to augment the collection rate by a given percentage, or what if the design is modified for easy disassembly. Concretely, an exciting line for future work would be to collaborate further, e.g., with a manufacturer of catalytic converters to feed the simulation model with industrial data, and thus, to assess the several circular economy strategies that this manufacturer might considerer to implement. In fact, more quantitative data, both from European statistics and catalytic converters manufacturers, are needed to run the system dynamics model and simulations, refined in accordance with the key action levers highlighted through the deployment of the present multi-tool methodology.

Note that while the developed multi-tool methodology has been tested and illustrated through the specific example of platinum from catalytic converters, it is designed to be applied and/or replicated to any relevant products and materials of interest. Though, a current limitation for its actual uptake by industrial practitioners may lie in the fact it requires to download and use different software, or work environment, even if we argue and have illustrated throughout the paper their relative user-friendliness.

Last but not least, the ultimate step would consist of comparing the new (simulated) circularity performance to the initial one mapped out in the first step – through material flow analysis and circularity indicators, as closing the material flow does not systematically guarantee environmental sustainability (Contreras-Lisperguer et al., 2020) – to ensure that an improvement in the circularity score would effectively lead to economic and environmental benefits. Indeed, it has been shown that augmenting the circularity performance of systems “does not necessarily result in favorable alternatives, as trade-offs may occur concerning environmental, economic, or social impacts” (de Oliveira et al., 2021), and adequate circularity indicators combined with life cycle assessment and life cycle costing could help understand the link between changes at the micro- and macro-level when transitioning to more circular systems, and the environmental and economic consequences (Harris et al., 2021).

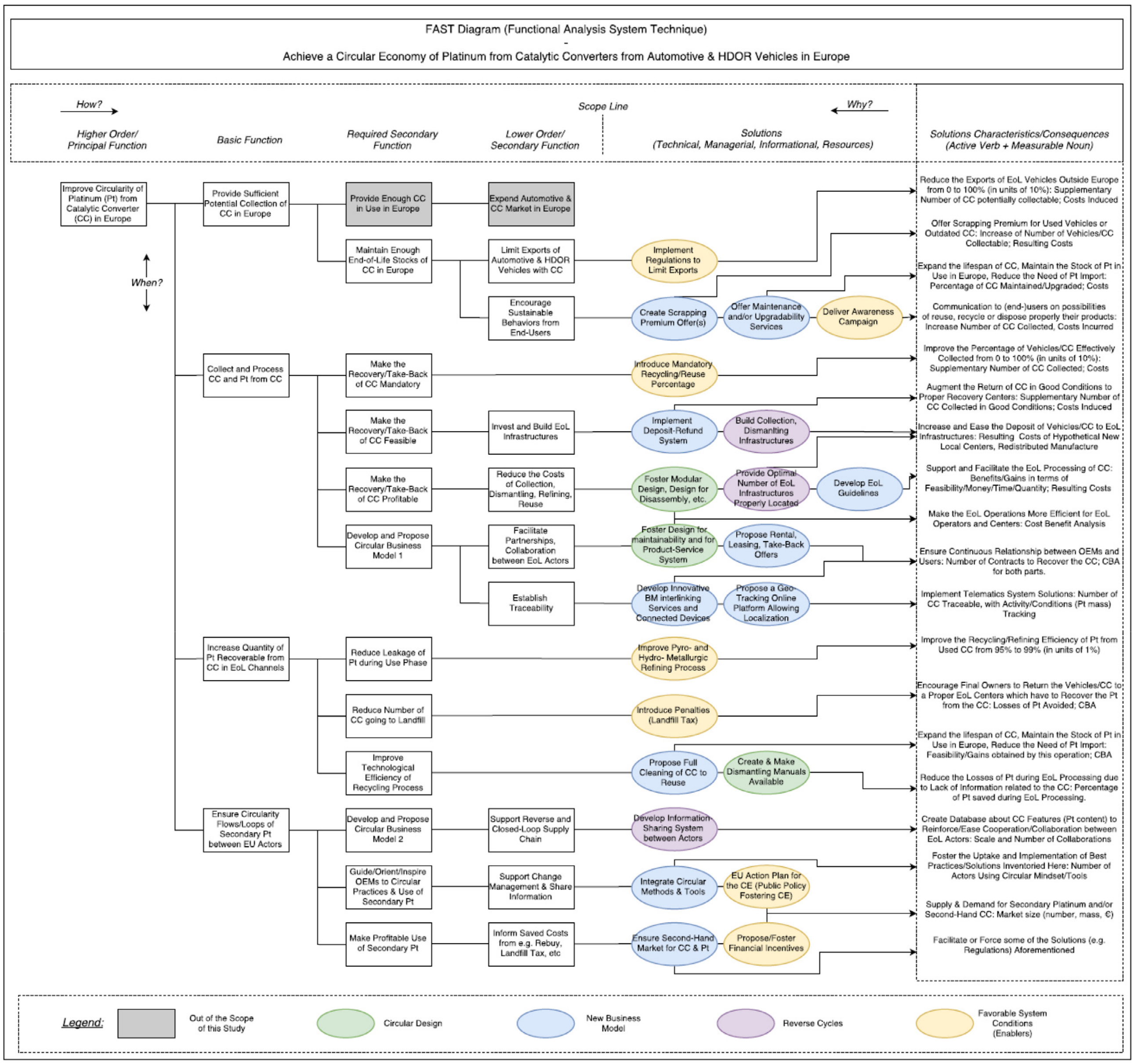
Declaration of Competing Interest

None.

Acknowledgements

This paper is partially based on the models initiated in the thesis manuscript of the first author (Saidani, 2018). They have been restructured and augmented to be presented at the Online Symposium on Circular Economy and Sustainability (INFER2020-Thrace), as well as to stand as a self-contained research article providing further methodological and practical insights to close the loop on products and materials in the light of the current transition towards a sustainable circular economy. Particular thanks are due to the organizers of the first edition of this Symposium on Circular Economy and Sustainability, to the Guest Editors of this special issue, and to the reviewers for their meaningful suggestions in improving the structure and scientific soundness of this research work.

Appendix A. Functional Analysis System Technique (FAST) diagram



Note that the action levers identified through the functional analysis system technique have been classified according to the four building blocks of circular economy defined by the Ellen MacArthur Foundation, namely: circular product design, new business model, reverse cycles, and favorable system conditions.

Appendix B. List of factors potentially influencing the circularity of platinum in catalytic converters

Categories	#	Name
Improvement areas	1.1	Potential collection of catalytic converters in the European Union (EU)
	1.2	Effective end-of-life collection and processing of catalytic converters in the EU
	1.3	Quantity of platinum recoverable in catalytic converters end-of-life streams in the EU
	1.4	Circularity of platinum from catalytic converters in the EU
Intermediate influence parameters	2.1.1	Automotive, plus heavy-duty and off-road vehicles exports with catalytic converters
	2.1.2	Catalytic converters in use in the EU
	2.1.3	End-of-life stock of catalytic converters in the EU
	2.2.1	End-users behaviours, including constraints (regulatory) and motivations
	2.2.2	Partnerships for better traceability
	2.3.1	Average age of end-of-life vehicles in the EU
	2.3.2	Average quantity of platinum coated in a catalytic converter
	2.3.3	Average mileage of end-of-life vehicles in the EU
	2.3.4	Leakage of platinum during use
	2.4.1	Costs of collection, dismantling, storage, and end-of-life treatment (refining)
	2.4.2	Value of secondary platinum
	2.4.3	Saved costs (e.g., from rebuy, or landfill tax)
Action levers – "What if?" variables	3.1.1	Regulations to limit the number of exports
	3.2.1	Financial incentives (e.g., scrapping premium)
	3.2.2	Awareness campaign
	3.2.3	Mandatory recycling/reuse rate
	3.2.4	Economic penalty (e.g., landfill tax)
	3.2.5a	Availability of maintenance and/or upgradability services
	3.2.5b	Deposit-refund (or take-back) scheme
	3.2.5c	Rental or leasing offers
	3.2.6a	Geo-tracking online (telematics) platform for localisation
	3.2.6b	Information-sharing system between users and end-of-life stakeholders
	3.3.1	Innovative design and/or technology (downsizing, substitution)
	3.3.2	Enhanced technological feasibility (recycling, refining process, full cleaning)
	3.3.3	Design for circularity (e.g., modular-design, easy-disassembly)
	3.3.4	End-of-life infrastructures (for collection, dismantling, processing, refining)
	3.4.1	Financial support for manufacturers and/or end-of-life actors (e.g., taxes reduction)
Drivers (tier 1)	4.1.1	Industrial (automotive industry) market demand for catalytic converters
	4.2.1	EU Action Plan for the circular economy
	4.3.1	Uncertainty around platinum price (volatility for original equipment manufacturers)
	4.4.1	Geostrategic issue for the EU (platinum dependency)
Drivers (tier 2)	4.1.2	Emissions regulations (e.g., on NOx, CO, particles)
	4.1.3	Sales in the new vehicles
	4.2.2	Environmental and economic costs of platinum extraction/production
	4.3.2	Strikes in platinum ore mines in South Africa
	4.4.2	Platinum ores depletion (i.e., decrease in concentration/content)

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