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EXPLORING THE DYNAMIC AND COMPLEX INTEGRATION OF SUSTAINABILITY PERFORMANCE MEASUREMENT INTO PRODUCT DEVELOPMENT

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1. Introduction

There is a need for a joint effort of several actors in society to addressing global sustainable development goals [United Nations 2015]. Corporate sustainability performance measurement plays an important role within this context, as it aims to manage businesses "holistically balancing economic, environmental, and social issues in the present generation and for future ones" [Lozano et al. 2015, p.430]. The multi-dimensional components of corporate sustainability encompasses: triple bottom line considerations [Elkington 1997]; integration of several (and many times conflicting) interests of firm's stakeholders [Epstein and Widener 2011], [Matos and Silvestre 2013], and different time frames (short, medium and long term)[WCED 1987]. Furthermore, sustainability initiatives can be implemented in the various business processes [Lozano 2012], such as supply chain management [Seuring and Müller 2008] and product development [Pigosso et al. 2013]. The capture of sustainability performance involves setting and managing specific indicators for different business processes.

Product development process (PDP) is a key business process to embed sustainability in - ca. 90% of the sustainability performance of a product is defined in the early stages of its product development [McAloone and Bey 2009]. Measuring performance in product development is a complex and difficult task in itself [Loch and Tapper 2002], [Costa et al. 2014]. If taken incorrectly or inefficiently, there is a risk to originate misleading measures and associations. This may, in turn, disseminate the wrong signal regarding the status of projects, programs and processes and therefore result in poor decision-making with negative results for the company [Costa et al. 2014].Furthermore, if sustainability is added in product development performance measurement, a complex and dynamic challenge arises. On one hand, sustainability is a multi-dimensional approach with interdependent social, environmental and economic goals, which many times are conflicting and mutating [Hahn et al. 2010]. On the other hand, measuring performance in product development process is a complex issue due to a set of five main challenges, namely the intangibility, lack of routine, uncertainty, organizational complexity of product development typical activities and information management [Tatikonda and Rosenthal 2000], [Tatikonda and Montoya-Weiss 2001], [Tatikonda 2007].

In order to address these highlighted challenges sustainability performance measurement in product development processes, it is important to characterize the dynamism or “dynamic complexity” of a system. The main characteristics of such dynamic systems are [Sterman 2001]: constantly changing and past-dependent (system’s current state is mainly characterized by changes in the variables over time, in which past directly influences future); tightly coupled and governed by feedback (strong interaction among variables with feedback loops, in which variables influence themselves); self-organizing (structural interactions in the system determine their behavior over time); adaptive (systems are usually change-resistant and adaptive to new policies); and non-linear (the effects are not usually proportional to the cause) [Sterman 2000], [Gonçalves 2008]. In performance measurement, one of the sources of dynamism is the organization's tendency to perform constant revisions of its indicators to secure relevance and suitability [Kennerley and Neely 2003], [Henri 2010]. Figure 1 summarizes the multi-dimensional characteristic of corporate sustainability coupled with the challenges in measuring performance of product development. In this sense, the consideration of sustainability measurement in PDP can be framed as a dynamic complex system.

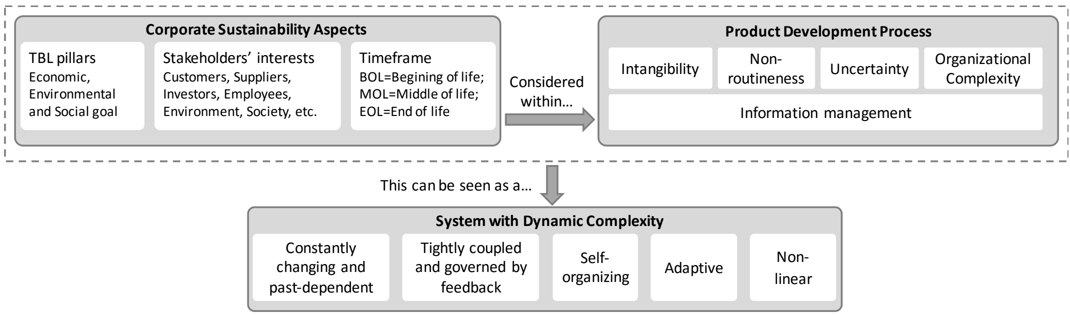

Figure 1. Overview of the theoretical background

In order to tackle this complex and dynamic nature of sustainability integration into product development, a systems-based approach that enables the understanding of the different elements in the system and how they relate to each other have the potential to bring valuable insights and contributions. System Dynamics (SD) [Forrester 1971] is increasingly seen as a promising approach for addressing complex and dynamic challenges. The SD-based modelling approach can be adopted to outlining the structure of systems and capturing the underlying behavior that drives processes. At later stages of the modelling process, it also allows quantification to be assigned to the relationships within an organization in order to launch the basis for simulating possible system behaviors over time [Bianchi et al. 2015]. One of the main advantages of using such approach is positioning the performance measurement process into the broader context of the system, tackling the fact that that apparently "simple" changes in processes and policies brings impact to outputs and outcomes that are not likely to be "simple" in a organizational context [Bianchi et al. 2008], [Hajiheydari and Zarei 2013].

One of the main underlying assumptions of SD is that the behavior of a system is the result of the structure of causal relationships, feedback and time delays. SD is well suited for studying complex systems where unknown attributes of system properties are usually unseen [Forrester 1961], [Sterman 2000], [Macinnis 2004]. Applications of SD span across different disciplines, such as project management [Lyneis and Ford 2007], product development [Rodrigues et al. 2006], [Ulrich and Eppinger 2008], large-scale development projects [Cooper 1980], [Sterman 2000], quality management [Ford and Sterman 1998], sustainability performance measurement [Parisi 2013], and knowledge management [Morecroft 2007]. This research aims to explore the use of a qualitative SD approach to discuss aspects of corporate sustainability in product development performance from a process-oriented and managerial perspective, as opposed to product-related and design-based view (see, for instance, [Choi et al. 2008] and [She and MacDonald 2013]). The research methodology is presented in the next section, being followed by the results discussion (Section 3) and final remarks (Section 4).

2. Research methodology

In order to explore the use of a qualitative SD approach in the context of PDP sustainability performance from a process perspective, we applied casual loops diagrams (CLD) as the main method of SD for conceptualization [Morecroft 2007]. CLD is a method for visualizing the interrelationships of the elements of a system through the use of directed arrows. The CLD plays a important role in finding and communicating the feedback structure of the system, which is core to SD [Sterman 2000], [Morecroft

2007]. It is also valuable to elicit and capture mental models within teams or in individuals. Experts have argued that SD-based analysis can be performed without building formal simulation models, relying on the insights and understanding provided by the CLD – this approach is usually referred to as the qualitative system dynamics [Wolstenholme 1985], [Lee et al. 2012]. The research methodology is composed of 2 main stages:

Stage 1: Literature analysis: focus on the main aspects of sustainability performance in a corporate context, the challenges in measuring product development performance from a process perspective, and the application of a qualitative system dynamics approach, mainly related to CLD building.

Stage 2: Case study, based on [Yin 2009], carried out with the main objectives of: (i) gathering empirical evidence on how the main aspects of sustainability are being addressed in a real product development process, along with (ii) eliciting the main performance indicators used within this context. The case study was composed of the following steps:

1. **Selection of case study:** large multinational manufacturer of vehicle parts and accessories, with technology development center and office in São Paulo, Brazil;
2. **Data collection:** based on (i) semi-structured interviews with Senior Manager of Innovation focused on understanding the company's product development process and what types of performance indicators were used, and (ii) secondary data, based on videos of recorded interviews, organizational documents and company's public communication material;
3. **Case study description:** overview based on a general description of the company;
4. **Data analysis**: development of causal loop diagrams (CLD), based on the data retrieved from the case study and following the best modeling practices suggested by [Sterman 2000].

3. Case study: results and discussions

The case study was conducted in an automotive parts manufacturer with worldwide operations. Research and Development (R&D) in the company is fundamental, counting with technological centers in different parts of the globe and with several strategic partnerships. The focus of our research is the R&D Department located in Brazil. In this department, project management processes are well structured, following the logic of stage-gates approach. In this sense, pre-established check-points for each project are verified, before its development reaches the next stage. This enables the company to conduct a structured portfolio management with clear status report for the projects.

3.1 Corporate sustainability performance indicators in company's PDP

During the interview, aspects of sustainability throughout the company's PDP were identified (Table 1, under the column "Applications in PDP"). Based on these aspects and supporting evidences, specific corporate sustainability performance indicators for PDP were derived, and they are shown in column "Elicited performance indicators". These indicators were obtained through analysis based on a combination of empirical data collected directly from the interviews with a senior management role and the company's documental analysis, which included recorded interviews, presentations and public communication material. Some of the indicators were directly asked and reported by the interviewee, while others emerged during open discussions carried out as part of the semi-structured interviews. The relationships (dynamic hypothesis) between the indicators (variables) were a result of the researchers' analysis of the totality of the data gathered (i.e. interviews and documents). The present section describes the aspects of sustainability in PDP, while the next section (3.2) discusses the sustainability indicators as the variables for the CLD.

Regarding the triple bottom line aspect of corporate sustainability, economic issues are mainly addressed by strategic alignment of portfolio management. One of the strategic drivers is to improve car efficiency and reduce greenhouse gases emission. Moreover, the company seeks to keep a balanced project portfolio, combining projects with clear market demand (approx. 80% of the projects) and internal projects for future capability development (remaining 20%). Environmental goals are included in the PDP with particular focus on products that are able to improve urban mobility, such as cleaner technologies for public transportation and increase electric cars autonomy. No evidence was found on direct inclusion of social goals in the PDP. This aspect tends to be addressed only by institutional project (such as with projects and fostering education and culture), rather than in product development projects.

Internal and external stakeholders are involved in the PDP process, seeking to combine capabilities to develop a specific product or technology. For example, the company conducts partnerships with capital goods suppliers for co-creation projects. One important factor to align different stakeholders' interests is to clearly define property rights of the knowledge generated by the project. By the end of the project, developed technology applied to the equipment belongs to supplier and to the product belongs to the studied company. Clients, who usually are vehicle assembly companies, are constantly involved in defining new projects and during the project development. This contributes to customer satisfaction and early validation of products in the development process. Internal partnerships are relevant, since project teams with participants from different areas of the company contribute to reduce costs and barriers during operations and production processes. The company also performs partnerships with independent inventors, other companies of the automotive industry, science & technology centers, and even competitors for the development of products and precompetitive technologies.

Corporate sustainability also has to do with considering the whole product lifecycle. During PDP of the studied company, implications on production process, operations and logistics are considered, enlarging the chances of product success during its beginning of life (BOL). Product's middle of life (MOL) serves as data input to improve product performance in the usage phase, while end of life (EOL) aspects are mainly focused on development of products that facilitate disassembly and recycling of vehicle parts. For example, the company developed an ecological filter, which enables to change only the outworn part of the filter and maintain the rest of the structure of this auto part. Another effort in this sense is the initiative to reduce welding when configuring the product, since it makes disassembly more difficult.

Table 1. Sustainability performance indicators in the company's PDP

Sustainability aspects		Applications in PDP	Elicited performance indicators
Triple bottom line goals	Economic	Strategic alignment and project portfolio management (risk management)	- Successful projects rate - Profit - Sales - Operational Costs - Investment in technology development - Technology development for vehicle efficiency
	Environmental	Improvement of urban mobility: cleaner technologies for public transportation, increase electric cars autonomy	- CO_2 emissions - Environmental burden - Cleaner technologies for urban transportation
	Social	(Not explicitly considered in PDP, but rather in institutional projects)	N/A
Stake-holders	Suppliers	Partnership with capital goods suppliers for co-creation projects	- Number of co-development partners
	Clients	Motor performance assessment/validation; close relation to identify needs	- Customer satisfaction - Amount of user data - Level of early client validation
	Internal partnerships	Project teams with participants from different areas of the firm contribute to less costs during operations and production processes.	- Level of internal integration - Degree of complementary competencies
	Individual inventors / other companies within the sector	Combined effort to develop technologies and products	- Breadth of consortia agreements - Number of co-development partners - Degree of complementary competencies

	Science & technology centers / Competitors	Consortium for development of precompetitive technologies	- Number of co-development partners - Degree of complementary competencies
Product life-cycle	BOL	Consideration of implications to production, operations & logistics.	- Number of Design for Recycling initiatives
	MOL	Activities in car maintenance provide data for future developments	- Number of spare parts for maintenance
	EOL	Legislation and social tendencies are pushing to the development of products that enable and facilitate recycling.	- Societal and legislative pressure - Number of Design for Recycling initiatives

3.2 CLD applied to sustainability performance indicators of company's PDP

A causal loop diagram comprises a set of variables connected by unidirectional arrows, representing the causal relation between them, which is the representation of the "dynamic hypothesis" conjectured for the systems. These relations are each one of the causal arrows have an assigned polarity, either positive or negative. If, for instance, variable X causes variable Y (X → Y), a positive (+) link means that "if X increases, Y will be always be higher than it would have been", while a negative (-) link means that "if X increases, Y will always be lower than it would have been" [Sterman 2000, p.141]. An alternative way of understanding them is by reading positive polarity as "X and Y move in the same direction" and negative polarity as "X and Y move in the opposite direction" [Sterman 2000, p.141].

The resulting CLD depicted from the case study's interviews is illustrated in Figure 2. Besides the polarity identification over the arrows, we have highlighted the main feedback loops in the CLD. The positive feedback loops are self-reinforcing and, therefore, denoted with the letter **R**. Complementarily, the negative feedback loops are balancing (self-correcting) and, therefore, denoted with the letter **B.** All negative feedback loops have goals, which represents the desired state of the system [Sterman 2000]. Both types of feedback loops are also represented with the loop orientation, either clockwise or counter-clockwise.

The variables considered in the CLD are the sustainability performance indicators, which are used to guide company's decisions during PDP. It is worth noting that, in the present context, performance indicators are not used as synonym for metrics and measures. This is because the variables in the CLD do not necessarily relate strictly to one quantitative form composed by a whole number and its measurement unit. Rather, we use performance indicators in a broader sense to represent a more multifaceted variable. In this case, measurement of a performance indicator usually demands more than one metric [Keong Choong 2013]. The ultimate indicator of the product development is the rate of successful projects within the organization. Therefore, this very variable is highlighted in the central part of the diagram. The CLD is better understood and interpreted in terms of its main feedback loops:

- **R1 ("The external partner's loop"):** it represents the contribution of the level of external partnerships as a way to complement competencies within the R&D organization towards more technically-savvy projects. The company has reported that the more successful projects they have, the more competent partners are attracted for co-development efforts, enabling the exploration of different competencies. This reinforcing loop is also boosted by higher levels of early client validation, internal sectors integration and the breadth of the co-development consortia that are defined, which all equip the company with more customer-centric insights and tools;
- **R2 ("Knowing your end user loop"):** one of the fastest and more reliable ways the company has found to constantly retrieve end user information is through their maintenance operations, as it provides them with customer use habits and patterns as well as important information on the product's performance in the market. This high amount of data is fed back to the process development and ultimately supports the conduction of more successful projects based on reliable information. Additionally, the more efficiency gains are rendered to their own technology, the more satisfied their immediate customer will be;

- **R3 ("The technology re-investment loop")**; this loop represents, in a high level of aggregation, the company's re-investment policy. It is worth noting that this feedback loop is closely related to R1 through the indicator "level of internal integration". In the diagram, this variable is duplicated in angled brackets, which is usually referred to as a "shadow variable" and used to build cleaner diagram representations. From the company's perspective, the higher the internal integral they achieve, the lower operational hurdles they face. This dynamic setting will be directly reflected in a lower operation cost, which leads to higher profits and a more robust re-investment policy in technology development:

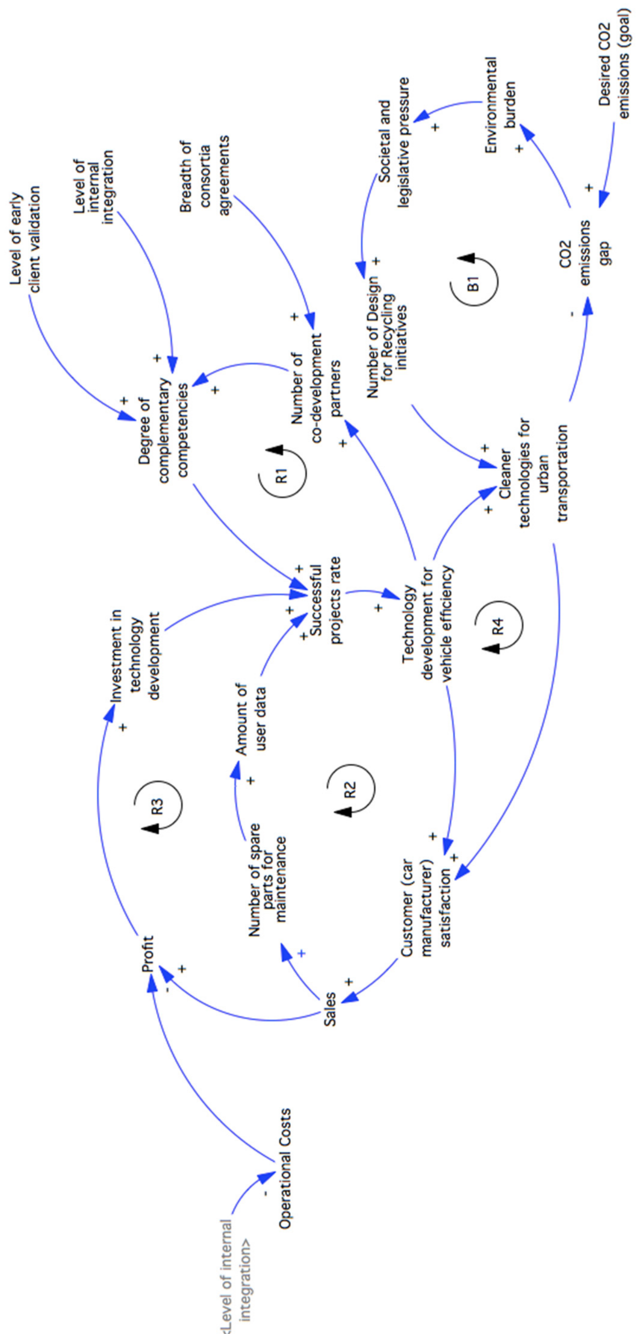

Figure 2. The resulting causal loop diagram (CLD) for the case study company

- **R4 ("The urban transportation loop"):** the development projects carried out by the company have a direct impact on the vehicle industry, which in turn is part of the larger urban transportation sector. The company has identified that providing this sector with cleaner technologies embedded into the vehicles is a source of their ultimate customer's satisfaction, upward in the value chain;
- **B1 ("The green urban mobility loop"):** the only balancing loop that was identified is related to the ultimate impact of the use of cleaner technologies in urban transportation, namely the development of "greener cities". On one hand, the more efficiency-based cleaner technologies are available for urban transportation, the less CO2 will be emitted in the use phase of the transportation, leading to a diminished emission gap and consequent environmental burden, as the desired state of the system is set by a CO2 emissions goal. On the other hand, the heavier the negative loads on the environment, the stricter the legislation tend to become, along with a more organized and compelling pressure from societal movements and organisms. This heavier pressure and demand leads the path for innovation in a number of DfX initiatives, mainly within the realms of Design for Recycling and Design for Disassembly.

In order to better visualize and interpret the CLD and its feedback loops, Table 2 presents the loops in terms of their constituent variables.

Table 2. The variables in each one of the identified feedback loops

Loop	Variables in the loop
R1 - "The external partner's loop"	Successful projects rate – Technology development for vehicle efficiency – Number of co-development partners – Degree of complementary competencies - Successful projects rate
R2 - "Knowing your end user loop"	Successful projects rate - Technology development for vehicle efficiency – Customer (car manufacturer) satisfaction – Sales – Number of spare parts for maintenance – Amount of user data - Successful projects rate
R3 - "The technology re-investment loop"	Successful projects rate - Technology development for vehicle efficiency – Customer (car manufacturer) satisfaction – Sales – Profit – Investment in technology development - Successful projects rate
R4 – "The urban transportation loop"	Successful projects rate - Technology development for vehicle efficiency – Cleaner technologies for urban transportation – Customer (car manufacturer) satisfaction – Sales – Profit – Investment in technology development - Successful projects rate
B1 – "The green urban mobility loop"	Cleaner technologies for urban transportation – CO2 emissions gap – Environmental burden – Societal and legislative pressure – Number of Design for Recycling initiatives - Cleaner technologies for urban transportation

This preliminary and exploratory case study might indicate that a CLD-based approach could address some of the challenges in measuring PDP performance discussed above because it is a tool capable of extracting sets of tacit knowledge, believes and values of individuals and teams, which is usually materialized in the SD literature as mental models. However, it also presents various limitations as a modelling tool. Both advantages and limitations of CLDs derived from the case study are summarized in Table 3.

Table 3. CLD advantages and limitations

Main challenges of measuring PDP performance	CLD advantages	CLD limitations
Intangibility	- Stimulates the depiction of the system's structure in terms of measurable variables and derive the relationships among them	- Does not offer direct support in defining the most suitable metric that would correctly represent variables - Does not allow direct quantification

	- Evidence the potential improvement opportunities and focus areas	
Non-routineness	- Draws a more precise line between routine and non-routine aspects of product development with a view to address better (and more efficient) treatment to routinely-generated tasks	- Needs constant revisions of the variables and relationships for each project and/or new situation (such in situations as discussed in [Henri 2010]) - Does not guarantee that the particularities and details are fully captured
Uncertainty	- Identifies the cause-and-effect relations in order to drive risk management initiatives - Reduce ambiguity in the relations between actions and results (such as discussed in [Parisi 2013])	- Does not consider probabilistic distributions - Does not capture system's behavior over time (future dynamics)
Organizational complexity	- Stimulates the identification of main roles and action's consequences for project and company's partners (both internal and external)	- Does not capture the company's structure and processes explicitly - Becomes harder to represent large systems, in a classic trade-off between the level of aggregation and the possible insights gained from the diagram
Information system	- Points out the main types of data required to effectively and efficiently manage business processes	- Does not capture the company's structure and processes for information technology (IT)

Furthermore, the CLD was capable of showing practices that could be enhanced within the company in order to produce more successful projects, such as drawing attention to stronger and broader consortium-based partnerships for co-development, which is something that hasn't been fully exploited yet.

4. Final remarks

This paper presented the results of an exploratory empirical study in the context of sustainability performance measurement in PDP. The main objective was to exploree the use of a qualitative SD approach, namely CLD modelling, in such context. A literature analysis was followed by an industrial case study in the R&D department of a multinational manufacturer of vehicle parts and accessories. The paper leads to an indication of both advantages and limitations of using CLD to address the challenges of measuring performance in PDP. The main advantages are related to the simple yet powerful way CLD represents cause-and-effect relations and stimulate product development and project managers to think in terms of the results of a set of actions that are not linearly arranged, but rather encompassed in a set of different and overlapping informational feedback loop. By means of it, it is possible to depict the ingrained mental models that are built around the variables being considered in product development performance, as well as identifying the roles of multiple stakeholders. Despite the social sustainability aspect is not explicitly explored in the diagram, CLDs are suitable for representing and discussing sustainability-related subjects, as it is capable of capturing the multi-dimensional characteristics that usually emerge. Additionally, the main limitations are based on the fact that the CLD is only a conceptual diagram that does not provide any support for neither identifying metrics nor explicitly representing a company's structure and processes, both from a business as well as a technical perspective. Additionally, the CLD is a tool that can easily explode in complexity, resulting in an intricate and confusing map, which does not provide insights or becomes too hard to read and interpret. Therefore, there is a clear trade-off between the amount of information being captured and represented in the diagram and the quality and extent of insights and analysis one expect to derive from such a diagram. It is important to note that many of the mentioned limitations of the CLD can be overcome by a thorough SD modelling approach that includes the simulation phase, in which the actual system behavior's change over time can be understood and further analyzed, as well as coupling CLD with other techniques and tools for process and information modelling. The sole use of causal loop diagrams is not enough to actually gain a deep and insightful understanding of the system's emergent behavior over time.

It is worth noting that the CLD presented in this paper is a first approximation of what the dynamic hypothesis (i.e. cause-and-effect relations) from a process-related perspective and derived from the case study interview would look like. The CLD is not originally intended to be a specific tool tailored for designers to use – it is rather a way for product development managers and project managers to representing and eliciting the potential sustainability indicators for product development processes and how they can be linked and grouped together around informational loops. The overall modelling procedure goes beyond the first representation of the CLD and constitutes an iterative activity aimed at refining the dynamic hypothesis and generating insights on the variables' relationships and informational feedback loops that are derived. Therefore, one of the major limitations of this study is based on the few iterations the researchers had with the practitioners in order to refine the relations in the CLD. Some other limitations include (i) the lack of wider and comprehensive identification of the so-called "rebound effects", generated by the shifts in the end-user behavior in the urban mobility context, and (ii) the high level of aggregation of some variables (e.g. 'societal and legislative pressure'), which can eventually be translated into lower-level variables that are able to capture specificities and details about the indicator that is being related. It should be noted that there is an intrinsic challenge in quantifying variables in any typical SD-based engagement, due to the qualitative nature of some variables (e.g. "customer satisfaction" or "social and legislative pressure"), the lack of available data and need for developing tailor-made scales.

The main contribution of the paper is the presentation of a preliminary SD-based approach for overcoming some of the challenges of measuring sustainability performance in PDP and supporting the identification of improvement areas, when it comes to incorporating sustainability into PDP measurement. By doing so, the research invites future research to (i) further understand and represent the rebound effects in an end-user and value chain context, (ii) perform a full SD modelling and simulation approach by quantifying, simulating and validating the conceptual model and (iii) apply SD-based approaches to measure sustainability in other business processes and industrial sectors.

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