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Business cases for ecodesign implementation: a simulation-based framework

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ABSTRACT

The lack of quantitative mechanisms aimed at evaluating the potential business benefits of ecodesign prior to implementation is a major barrier to wider adoption in manufacturing companies. Ecodesign is defined as the consistent integration of environmental aspects into product development processes. Within this frame, there is a need to understand how the development of ecodesign capabilities affect overall business performance over time. Drawing upon the Ecodesign Maturity Model (EcoM2) as the theoretical foundation, this paper systematically reviews the literature on (i) relevant applications of dynamic modelling and (ii) relationships between ecodesign management practices and key business performance outcomes, in order to develop a simulation-based approach aimed at deriving a business case framework for ecodesign implementation. The resulting framework originates the "business case simulator", which was subjected to the judgement and evaluation of six industry experts regarding its applicability and usefulness to manufacturing settings. The results are discussed and future research streams – coupled with improvement opportunities to the business case simulator – are pointed.

1. Introduction

Despite the significant growth in the number of researchers and corporations reporting the benefits of ecodesign-related efforts (Haned et al., 2015; IRRC Institute, 2015; Plouffe et al., 2011), a number of challenges still hinder a broader and consistent implementation of ecodesign in manufacturing firms. There is a particular lack of proper mechanisms to evaluate the potential business benefits originated by ecodesign (Boks, 2006; Dekoninck et al., 2016; McAloone, 1998; Rodrigues et al., 2017a, 2016b), which can be defined as a proactive approach for the integration of environmental aspects and considerations into the product development processes (Pigosso et al., 2013, 2015). With that, the concept of "business case" emerges as the set of arguments that support and elicits the key reasons why an organization should implement or advance a specific cause (Carroll and Shabana, 2010; Rodrigues et al., 2018a,b; Schaltegger and Lüdeke-Freund, 2012; Weber, 2008; Whelan and Fink, 2016). In general, most business cases typically account for *a posteriori* analysis of the influences of ecodesign-related practices, as opposed to *a priori, predictive* business cases, which focuses on how to collect information and measure the overall and strategic performance of a company in financial (e.g. profitability, revenues, costs, return on investment etc.) and non-financial terms (e.g. water usage, material usage, energy usage, CO_2 emissions, water footprint etc.).

The integration of ecodesign aspects into product development is considered a complex task, which means that the it typically has high interconnectedness and trade-off among key variables over time, such as cost, potential revenue, profitability, risk or environmental/social performance, among many others (Costa et al., 2014; Rodrigues et al., 2016a; Tatikonda, 2007). As a very simple example, the selection of material influences the product's environmental performance as well as its cost and applicability over time which, in turn, feeds back into the material decision as a set of criteria. Therefore, this is a problem that displays dynamic complexity, which arises from the interactions of several agents and relationships over time (Sterman, 2000). Some fundamental characteristics of systems with dynamic complexity are: *constantly changing and past-dependent*; *tightly coupled and governed by feedback* (i.e. strong interaction among variables with feedback loops); *self-organizing* (the system's structure drives its behavior over time); *adaptive* (i.e. resistance to change and adaptation to newly introduced policies)

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and *non-linear* (i.e. effects are not typically proportional to the cause) (Repenning and Sterman, 2001; Sterman, 2001, 2000). With the objective of addressing systems displaying such dynamic complexity, the System Dynamics method was proposed as an application of control theory to socio-technical complex systems, supported by computational modelling and simulation, and targeted at analyzing complex and dynamic behavior (Forrester, 1971; Lee et al., 2012; Liao et al., 2015; Sterman, 2001). System Dynamics is both a modelling and a simulation technique that has been widely applied to examine, understand and intervene in complex systems in a large range of disciplines and contexts (de Salles et al., 2016; Forrester, 1961; Lee et al., 2012; Rabelo et al., 2005; Sterman, 2015, 2000). Within this context, ecodesign implementation can be viewed and understood as a complex system itself. As such, the fundamental structure of ecodesign implementation (e.g. practices, resources etc.) can be modelled, and its behavior (e.g. performance metrics over time) can be analyzed through the use of a System Dynamics approach.

A maturity-based management framework for ecodesign implementation and management, namely the Ecodesign Maturity Model (EcoM2) (Pigosso et al., 2013; Pigosso and McAloone, 2016; Pigosso and Rozenfeld, 2011) is used as the theoretical background for this work. The EcoM2 focuses on process improvement from a managerial perspective, rather than on product's improvement solely from a technical standpoint. As such, the EcoM2 has been designed and improved towards assisting the systematic integration of ecodesign aspects, aiming at deploying improvement projects targeted at the product development processes (Pigosso et al., 2013). The EcoM2 offers a systematized selection of ecodesign management practices related to the integration of environmental issues into the strategic and tactical levels of the product development process.

From a process-oriented perspective, each one of the ecodesign management practices in the EcoM2 can be assessed in terms of the systematization level they have within product development. In other words, it is important to understand how systematized the ecodesign practice is in order to be able to move towards a more systematized implementation of ecodesign in the company (Pigosso et al., 2013). Examples of ecodesign management practices include (Pigosso and Rozenfeld, 2012; Pigosso, 2012; Rodrigues et al., 2018a,b, 2017a): **(i)**"*assess technological and market trends related to the environmental performance of products*" and **(ii)** "*establish cooperation programs and joint goals with suppliers and partners aiming to improve the environmental performance of products*".

This paper draws upon the particular concept of capability of ecodesign management practices with the main objective of understanding how ecodesign-related capability building might theoretically influence a range of corporate performance outcomes over time (i.e. revenue, market value, expenses, resource efficiency etc.). Capability levels can be understood as a qualitative measure of how systematic a company applies a certain ecodesign management practice, in the context of the EcoM2 (Pigosso et al., 2013). Regarding the capability measurement within the EcoM2, the model defines a 5-point scale, based on the CMMI (Capability Maturity Model Integration) (Chrissis et al., 2011; Pigosso et al., 2013).

The 5 capability levels are (Pigosso et al., 2013; Rodrigues et al., 2018a,b): level 1 (*incomplete*) means that a practice is not considered at all or is applied in an incomplete way; level 2 (*ad hoc*) defines a practice as only being applied to accomplish very specific tasks or correct certain issues, in a non-systematic way; level 3 (*formalized*) is reached when the practice is fully documented and accompanied by an account of its resources, infrastructure and responsibilities; level 4 (*controlled*) brings the ecodesign management practice to a controlled/monitored space, meaning that performance is measured and monitored; level 5 (*improved*) means that the ecodesign management practice has its performance continuously and systematically improved over time. The EcoM2 also prescribes an application method (Pigosso et al., 2013). Within this method, it becomes important to highlight the positioning of the business case within the process of implementing ecodesign. Fig. 1 displays a schematic representation of the application method, along with the roles of the business case.

The first phase has 3 application steps: **1)** the diagnosis of the current maturity profile, whose main output is the current capability levels of the management practices; **2)** the definition of a vision for improved maturity, according to the company's strategy and drivers, and whose main output is the desired capability levels for the management practices; and **3)** the deployment of actionable roadmaps of improvement projects, based on the gap between current capability levels (Step 1) and desired, future capability

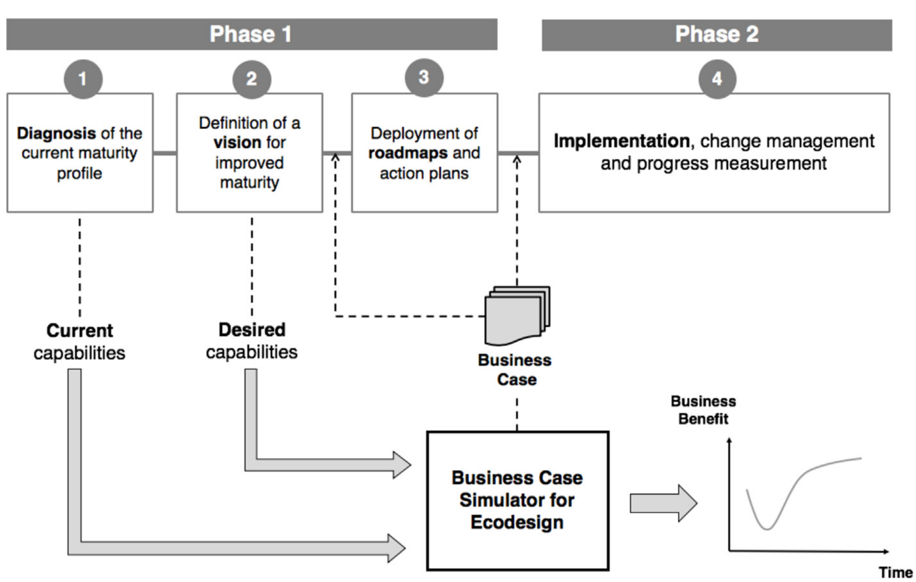

Fig. 1. EcoM2 application method and the positioning of the business case (Rodrigues et al., 2017b)).

levels (Step 2). The second phase entails project implementation, outlined in the roadmaps, together with efforts in change management and performance measurement. The business case plays a very important role in two moments for: **(i)** testing how different desired capability levels would potentially behave, this being a support to deriving the roadmap and (**ii**) connecting the deployment of structured roadmaps with actual, consistent implementation – in other words, bridging the gap between Phase 1 and Phase 2 of the EcoM2 application method. As highlighted before, the business case framework therefore makes use of the current and desired capability levels to simulate the expected behavior of selected corporate performance outcomes, under specific circumstances and assumptions.

Within this context, this paper seeks to answer the following research question: *how does the development of ecodesign capabilities affect corporate performance over time?* This paper proposes an exploratory simulation-based framework with the objective of assisting the development of a business case for ecodesign implementation within manufacturing firms. The fundamental rational for targeting at manufacturing firms is based on their product- and process-oriented perspectives, as opposed to pure services. The business case framework is further tested in three case studies, by six industry experts. The results of this study are intended to be used by key managers and decision-makers across the organization in their daily attributions related to both gathering information on business cases for ecodesign as well as presenting them to senior leadership.

This paper is particularly innovative as it builds a predictive business case framework for business case from a process perspective, as opposed to both the product-centric view and the *posteriori* stances of a typical development of business cases. It differs predominantly from previous studies in the field of ecodesign when it encompasses a simulation method, based on System Dynamics, that gives rise to a practical tool that can be readily implemented and improved by organizations at large in order to derive their own business case rationale for ecodesign, based on their very own processes.

2. Research methodology

With a view to building a simulation-based business case framework for ecodesign implementation, the research methodology employed in this paper is comprised of five phases, which are depicted in Fig. 2, along with their main results. These phases are further explained in this section.

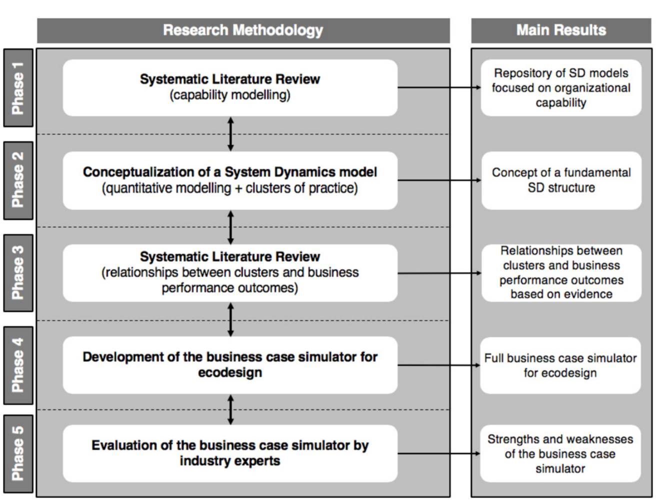

Fig. 2. Research approach of the paper, with main results.

2.1. Phase 1: systematic literature review on capability modelling within a process-oriented context

Phase 1 focused on learning what the literature of System Dynamics proposed in terms of how to approach the modelling of capability within a process-oriented context. The systematic literature review was based on the procedures proposed by (Biolchini et al., 2005), which builds upon three sub-steps: (1) planning of the review process; (2) execution of the systematic literature review and (3) analysis of the results. The sub-steps are detailed as follows. For the review planning, three fields were identified as relevant - namely organizational capability (OC), product development (PD) and project management (PM) - due to their complementarities and proximity as research fields. In particular, the field of project management was included in the systematic literature review because it has been traditionally very well connected to cases and applications in the product development space in the literature of System Dynamics (Ford and Sterman, 1998; Lyneis and Ford, 2007). The review protocol was tailored to support three independent searchers within each one of the fields, based on three groups of keywords. For the field of *organizational capability*, the wildcard "capabilit*" was combined with the keyword "system dynamics". For *product development* field, six synonyms and other related terms were combined with the "system dynamics" keyword ("product development", "engineering design", "concurrent engineering", "eco-design", "ecodesign" and "design for environment"). Finally, for the field of *project management*, the "project management" keyword was combined directly with "system dynamics".

The selected database for performing the searches was Web of Science due to its relevance to the fields of System Dynamics and its rigor in the selection of publications to be covered by the database (Adriaanse and Rensleigh, 2013; Gavel and Iselid, 2008). Only journal papers in English were searched. Dates of publication have not been restricted in the literature searches. Two inclusion criteria were defined for the papers to meet: (1) propose, report or review at least one System Dynamics formulation for capability modelling and (2) focus on an organizational context or application, and not on topics of public policy, or macroeconomic modelling. Based on the two proposed criteria, the papers were then examined by reading the: (a) title, (b) abstract and keywords, (c) schematic figures and representations, introduction and conclusion and finally (d) reading the full paper. As for the review execution, once the papers were selected, the information on the System Dynamics application was extracted and catalogued in a paper repository and classified according to the field of application (OC, PD or PM). Supplementary information and other comments on relevant aspects of the paper were also recorded in order to support content analysis. A repository of selected papers was finally consolidated and systematized on Mendeley Version 1.19.4, a reference manager software, for easy access and analysis.

Subsequently, a content analysis was performed in order to identify the key elements and the emerging patterns in the papers selected in Step 1 (Bashor, 2003; Starks, 2007). These elements and patterns were composed of System Dynamics formulations, conceptualizations or any other modelling strategies that were relevant to the dynamic modelling effort in this research. In particular, the content analysis aimed at identifying System Dynamics structures that could be potentially useful for depicting and modelling the development of ecodesign capabilities and their links to corporate performance, within the context of the EcoM2.

2.2. Phase 2: conceptualization of the system dynamics model

Subsequently, Phase 2 concentrated on conceptualizing a System Dynamics model based on formulations derived from the literature as well as reorganizing the set of ecodesign management practices in order to achieve a more suitable level of aggregation for modelling, with few variables being simultaneously considered by decision-makers while manipulating the model. A System Dynamics modelling approach was derived, following the System Dynamics methodological procedure, which is based on: the conceptualization of the problem, the formulation of variables, relationships and parameters, the evaluation of the model's behavior and the analysis of potential policies and model's use (Lee et al., 2012; Luna-Reyes and Andersen, 2003; Sterman, 2000). The System Dynamics modelling procedure produces a stock and flow diagram as the basis of the simulation model, with the objective of describing the accumulations (stocks) and rates of increase/decrease (flow) of key variables in the system (Dangelico et al., 2010; Liao et al., 2015; Sterman, 2000). The System Dynamics model was built using the software package Stella Architect version 1.4.1, developed by *isee systems*.

It is important to note that the EcoM2 covers 51 ecodesign management practices. One of the main challenges based on this modelling approach is to represent the full set of ecodesign management practices due to the large number of practices and their heterogeneity across the product development process. Since the main objective of the business case is to bridge the gap between ecodesign implementation roadmaps and their actual implementation, corporate decision-makers might not necessarily make judgments and assessments at the granular level of the individual practice. The implementation roadmaps are composed of packaged projects geared towards improving the capability of ecodesign management practices across the organization. If practices were considered individually, this would amount to a total of, at least, 51 variables to be factored and considered when designing a business case. This would be intractable in practice due to the large number of different variables being handled and considered at the same time. Therefore, it was important to aggregate practices according to thematic clusters as a way to reduce complexity in developing and manipulating the business case.

In particular, the clusters of practices are mostly important to support corporate decision-makers in quickly identifying the practices by their theme. Besides allowing decision-makers to better connect the ecodesign practices to their own company's structure and processes, the clustered representation of practices also supports a more straightforward manipulation and development of the business cases. For this, an inductive thematic analysis (Braun and Clarke, 2006; Eisenhardt and Graebner, 2007) was employed towards analyzing themes/patterns within the body of 51 ecodesign management practices of the EcoM2. This methodological procedure is further detailed in (Rodrigues et al., 2018a,b), whose derived clusters are used in this paper. The 51 ecodesign management practices were structured in 11 thematic clusters of ecodesign management practices. The management practices in a cluster are sufficiently homogeneous, while being heterogeneous across all the clusters. Table 1 exhibits the clusters of practices derived from the thematic analysis, together with examples of practices in the cluster (Rodrigues et al., 2018a,b).

2.3. Phase 3: systematic literature review on the relationships between clusters and business performance outcomes

To further develop the business case framework and cover all defined clusters of practice, the relationships between the clusters and the potential business performance outcomes needed to be systematically established. The logic model approach and the consolidated database of business performance outcomes proposed in (Rodrigues et al., 2018a,b) were used in this paper. The logic model represents a logical sequence of events triggered by an initiative/intervention in terms of bringing change to an organization's current state (Goldman and Schmalz, 2006; Rodrigues et al., 2018a,b; Seidman, 2017; W.K. Kellogg Foundation, 2004). The logic model structure may vary according to the application context and data available, and in this paper the clusters of ecodesign management practices are conceptualized as activities that will potentially exert influence on business performance outcomes, which are the long-term results or impacts a business may face (e.g. revenue, expenses, market value etc.). Therefore, a systematic literature review was designed with the objective of collecting evidence about the potential relationships between the clusters and the performance outcomes.

First of all, the business performance outcomes with at least 10 mentions (recurrence) were selected from the consolidated database of business performance outcomes (Rodrigues et al., 2018a,b). The selected outcomes were: (1) profitability (35 mentions); (2) market value (30 mentions); (3) employee welfare (30 mentions); (4) liquidity (21 mentions); (5) revenue (17 mentions); (6) expenses (17 mentions); (7) emissions (13 mentions); (8) operational

Table 1
Clusters of ecodesign management practices, with examples, adapted from (Rodrigues et al., 2018a,b).

Cluster	Thematic cluster (Rodrigues et al., 2018a,b)	Number of practices in the cluster	Example of ecodesign management practice in the cluster (retrieved from (Pigosso et al., 2013; Pigosso, 2012; Rodrigues et al., 2018a,b, 2017a))
1	Environmentally-enhanced technological strategy	5 practices	*Assess technological and market trends related to the environmental performance of products*
2	Development of support processes, training and knowledge for ecodesign	4 practices	*Develop the technical support processes (e.g. maintenance, change of spare parts, etc.) aiming to improve the environmental performance of the product over its entire life cycle*
3	Incentives and awareness for ecodesign	2 practices	*Increase consciousness and awareness about the opportunities and benefits of the integration of environmental issues into product development*
4	Marketing and communication for ecodesign	2 practices	*Communicate the environmental performance and benefits as part of the total value proposition of the product, exploring the green marketing opportunities*
5	End-of-life strategies, packaging and operations	5 practices	*Select and/or develop new manufacturing and processes with improved environmental performance*
6	Strategic management of ecodesign implementation	9 practices	*Develop business, product and market strategies considering the environmental trends*
7	Portfolio management and environmental trends	4 practices	*Strategically consider the product environmental performance in the company portfolio management*
8	Product development management	11 practices	*Implement Life Cycle Thinking*
9	Value chain management	3 practices	*Consider the environmental aspects in the identification, qualification and management of suppliers*
10	Regulatory compliance	2 practices	*Formulate mandatory rules and/or product requirements*
11	Program management and ecodesign benchmarking	4 practices	*Conduct management reviews to evaluate the effectiveness of the integration of environmental issues into product development and related processes*

effectiveness (11 mentions); (9) resource efficiency (10 mentions); (10) customer satisfaction (10 mentions). Based on these 10 selected business performance outcomes and the 11 clusters of ecodesign management practice, a protocol for the systematic literature was developed.

The same methodological procedure adopted in Phase 1 (Biolchini et al., 2005) was used. For the review planning, three sets of keywords were combined: **(i)** keywords from each one of the 11 clusters (“tech* strategy”, “support processes”, “employee training”, “employee knowledge”, “incentives”, “awareness”, “marketing”, “end of life”, “packaging”, “end-of-life”, “strategic management”, “portfolio management”, “product development management”, “value chain management”, “regulatory compliance”, “program management” and “benchmark*”); **(ii)** keywords related to the business performance outcomes (“profitability”, “market value”, “employee welfare”, “liquidity”, “sales”, “revenue”, “expense”, “cost”, “emissions”, “operational effectiveness”, “resource efficiency” and “customer satisfaction”) and **(iii)** keywords related to the overarching topic (“product development”, “ecodesign”, “eco-design”, “eco-efficiency", “concurrent engineering”, “product/service-systems", “eco-innovation" and “corporat*”).

Due to their relevance, coverage (Adriaanse and Rensleigh, 2013; Gavel and Iselid, 2008) and comprehensiveness, both Scopus and Web of Science were selected as databases for this review, since considering the two databases would bring more coverage of potential business performance outcomes and their relationships with the ecodesign management practices. Only journal papers in English were selected. Dates of publication have not been restricted in the literature searches. Two inclusion criteria were defined: (1) report of evidence – either theoretical or empirical – regarding the relationships between the theme of the cluster (e.g. “regulatory compliance”) and a business performance outcome (e.g. “expenses”) and (2) focus on an organizational context or application. Once a paper was selected, its content was inspected with a view to identifying and classifying the evidence of the relationship between clusters and business performance outcome. A scheme based on procedure suggested by Züst and Troxler (2006) for the classification of effects between two elements was followed. The authors proposed and use a classification matrix based on 3 levels of relationship intensity: value 1 means that the influence is “below average”, while value 2 means “on average” and value 3 means “above average” (Züst and Troxler, 2006). For this particular research, the evidence presented by the papers were also classified in 3 levels: **value 1**, if only theoretical claims or hypothesis were developed about the relationships cluster-outcome; **value 2** was assigned when limited empirical evidence was presented (e.g. a case study or a review/analysis of other case studies) and **value 3** was assigned only for papers presenting empirical evidence with high levels of generalization (e.g. comprehensive surveys, data-rich quantitative models, meta-analysis etc.). Fig. 3 shows the generic structure of the relationship matrix. Based on these relationships and the System Dynamics conceptualization, the business case simulator could be developed.

2.4. Phase 4: development of the business case simulator for ecodesign

The clusters of practice formed the building blocks of the business case simulator, against which the conceptual System Dynamics structure developed under Phase 2 was applied. Because the entire research was driven by understanding how the development of ecodesign capabilities would potentially affect corporate performance, two inputs were required for the business case simulator: the current capability level and the desired capability level for each one of the 11 clusters of practice. Given that the clusters are aggregations of practices, the cluster's current capability was calculated with the *mode*. The mode is a statistical concept that refers to the value with the highest number of occurrences in a given set. In the case where more than one capability level had the same number of occurrences, the lowest capability level was chosen to represent the current capability level of the cluster. As an example, take a hypothetical case where a ecodesign cluster has six practices. Three of these practices were evaluated at capability level 2 and the other three practices were evaluated capability level 1. In this case, the current capability level of this particular cluster would then be at level 1 (lowest capability level).

The fundamental System Dynamics structure developed under Phase 2 was expanded and adapted to cover all clusters of ecodesign management practices, following System Dynamics best practices for quantitative modelling (Schwaninger and Groesser, 2016; Sterman, 2000). Furthermore, the evidence-based relationships found under Phase 3 informed the quantification of the relationships in the System Dynamics model. The business case simulator for ecodesign was also built on Stella Architect version

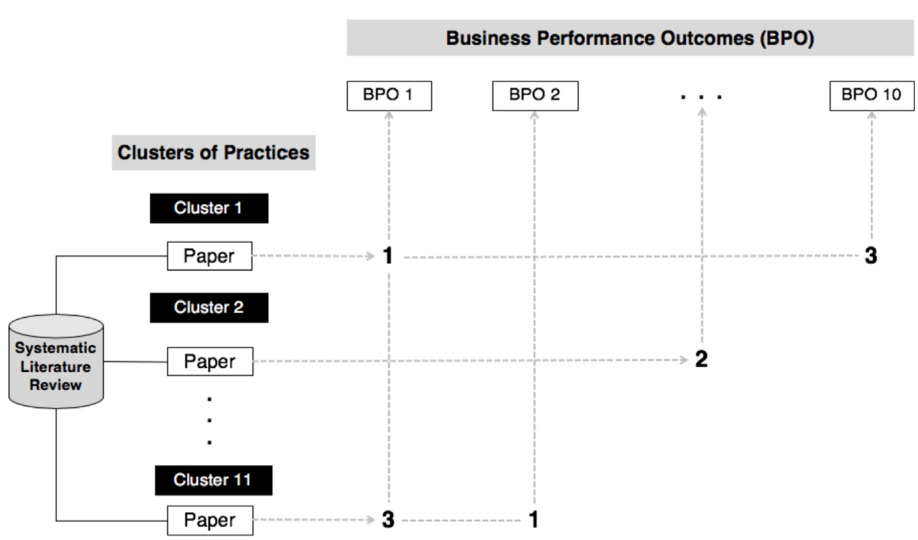

Fig. 3. Generic structure of the relationship matrix (clusters of practice x business performance outcomes) based on evidence retrieved from the papers selected in the systematic literature review.

1.4.1 using the features of Model Interface. After finished, the business case simulator was made available through *isee Exchange*, which is an online repository to build, manage and publish System Dynamics based models built on Stella. With this, the business case simulator was freely available via a URL link and ready to be evaluated by industry experts.

2.5. Phase 5: evaluation of the business case simulator by industry experts

The evaluation of the business case simulator was performed in three case studies by six industry experts, in a workshop-based setting, in line with approaches adopted in the literature (Issa et al., 2015; Pigosso et al., 2013; Rodrigues et al., 2018a,b). Three manufacturing companies from different sectors (refrigeration compressors, cosmetics and aeronautics) were selected based on their previous experience in the application of the EcoM2 framework. All experts involved in this evaluation procedure were familiar with the EcoM2 and its application method. Six experts from three companies (herein referred as Company A, Company B and Company C) participated in the workshop-based evaluation sessions. Three workshops were individually performed with each one of three companies at their own headquarters.

Company A is a multinational manufacturer of cosmetics, beauty products and personal hygiene items. It is widely recognized in the market as an eco-friendly and sustainable company, which strives for implementing and promoting sustainability-oriented practices. Company B is multinational aerospace manufactured focused on commercial, military, agricultural and executive aircrafts and related services. The company is very active in global sustainability-oriented discussion platforms and groups in the aviation sector, being one of the leaders championing the transition from a reactive stance to a more design-oriented and proactive embedding of sustainability intro products and services. Company C is multinational manufacturer of compressors for air conditioning and refrigeration products. The company has been steadily allocating efforts into building a global agenda for ecodesign within the organization and its value chain. Despite the efforts are still locally concentrated in few plants and operating sites, the company has been successful in getting the commitment and attention of high-level executives in order to derive a plan for streamlining ecodesign in their entire product portfolio in the next decade. Table 2 exhibits a summary of the roles of the experts.

The main rationale for emphasizing the experts' familiarity with the EcoM2 relates to the fact that knowledge and experience with core components and the application method of the EcoM2 allow them to better judge the usefulness and applicability of the business case in their own businesses, under the auspices of the EcoM2. Furthermore, experts who are already familiar with the framework tend to be better equipped with real and consistent information of how the application of the EcoM2 took place at their companies. However, it does not mean that the proposed approach is only suitable for companies that have tried or applied the EcoM2 framework before. Since this is an initial evaluation of the framework, companies with background knowledge of EcoM2 application would potentially provide thorough evaluations over the constrained time frame of this research project.

The workshops were performed at the companies and started with the experts being presented with an introduction to the project, the fundamentals of a business case, a short description of the EcoM2, an introduction to the eleven thematic clusters of practice and the business performance outcomes (i.e. business benefits) used in the business case and, finally, instructions on how to use the business case simulator. Then, experts were presented to the online version of the business case simulator, which was reached via an URL link and can be fully accessed via http://www.ecodesign.dtu.dk/process-performance. After potential questions on how to use the tool were cleared, experts were invited to use the simulator and manipulate it as they wished. Afterwards, experts could choose whether they would use the results of their real diagnosis or not. When the current capabilities for the clusters were inputted into the simulator, a visioning exercise was facilitated in order to derive potential visions of desired capability levels for each one of the 11 clusters. The visioning exercise was supported by the experts' own knowledge about the company's strategy regarding ecodesign and other sustainability-related topics. With this, a definition of the desired capability level for each one of the clusters was reached.

Experts could then experiment with the business case simulator by asking themselves “what-if” questions and changing the assumptions regarding both the current and the desired capability levels. Then, the experts started to design different future scenarios and check the implications displayed by the simulator. Finally, an online evaluation questionnaire – based on the questionnaire developed by (Issa et al., 2015; Pigosso, 2012) – was presented to the experts. The questionnaire evaluated each one of the nine dimensions of the business case simulator based on one multiple-choice questions and one open question, totaling 18 questions (nine multiple-choice questions and nine open-ended questions). The dimensions were: **1)** utility (i.e. “selling” ecodesign internally); **2)** consistency (i.e. the results generated by the tool are consistent across different ranges of inputs and assumptions); **3)** completeness (i.e. the extent to which important aspects of ecodesign are covered by the simulator); **4)** applicability (i.e. the extent to which the simulator is readily applicable for deriving business cases within the context of the company); **5)** simplicity (i.e. how easy was it to operate the simulator itself); **6)** clarity (i.e. how easy was to understand how use it); **7)** objectivity (i.e. the simulator represents reality without

Table 2
Summary of the roles of the industry experts involved in the evaluation of the business case simulator.

Company	Industry	Roles of the experts
A	Cosmetics, beauty products and personal hygiene items	• **Innovation Analyst and Researcher**, with 6 years of practical and academic experience in ecodesign and environmental management
B	Aerospace (commercial, military, agricultural and executive aircrafts and related services)	• **Head of Design for Environment**, with more than 20 years of practical experience in ecodesign, both from a technical and managerial perspectives; • **Product Development Manager**, with over 8 years of practical and academic experience in integrated product development, product stewardship and circular economy;
C	Compressors for air conditioning and refrigeration products	• **Marketing Director**, with over 20 years of experience in marketing, innovation management and ecodesign implementation; • **Project Management Officer**, with more than 12 years of practical and academic experience in product development and ecodesign implementation; • **Lean Manufacturing Manager**, with over 10 years of experience in quality and environmental management, continuous improvement and ecodesign management.

any major biases), **8)** data required (i.e. current and desired capability levels for the clusters) and **9)** the clusters of practice (i.e. in terms of how they were defined). The scale for the multiple-choice questions was composed of the following levels: "very satisfactory", "satisfactory", "need improvement" and "unsatisfactory". An open field for comments, suggestions and/or questions was available for each one of the questions, however a response was not mandatory. Finally, one final open-ended question invited participants to write about their general comments and impressions of the business case simulator. The full questionnaire can be accessed via the link https://goo.gl/forms/689yTKQcaXQvzbI73.

3. Results and discussion

3.1. Results and discussion from phase 1: systematic literature review on capability modelling within a process-oriented context

The performance of the systematic literature review resulted in three independent searches, based on the three topics: organization capability, product development processes and project management. In total, 492 papers were evaluated according to the inclusion criteria, specified under Section 2.1. Table 3 displays the summary of the results from the systematic literature review on System Dynamics related approaches in the three different fields.

Although the search in the fields of *organizational capability* was expected to provide the largest number of selected papers - due to its relevance to the core topic of the modelling efforts - it turned out to be the second lowest yield in relation to the total number of papers (2,02%), just after the field of *project management*, which had no papers selected (0%). One of the main reasons for such a low yield for *organizational capability* has to do with the fact that the majority of dismissed papers were related to qualitative discussions around the topic of organizational capability, supported by a "systems thinking" lens, therefore neither providing a suggestion of System Dynamics structure nor a modelling strategy. Besides, as capability itself has become a very broad a widely used term, several papers were dismissed because they were treating capability with a completely different definition or from an unusual point of view. However, the selected papers from the searches in this field proved to be among the most relevant ones in terms of providing substantial contributions towards building a System Dynamics model for capability development, because they were explicitly modelling organizational capability and defining the model parameters and boundaries around this core concept.

As for the searches in the fields of product development processes, the majority of the papers developed models or analysis at a lower level of aggregation (e.g. design tasks, time allocation, team structure etc.). Several studies in this field focus on product launches and market conditions of newly launched products, with many papers emphasizing the marketing lifecycle of products and how to plan accordingly. The large amount of studies focusing on this issues might be connected with a traditional application of System Dynamics models based on the classic Bass Diffusion Model (Bass, 1969; Cui et al., 2011), which explains the dynamics of innovation diffusion using a rigorous mathematical formulation with a view to managing product launches and its lifetime in the market. The early adaptations and modelling efforts for the Bass Diffusion Model might have triggered a widespread consolidation of models looking into the product development phenomenon from the standpoint of marketing and market lifecycle. Furthermore, most of the System Dynamics applications in product development were not explicitly modelling the concept of capability. Bearing a lot of overlaps and similarities with the literature from the product development field, the search in the field of *project management* has not provided any relevant paper, based on the set of criteria defined under Section 2.1.

Similarly, the proposed models in this literature stream were more granular (e.g. tasks, backlog, costs, resource allocation etc.) and were not treating the concept of capability explicitly in the models. Nevertheless, the literature on project management was particularly helpful to understand how to structure project-specific models, whose main objective is to solve particular management challenges relative to the project's scope, quality, time or cost — an aspect that could be further embedded in a business case framework. In a broader sense, this particular field has not informed our modelling efforts towards building a generic approach for capability development in ecodesign. Therefore, it is possible to assert that relevant literature on System Dynamics applications to the modelling of capability in organizations is scarce and highly concentrated on few researchers and research groups, particularly at the System Dynamics Group in the Sloan School of Management at the Massachusetts Institute of Technology (Rahmandad, 2015, 2012; Rahmandad et al., 2016; Rahmandad and Repenning, 2016; Repenning, 2003, 2001). Table 4 provides a summary and overview of selected papers (7 from the OC literature; 3 from the PDP literature) that were utilized as theoretical basis for the modelling efforts described later in this paper.

3.2. Results and discussion from phase 2: conceptualization of the system dynamics model

3.2.1. Ecodesign capability as a stock-and-flow structure

In the proposed business case framework, the clusters of ecodesign management practices are treated and modelled as having their own capability level, which is calculated as the mode of the cluster's individual practices. In the field of strategy, the resource-based view of the firm builds upon the concept that organizations are "bundles" of capabilities and resources (Rahmandad, 2015). The resources can be composed of tangible assets (e.g. human resources, machinery, capital etc.) or intangible assets (e.g. intellectual property, reputation etc.), while capabilities can be understood as organizational routines through which organizations perform several tasks in order to produce products and services (Rahmandad, 2015; Winter 2000). Capabilities, in turn, can be distinguished between operational and dynamic capabilities (Winter 2003). While operational capabilities allow the firm to perform short-term activities (e.g. production, sales, customer care etc.) and survive, the dynamic capabilities are connected to higher-

Table 3
Number of papers analyzed in the systematic literature review per field.

SLR Evaluation Steps	Organizational Capability	Product Development Processes	Project Management	Total per step
Total number of papers	346	66	80	492
Abstract and keywords	231	45	38	334
Schematic figures, introduction and conclusion	188	37	10	255
Selected papers (% of total number of papers)	***7 (2,02%)***	***3 (4,54%)***	***0 (0%)***	***10 (2,03%)***

Table 4
- Summary of the main contributions of selected papers from the SLR.

Field/Search	Reference	Type of contribution		Main contribution to the modelling effort
		Specific	*Generic*	
Organizational Capability	Rahmandad et al. (2016)	X		*Stock and flow formulation of organizational capability*
	Rahmandad and Repenning (2016)	X		*Theoretical considerations on capability erosion*
	Rahmandad (2015)	X	X	*Discussion on capability definitions (general) and typology, and stock and flow formulation (specific)*
	Morrison (2012)		X	*Further development on the concept of capability traps*
	Rahmandad (2012)	X		*Stock and flow formulation of organizational capability*
	Repenning and Sterman (2002)		X	
	Repenning and Sterman (2001)		X	*Conceptualization and formulation of the capability traps*
Product Development Processes	Repenning (2003)		X	*Application of System Dynamics to a socio-technical context*
	Repenning (2001)		X	*Concept of "firefighting" in product development*
	Ford and Sterman (1998)		X	*Overview of dynamic modelling applied to PD processes*

order routines that firms use to extend their competences and change other capabilities (Felin and Powell, 2016; Pisano, 2017; Rahmandad, 2015; Teece, 2007; Teece et al., 1997). In the EcoM2, the capability levels are defined as a measure of how systematic a company applied an particular ecodesign management practice (Chrissis et al., 2011; Pigosso et al., 2013).

Aligned with the formulations in the literature (Rahmandad, 2012; Rahmandad et al., 2016), ecodesign capability is then conceptualized as a stock variable, which changes according to two main mechanisms (represented as flows): capability growth and capability erosion. Since capabilities cannot be directly acquired (Dierickx et al., 1989), managers can only influence its rate of change over time, as opposed to influencing its stock level directly. Fig. 4 displays the generic structure of a stock and flow diagram to represent the capability of ecodesign management practices (Rodrigues et al., 2017b).

The capability stocks are initialized with the cluster's *current capability (CC)*, which is the result of diagnosis step in the EcoM2. The goal of managers is to then reach the cluster's *desired capability (DC)*, which comes from the visioning step of the EcoM2. The capability investment rate is then based on a *"stock management structure"* formulation (Sterman, 2000), which has an inflow (capability investment) adjusting to a goal (*desired capability*) and also taking into consideration the expected outflow (*capability erosion - CE*). Therefore, the capability, *C*, is constantly changing as a function of the processes of capability investment, *CI*, and capability erosion, *CE*, and is given by:

$$\frac{dC}{dt} = CI - CE \quad (1)$$

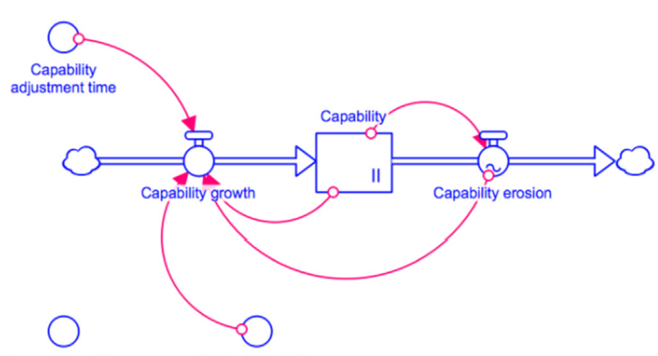

Fig. 4. Generic stock and flow structure for cluster's capability.

$$CI = \text{SMTH(CE, Averaging Time)} + \frac{(\text{DC} - \text{C})}{CAT} \quad (2)$$

Equation (1) describes the variation of the capability stock over time. Equation (2) gives the formulation for the inflow. Since the instantaneous rate cannot be measured, the expected outflow (CE) is usually formulated by averaging the past outflows (exponential smoothing) (Sterman, 2000), together with the gap between capability level and the desired capability being adjusted in terms of the capability adjustment time (*CAT*). This exogenous adjustment time (parameter) can be understood as the average time required to close the gap (Sterman, 2000). In other words, it can be seen, from an implementation point of view, as the time for improvements in ecodesign capability to be perceived and materialized by the company - representing the time needed to adjust for the desired capability level for a particular practice. This parameter could be set by the manager in order to reflect the particular context of a company, but as a default in the business case simulator, the capability adjustment time was set at 24 months, representing the average time taken between two implementation cycles of the EcoM2.

Additionally, the erosion mechanisms are grounded in the concept of "organizational forgetting", with turnover and insufficient organizational memory as the main elements driving the erosion of capability (Rahmandad and Repenning, 2016). The capability erosion flow is based on a graphic function (also known as table function), in which the erosion decreases when the capability increases, as a result of the increased level of systematization, documentation and routineness reached at higher capability levels (Pigosso et al., 2013), therefore $CE = f(C)$. The highest erosion rate is reached between capability levels 1 and 2, and then decreases as the capability level increases from level 2 onwards. This function shape is preferred over a hump-shaped curve (i.e. with capability erosion increasing for capability levels from 1 to 2 and then decreasing afterwards), because a hump-shaped curve is ambiguous in terms of the influence of capability on capability erosion, as it indicates the presence of multiple causal pathways between the capability level and rate of capability erosion (Sterman, 2000).

3.2.2. Linking capability to corporate performance

Corporate performance is formulated as a Cobb-Douglas function of the capability, in line with the literature on organizational capability (Rahmandad, 2012; Rahmandad et al., 2016; Repenning and Henderson, 2010; Sterman, 2000). This is a very well-known production function formulation in the fields of economics and econometrics, which maps out the relationships between a set of inputs and a specific output (see, for instance (Cobb and Gouglas, 1928),). In its most standard form, the Cobb-Douglas function represents an output Y (e.g. production) as a function of two inputs L and K (e.g. labor and capital):

$$Y = AL^{\alpha}K^{\beta} \tag{3}$$

In Equation (3), α and β are the *output elasticities* relative to each one of the inputs, L and K, respectively, and A is a productivity factor. This means that a 1% increase in L will lead to an approximately α% increase in the output, if everything else is held equal. Similarly, a 1% increase in K will lead to an approximately β% increase, *ceteris paribus*. If , then the function displays constant returns to scale. If , returns to scale are decreasing and, if , returns to scale are increasing. More generally, the Cobb-Douglas function can be written as follows for N inputs:

$$Y = f(x) = A\prod_{i=1}^{N} x_i^{\lambda_i} \ , \ x = (x_1, \ldots, x_N) \tag{4}$$

Instantiating the Cobb-Douglas function for an example in our formulation for the development of ecodesign capabilities, with only two cluster capabilities, say C_1 and C_2, contributing to the company's performance (e.g. revenue, R), it would take the form:

$$R = AC_1^{\alpha}C_2^{\beta} \ , \ \ with \ \ \alpha > 0 \ and \ \beta > 0 \tag{5}$$

Since ecodesign capabilities are typically expected to exhibit *increasing returns to scale* - i.e. the higher the capability level, the higher its contribution to performance, as reported by literature (Pigosso et al., 2013) - parameters α and β can be normally defined such as $\alpha + \beta > 1$. For instance, setting , hypothetically, we assume that for each 1% increment in the capability 1 (C_1), revenue will be incremented by 0.8%, whereas a 1% increase in the capability 2 (C_2), revenue will increase by 0.6%.

A generic System Dynamics representation of such model is presented on Fig. 5. The model represents a generic set of two ecodesign practices linked - through the Cobb-Douglas function - to a corporate performance indicator, namely revenue. Each one of the cluster's capabilities (and) can have its own parameters, such as the capability adjustment time and the capability erosion curve. Moreover, each one of the capabilities has its own current level (resulting from the EcoM2 diagnosis), which is the initialization of the stock of capability, and the desired level (resulting from the visioning exercise of the EcoM2).

3.3. Results and discussion from phase 3: systematic literature review on the relationships between clusters and business performance outcomes

The systematic literature review resulted in a total number of 833 papers: 456 were unique results retrieved from Scopus, 252 were unique results retrieved from Web of Science, and 125 papers were indexed in both databases. With the application of the inclusion criteria, 498 papers had their abstracts and keywords analyzed (59,7%), 125 papers were analyzed in terms of their schematic figures, introduction and conclusion (15,0%), whereas 85 papers were fully read and selected to be part of the repository. Then, each one of the selected papers were rigorously analyzed based on the type and consistency of the evidence provided in order to support the relationships between a specific cluster and a business performance outcome, using the value provided in the Research Methodology section. Although all 85 papers were individually evaluated for evidence - with an individual value assigned for each paper - the mode was calculated to represent the final value for cluster-outcome relationship, as a way to capture the intensity of that particular relationship, instead of just counting the number of papers displaying evidence on the relationship. Table 5 displays the final value (mode) for each pair cluster-outcome. The total is taken as a sum, instead of the mode, with the objective of understanding which clusters are the most influential and which outcomes are the most influenced by the clusters of practice. The sum provides a more detailed account of the "intensity" of such relationships.

It is important to highlight that no evidence was found regarding potential relationships between *liquidity* and the clusters of practice. This does not necessarily mean that it is a weak relationship, but rather that this particular relationships has not been explored in the sources surveyed in this systematic literature review. Therefore, only 9 outcomes are represented in Table 3. Of the 99 possible relationships (11 clusters x 9 outcomes), 30 of them were valued as 1, while 21 were assigned with value 2, 14 with value 3 and, finally, 34 relationships had no value assigned due to the lack of evidence from the literature. The most influential cluster, measured by the sum of the modes of its relationships, is cluster 6 - *strategic management of ecodesign implementation* (16 points), followed by cluster 4 - *marketing and communication for ecodesign* (14 points) and finally cluster 5 - *end-of-life strategies, packaging and operations*, cluster 8 - *product development management* and cluster 9 – *value chain management* (all three with 12 points). Cluster 6 is formed by a series of practices with very high-level aims, which are potentially deployed to several areas and functional areas of the company and its value chain. Therefore, it was expected that this

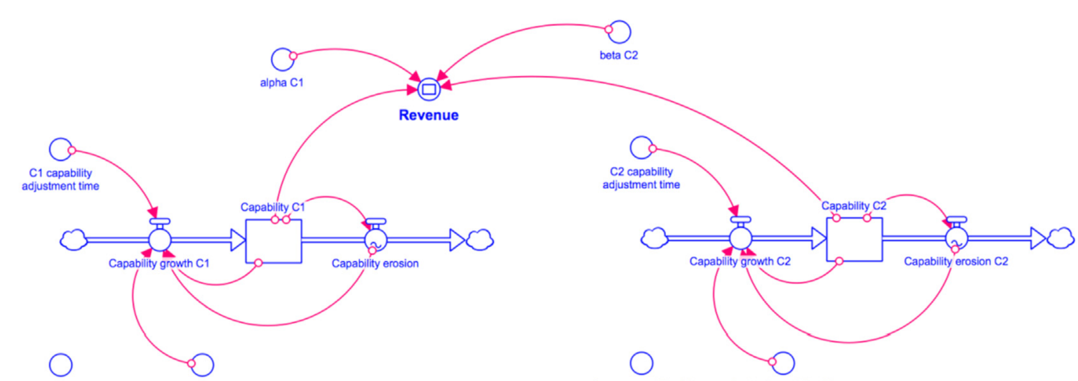

Fig. 5. Simplified and generic System Dynamics model for a business case with two generic practices and one performance outcome (e.g. revenue).

Table 5
Final value for the relationship of each pair cluster-outcome (mode).

Clusters	Business Performance Outcomes (BPO)									
	Profit	Market Value	Employee Welfare	Revenue	Expenses	Emissions	Operational Effectiveness	Resource Efficiency	Customer Satisfaction	TOTAL
1. Environmentally-enhanced technological strategy	1	2	–	2	1	–	–	3	–	**9**
2.Development of support processes, training and knowledge for ecodesign	–	–	2	3	1	–	2	–	1	**9**
3.Incentives and awareness for ecodesign	1	1	1	2	1	1	1	–	2	**10**
4.Marketing and communication for ecodesign	3	2	–	3	3	–	1	–	2	**14**
5.End-of-life strategies, packaging and operations	1	2	–	–	2	2	2	1	2	**12**
6.Strategic management of ecodesign implementation	1	3	–	3	1	–	3	3	2	**16**
7.Portfolio management and environmental trends	–	3	–	–	3	–	2	–	–	**8**
8.Product development management	1	1	–	2	1	2	1	1	3	**12**
9.Value chain management	1	1	–	2	2	–	2	1	3	**12**
10.Regulatory compliance	1	1	–	–	1	3	1	1	–	**8**
11.Program management and ecodesign benchmarking	–	–	–	2	–	–	–	1	1	**4**
TOTAL	**10**	**16**	**3**	**19**	**16**	**8**	**15**	**11**	**16**	**114**

cluster would be among the most influential, mainly due to its high potential impact. The next most influential one, cluster 4, touched the topic of marketing and external communication, for which a relatively high number of studies backed by evidence exist.

In particular, marketing and communication activities can exert a large influence in the financial outcomes, such as profit and revenue, since it can be used a mechanism for promoting a company's products, services, systems or even practices. Cluster 8 bundles the practices that are directly related to the management of the product development (e.g. stage-gate management, performance measurement etc.) and are therefore relatively overarching and influential. Lastly, cluster 5 and 9 are related to practices overseeing the relationships with the supply chain and its operations. These kind of practices tend to be influential as they might create value through multiple channels and points across the value chain.

From an outcome perspective, the most influent ones are: revenue (19 points), market value, expenses and customer satisfaction, all three with 16 points. Employee welfare was the least influenced outcome due to the lack of studies reporting evidence on this relationship. On the other hand, the overwhelming majority of the studies report on financial outcomes, as opposed to environmental or social-oriented ones (e.g. emissions or employee welfare). However, several efforts are being directed to integrated reporting (The International Integrated Reporting Council (IIRC), 2013) which, simply put, is geared towards reporting on both financial and non-financial measures in an integrated way. The full database of studies underpinning each one of the relationships is available at http://www.ecodesign.dtu.dk/process-performance.

3.4. Results and discussion from phase 4: development of the business case simulator for ecodesign

The expansion of the System Dynamics model structure presented in this paper to cover other clusters of practice can, therefore, lead to the development of structured and more rigorously grounded business cases for ecodesign implementation. With a comprehensive simulation model covering all clusters of practices in the EcoM2, managers are able to experiment on the business case simulator to test different scenarios and ecodesign implementation paths. This means that decision-makers will be able to evaluate how different speeds and strategies of implementation (e.g. which clusters to focus and how fast to implement them) could potentially lead to changes in their company's most relevant business performance outcomes.

In the System Dynamics model behind the business case simulator, the relationships between the clusters and the outcomes were modelled as a Cobb-Douglas function, as previously explained. The coefficients of the function were parametrized according to the mode calculated for each one of the relationships. For instance, if a relationship between a cluster and an outcome had value 1, the coefficient of such relationship would be 0.1 in the Cobb-Douglas function. Similarly, if the relationship was labelled as 2, the coefficient would become 0.2, whereas a value 3 would amount to a coefficient value of 0.3. Furthermore, the range of possible values for the business performance outcomes were defined according to generic figures reported by business case reports and studies from the systematic literature review, when information was available (see for example (CDP, 2014; Eccles et al., 2014; Grayson and Howard, 2011; Haned et al., 2015; Harter et al., 2009; IRRC Institute, 2015; Khan et al., 2016; Moorhead and Nixon, 2016; National Environmental Education Foundation, 2010; Palmer and Laura Mooney, 2011; Plouffe et al., 2011; Pure Strategies, 2014; Reputation Dividend, 2018; 2017a; 2017b; Rochlin et al., 2015; The Economist, 2008; Willard, 2005)).

The simulation's user interface (Bayer et al., 2014) was built as a flow of preparatory information, with a short introduction to the project, the main objectives, overall structure of the business case simulator and an introduction to the 11 clusters of ecodesign management practice and the 9 business performance outcomes. Finally, a set of instructions is provided to users, leading to the simulator page itself. The interface is rather simple and emphasizes the sliders for the current and desired capability levels for each one of the clusters. At the bottom of the interface page, three graphs display the behavior over time of selected outcomes. A drop-down menu enables the user to select which three graphs to simultaneously see. Fig. 6 shows the business case simulator interface, with hypothetical examples of current and desired capability levels, along with the graphs for profitability, emissions and customer satisfaction. The default simulation running time for the business case simulator was defined at 4 years (48 months), as this is the average time within which companies are able to realize and measure consistently the potential business benefits of ecodesign (Pigosso et al., 2013). The full-fledged business case simulator is open and can be fully accessed via http://www.ecodesign.dtu.dk/process-performance.

3.5. Results and discussion from phase 5: evaluation of the business case simulator by industry experts

All six experts reported that they were familiar with the EcoM2 before being introduced to the business case simulator. Experts

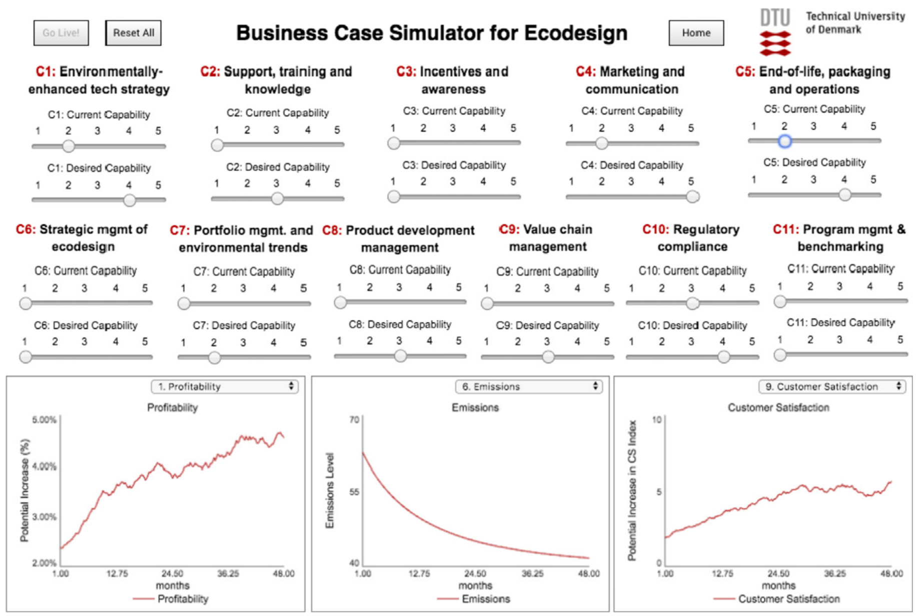

Fig. 6. Interface of the business case simulator for ecodesign, displaying three outcomes: profitability, emissions and customer satisfaction.

then evaluated each one of the 9 dimensions (utility, consistency, completeness, applicability, simplicity, clarity, objectivity, data and the clusters of practice) in terms of a qualitative scale with answers "very satisfactory", "satisfactory", "needs improvement" and "unsatisfactory". Besides answering against the scale, each one of the dimensions had a slot for open-ended response, so they could elaborate further and provide more detailed feedback. Fig. 7 shows the consolidated summary of the scale-based answers for each one of the dimensions evaluated by the experts. Clarity was the only dimension that was fully deemed as "very satisfactory". In particular, experts emphasized that the tool was assertive and once the main concepts - such as capability levels, practices and clusters - were clear, the business case simulator was easy to understand and manipulate.

For the dimensions of simplicity and clusters, experts evaluated that the tool still needs improvement. In particular, it might be difficult to keep all the meanings of the capability levels in mind while manipulating the simulator — a more intuitive approach to keep the concepts fresh for users would be desirable. As for the definition of the clusters, experts emphasized that the number of clusters might be a problem. Thinking in terms of high-level strategic decision-making, some topics could still be even more aggregated when displaying the business case, and further disaggregated back into more granular topics when implementation takes places and more specialized focus areas are required. The remaining six dimensions were evaluated as being a combination of "satisfactory" and "very satisfactory". No dimension was evaluated as "unsatisfactory". Furthermore, there were no relevant differences in responses patterns across the different companies that participated in the evaluation procedure.

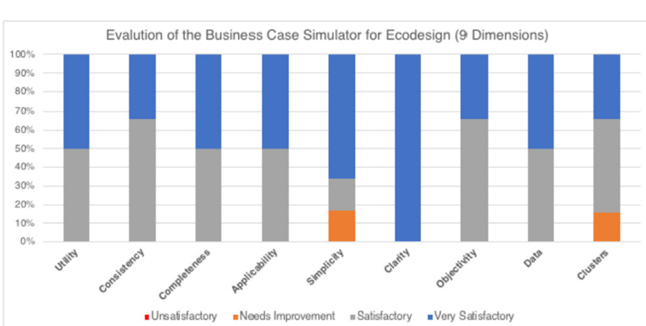

Fig. 7. Consolidated summary of scale-based answers from the evaluation questionnaire (n = 6).

Regarding the **strengths** of the business case simulator, experts considered the language used in the tool to be aligned with the one used by top executives at their companies. This means that strategic decision-makers would potentially connect well with the tool and the business performance outcomes. Furthermore, experts reported that the business cases for ecodesign have been a persistent gap within the managerial aspects of decision-making in strong finance-oriented cultures, and therefore the simulator can play an important role in changing the direction of the discussion and bringing more subsidies to potentially advancing the topics of ecodesign internally. The dynamic and prospective aspects of the simulator were also underscored as an authentic contribution: it helps to understand the impacts of the decisions, the cause-and-effect chain as well as the possibility of assessing "what-if" scenarios. Experts stressed that the simplicity of the tool, as being only dependent on the capability levels and few parameters from the company, makes its acceptance and use potentially easier in organizational contexts.

As for the **weaknesses** of the business case simulator, the industry experts considered that decision-makers would be willing to understand more about the underlying System Dynamics model. In particular, they highlighted that this might be complicated due to the technicalities of the method and the limited amount of time usually available for this kind of interaction. However, it is important not to create a "black box" effect, which would eventually decrease trust and confidence in the simulator. This is a particularly important aspect of System Dynamics modelling, as highlighted in the literature (Lane, 2015; Schwaninger and Groesser, 2008; Sterman, 1994). Connected to this, experts discussed the potential concerns raised regarding the accuracy of the numbers. Even though this study on the business case for ecodesign was geared towards making the rationale behind capability improvement explicit and emphasizing the patterns of behavior instead of accurate numbers, experts considered accuracy to be one of the main opportunities for improvement in later versions of the simulator. Another area of concern is related to the EcoM2 knowledge: experts considered that not knowing the EcoM2 or being a new-comer to the framework would impose higher barriers to learning how the business case works and how the implementation would unfold, together with the realization of the benefits. Experts mentioned that in order to be of value, the business case must build on top of a well performed diagnosis and a structured corporate strategy, otherwise it might take too long to define the next steps in terms of ecodesign implementation and understand how it support the corporate vision. Finally, experts raised the possibility of having the business case as a sector-specific tool that would cover specific facts and figures of individual sectors, instead of a generalized business case simulator.

4. Final remarks

This study originated a business case simulator for ecodesign. It was driven by the questions of understanding how the development of ecodesign capabilities – within an EcoM2 context – would potentially affect corporate performance over time. The System Dynamics methodology was applied to build a simulation-based business case framework, informed by theory-driven data. Instantiated in an online interface, the business case simulator was then evaluated by six industry experts from three different sectors. It is important to highlight that the development of the business case simulator was not geared towards having highly precise numbers and figures behind all the relationships and business performance outcomes, but rather to display and make the rationale behind capability improvement explicit. The behavior of the outcomes over time – and their patterns – were emphasized over numerical accuracy. The more the business case simulator is tested and adopted across different organizational structures and sectors, the more data and information about the real *a posteriori* effects of ecodesign practices on business performance outcomes could be available to inform the development of improved, more accurate versions of the simulator. It might also be the condition necessary towards deploying the simulator to different industrial sectors. For example, empirical data would be available to better define the output elasticities of the model's Cobb-Douglas function for different companies and/or industry sectors.

This research contributes to the literature of ecodesign by: **(a)** providing an overview of evidences of the potential effects of certain topics within the ecodesign management practices on relevant business performance outcomes (please refer to the full database of studies underpinning each one of the relationships is available at http://www.ecodesign.dtu.dk/process-performance); **(b)** structuring a System Dynamics oriented approach for modelling the capabilities of ecodesign management practices and their potential behavior over time, in an implementation setting – this could also be applied in different contexts, beyond ecodesign; **(c)** supplying practitioners with a practical tool geared toward developing a business case for ecodesign. Still, the limitations of this research are to be acknowledged: **(i)** the choice of keyword groups entered into the databases might have limited the comprehensiveness of the literature reviews; **(ii)** the lack of empirical evidence/validation for both the parameters and the analytic formulations can constrain the applicability of the models; **(iii)** the limited number of companies and experts consulted for the evaluation does not allow generalization of the results; **(iv)** only companies with previous knowledge on the EcoM2 were part of the evaluation.

Therefore, future research streams should ideally focus on: **(a)** expanding the coverage of the systematic literature review to prospect new relationships and parameters; **(b)** designing and performing empirical studies for the development of more robust parameters and analytic expressions, coupled with a strategy of applying and testing the business case simulator across different sectors; **(c)** capitalizing on the dissemination of the EcoM2 across manufacturing companies in order to have qualified experts to judge the applicability and usefulness of the business case simulator and **(d)** setting up evaluation and testing procedures with companies that have not applied the EcoM2 yet.

The results highlighted that the System Dynamics methodology is an adequate tool for modelling organization capability in the product development space. Despite the scarcity and concentration of the studies applying System Dynamics to organizational capability, an initial foundation could be built in order to instantiate specialized knowledge in ecodesign implementation. It is important to emphasize that this research is part of a broader effort towards building a solid understanding of how ecodesign performance can be captured, measured and thus translated into useful business cases that support decision-making in product development. Other simulation methods, such as agent-based modelling or fuzzy logic, can also be coupled with the System Dynamics oriented approach with a view to deriving solid results. Furthermore, other aspects of decision-making regarding ecodesign implementation could be explored, such as the behavioral dimension (individuals and teams) and the organizational dimension (structure and governance).

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