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Tool-kit development to facilitate decision making on eco-efficiency in manufacturing – insights from its application in production

Lampros Litos
Centre for Industrial Sustainability
University of Cambridge
17 Charles Babbage Road
CB3 0FS, Cambridge
UK
ll443@cam.ac.uk

Steve Evans
Centre for Industrial Sustainability
University of Cambridge
17 Charles Babbage Road
CB3 0FS, Cambridge
UK
se321@cam.ac.uk

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Abstract
Eco-efficiency at factory level is considered a milestone within a corporate agenda for adapting a sustainable manufacturing framework. This paper reviews approaches on eco-efficiency in terms of tools and techniques applied so far in the literature and discusses on a tool-kit that has been developed to assess eco-efficiency and identify and prioritise actions for implementation in production facilities. The tool-kit is the side result of case study and action research conducted with manufacturers on eco-efficiency management and follows a qualitative pathway for data collection and implementation, which is not common in the literature. The authors provide information on the tool-kit development and empirical data from case studies with manufacturers. The authors comment on the evolution of the tool-kit and assess its effectiveness in various manufacturing environments (small/medium sized companies, multinationals, etc.). This article provides insight and guidelines for tool developers in industry and academia who aim at helping practitioners to better visualise and rationalise improvement actions in factories.

Introduction
Sustainable manufacturing of products and services is considered as one of the basic dimensions of the roadmap to a sustainable world by 2050 and within this framework, eco-efficiency of resources and materials is a key variable with a four to tenfold improvement expectation by that year (WBCSD, 2010). Case studies from manufacturers on industrial eco-efficiency suggest that this tenfold improvement can be the outcome of various manufacturing strategies, such as re-manufacturing (Ayres et al., 1997), product life-cycle design (Saling et al., 2002), overall equipment effectiveness and asset management (Zuashkiani et al., 2011) and system's re-engineering (Pérez et al., 2007).

In order to study such initiatives, in the realm of industrial eco-efficiency, academics as well as industrial practitioners or professional consultants have developed theoretical approaches and frameworks that aim to map system inefficiencies and create momentum for improvement within the organization. The design properties and implementation methodology of these frameworks is the focus of this study. The authors review frameworks that have been reported in peer-reviewed literature and have guided the design of a toolkit that they have developed mainly for participatory type of research (i.e. action research) on industrial environmental performance and eco-efficiency. The basic module of the toolkit developed by the authors is in the form of a capability maturity grid and it is further analysed along a set of design dimensions that (Maier et al., 2012) have constructed. The authors also provide insights from the early application of their maturity grid in two occasions: rapid self-assessment and semi-structured interview. The second module, which is under development and has not been tested in any environment yet is a prioritization tool for visualization of actions that improve eco-efficiency. The basic properties of this module are discussed in relative detail as it has not been tested or validated. However, the authors would like to provide some insight of the overall research objectives that is facilitated by this toolkit.

Table 1. Publications that have influenced the capability assessment grid for eco-efficiency (CAGE) development.

Source	Theoretical contribution to the framework from the referenced work in first column	Design contribution to the grid construction
(Baumgartner and Ebner, 2010)	Corporate sustainability strategies (Table 1) Profiles of sustainability strategies (Figure 2). Maturity levels on triple bottom line dimensions (Tables 5–8).	Maturity grid and behavioural profiles, to be used as a self-assessment framework.
(Ngai et al., 2013)	Partial alignment regarding the behavioural change that a company undergoes on the road to sustainability. Ngai et al present a quantitatively based (measurements) framework for energy and utility only. Collaborative practice research example (Active research). The leverage points in this maturity grid are based on the measurements performed and the results of those measurements.	Use of a maturity grid based on CMM terminology is not followed, however, structure, aim and implementation is in alignment with the authors intentions. Moreover, the leverage points are not fully explored in terms of the underlying conditions for improvement. One of the interviewees notes that "SMEs need a step-by-step guide to achieve energy efficiency". This creates confidence in this study to populate the grid with established best practices rather than guidelines for practitioners.
(Campos et al., 2013)	The authors develop a maturity grid to tackle the issue of interoperability as the core of a toolkit for action research. Measurement within each maturity level is represented by the view of the managers involved in this action research who contribute and evaluate the artefacts of the model.	Figures 2 to 7 provide insight of how a maturity grid can be a part of a toolkit for action research and discuss on the methodology of performance measurement and self-assessment. However, facilitation of this process is not very straightforward in this study.
Chrissis M. B. et al	Continuous representation of maturity models – allowing work in parallel to all process areas. This is one of the highly cited handbooks on maturity models (CMMI).	This feature has implications for assessment tool design, allowing continuous representation and behavioural profiles. The continuous representation allows practices to float along process areas and it is also implied that not all process areas need to be at the same maturity level in order to move the organization forward in terms of eco-efficiency (i.e. good energy efficiency is not a necessary condition for good water efficiency), as the authors assess the underlying conditions that lead to improvements rather than specific outcomes.
(Ki-Hoon and Cheong, 2011)	Carbon footprint measurement framework in supply chain at Hundai MotorCo. 5 levels of maturity across 3 step of the supply chain with emphasis in measurements and information management. A quantitative perspective on a carbon footprint framework.	This is an example of a maturity grid that spans across 3 steps of the supply chain. The authors however do not emphasize how they have developed the framework or the leverage points for improvement.
(Veleva and Ellenbecker, 2001)	Discussion on environmental performance in 6 process areas (aspects of sustainable production) and the indicators that represent these: 1. Energy and material use 2. Natural environment (including human health) 3. Economic performance 4. Community development and social justice 5. Workers 6. Products	Insight in the possible process areas for sustainable production. However, the authors don't explore the leverage points for the improvement grid presented.
(Elrod and Tippett, 2002)	The planned approach to organisational change emphasises the importance of understanding the different states which an organisation will have to go through in order to move from an unsatisfactory state to an identified desired state.	Levels of progression through organizational change and re-construction.
(Claver et al., 2007)	Tangible and intangible resources and capabilities.	Qualitative assessment approach. Content for capabilities and practices.

Table 1 continues on next page. →

Source	Theoretical contribution to the framework from the referenced work in first column	Design contribution to the grid construction
(Yeo and Ren, 2009)	Lessons from risk management practices.	Content for framework design. Yeo and Ren discuss on the maturity model they created based on CMM, the assumption about robustness, security and capability areas and the necessary transitions mechanisms to move the system forward in maturity levels.
(Duflou et al., 2012)	Production facility as a complex control system (Figures 16, 17, 18, 19).	2 levels (process and multi-machine). Integrating complexity. Framework design content and content for the grid dimensions.
(Subic et al., 2012)	Capability Assessment Tool and gap analysis across suppliers.	3 scales of training cascading hierarchy and content for framework design.
(Ormazabal and Sarriegi, 2012)	6 levels of evolution: 1. Environmental Compliance 2. Training 3. Systematization 4. ECO2 5. Eco-Innovation 6. Leading Green Company	Maturity levels approach and dimensions. Content for framework design as well.
(Pigosso et al., 2013)	Eco-design maturity model. Insights in the development of the tool for eco-design. An action research approach.	Guidance for the development and implementation of the framework in action research. The way that they represent practices is quite novel.
(Păunescu and Acatrinei (Pantea), 2012)	Process areas discussed as: • Risk management and Improvement • Results evaluation and Improvement • Learning • Innovation • Process management and Improvement	Maturity levels and benchmarking calculations on a quantitative sustainability approach. Consideration for later positivistic research.

Review of literature on tools and relative frameworks

Eco-efficiency as a subject area for research has been addressed from various research angles and is extended to environmental management systems (Annandale et al., 2004), firm performance (Claver et al., 2007), indicator calculations (Zhou et al., 2012), or even mathematical simulations (Kuosmanen and Kortelainen, 2005). To simplify the review of the frameworks on eco-efficiency in this study, the authors focus in the frameworks that approach eco-efficiency with a qualitative methodology. Qualitative research in environmental performance and eco-efficiency has not received a lot of attention in the literature. However, the authors suggest that qualitative research like case studies and action research can reveal the drivers and barriers for eco-efficiency in industrial systems.

In Table 1 the authors review frameworks that have influenced the development of the maturity grid (CAGE) that is introduced in the following section. The authors refer to these frameworks in Table 1 as they have been developed within the realm of industrial sustainability and eco-efficiency, and are selected for their contribution in understanding this subject area and not only because of their design (grids). The table references the authors in the first column, the theoretical influence to the development of CAGE in the second column and the impact on its development in the third column. The content and application of the frameworks referenced is reviewed (in the third column) with regards to this current study. In the fourth section on the CAGE assessment the authors also discuss on the content of the CAGE and the underlying assumptions that it represents.

Toolkit development for research into eco-efficiency in factories

MATURITY GRIDS DESIGN PRINCIPLES

In this section on tool development, the authors present the design principles that have guided this theoretical research construct. Design work by (Maier et al., 2012) who reviewed maturity grids but not specifically on eco-efficiency provided the necessary design ground for CAGE. The most significant part in the framework that Maier et al. developed was the discussion on the underlying assumptions and conditions that drive research with maturity frameworks. The underlying conditions that move the system up in maturity is underpinning the research assumption about the system boundaries (i.e. the production facility and input-output flows of resources) and capabilities (i.e. rewarding system, IT support, etc.).

In Table 2 the authors present their analysis on the design principles of CAGE that are common in maturity grids using as basis the framework of Maier et al.

Table 2. CAGE assessment according to Maier et al., 2012.

Decision points	Decision options	Comments on CAGE development
Phase I – Planning		
1. Specify audience	Users (e.g. project member, project leader, change agent, or CEO); improvement entity (e.g. teams, organization, process or product).	The audience spans from maintenance manager to production manager/supervisor to manufacturing board member. It is meant to be applied in all three scales of management. The framework is meant to be facilitated as little as possible so that it can be circulated as a survey for self assessment within the industry (perhaps a case of multiple production sites). The audience should have working knowledge in the factory on energy, resources, waste, personnel training, maintenance and business strategy/scope.
2. Define aim	Raise awareness or best practice benchmark.	The aim is twofold. The grid has been designed as benchmarking platform where the audience can visualize their performance in a qualitative way when compared with exemplar case studies from the literature (peer-reviewed or excellent samples). However, raising awareness on eco-efficiency is expected as the company may not have included it in their manufacturing agenda and moreover, the way that eco-efficiency is presented through the grid where various concepts come together may also be part of the awakening process.
3. Clarify scope	Generic (e.g. energy management) or domain-specific (e.g. energy management in construction).	Eco-efficiency is the domain under investigation and the way that companies can reach certain objectives within this domain. It is specific in terms of definition and scope but the solution does involve multidisciplinary thinking which brings some breadth in options.
4. Define success criteria	High level requirements (e.g. usability, usefulness); specific requirements.	It is important to make sure that the design language (maturity grid and overall structure) and terminology is widely accepted and understood by the audience. Moreover, the authors expect that it can be used after a period of extended use without facilitation (some adjustments may enable this option). This will be a success for the authors as they can start generalizing the framework but also it can mean success for a company that is able to use such a framework for self-assessment (this can be an indication of their mind-set as well).
Phase II – Development		
1. Select process areas (components and theoretical framework)	E.g. reference to established body of knowledge; expert knowledge; defining goals.	Process areas were selected on a resource based-view of the company. The flows of resources, energy, waste and the way these interact with the assets of the company have been fragmentally discussed in the literature. This framework is trying to unify these processes to provide the audience with an overview of the possible areas (s to improve on eco-efficiency
2. Select maturity levels (underlying rationale)	E.g. existence and adherence to a structured process; alteration of organizational structure; emphasis on people; emphasis on learning	Justification of the choice of the levels and the content is provided in Table 1.
3. Formulate cell text	Type of formulation: prescriptive or descriptive. Information source: synthesizing viewpoints from future users or comparing practices of a number of organizations. Formulation mechanism: inductively generated from descriptions of practice or deducted from underlying rationale.	The authors' intention is to raise awareness in the audience by providing information in the cells from existing practices that improve eco-efficiency. These examples are drawn from the literature (case studies and action research type literature).
4. Define administration mechanism	Focus on the process of assessment (e.g. face-to-face interviews, workshops) or focus on end results (e.g. survey).	The CAGE has been initially designed to facilitate case studies with production practitioners (alternatively an interview guide for semi-structured interviews) but also with a long run view as an action research framework in workshops with wider audience in the company that is interested to work on system improvements for eco-efficiency.

Table 2 continues on next page. →

Decision points	Decision options	Comments on CAGE development
Phase III – Evaluation		
1. Validate	Correspondence between author's intent and user's understanding. Correctness of results.	Initial participatory events will be used as framework validation as well.
2. Verify	Correspondence with requirements specified.	The longevity of the framework will be decided after application within action research cases. It has been designed and populated to drive transformational change in the organization. Therefore, the results achieved with this framework will be part of its evaluation.
Phase IV – Maintenance		
1. Check benchmark (and adjust description in cells)	if applicable	This section is under development and will be further updated in the future along with the research activities.
2. Maintain results database	if applicable	
3. Document and communicate development process and results	audience specific	

CAPABILITY ASSESSMENT GRID FOR ECO-EFFICIENCY (CAGE)

Qualitative research for eco-efficiency is not fairly proportioned in the literature of sustainable production when compared to quantitative approaches that several authors have followed. However, a system's approach (Senge and Sterman, 1992) over production capabilities influenced by the resource based view (Grant, 1991; Russo and Fouts, 1997) of the manufacturing company has received the attention of academics recently in theory and practice (Ball et al., 2009; Despeisse et al., 2013).

This motivated the authors into developing a construct that would combine organisational learning and manufacturing capabilities for participatory research with manufacturers. The various dimensions of flows and the concept of developing skills found in the capability maturity models (Chrissis et al., 2007) provided the basis for the CAGE development.

The authors have originally populated the grid with case studies found in the literature (examples are given in Table 1 and Figures 1, 2). The process has been performed in reverse. This means that the authors have constructed the maturity grid as a logical sequence of literature base search of eco-efficiency practices. The maturity grid is the view of the authors on the progression, applicability and performance potential of practices reported by companies in peer-reviewed literature or governmental reports (grey literature).

Having created this progression of maturity the authors can use this approach for case study research (characterise the maturity profiles of participating manufacturers) and further try to address possible improvements using action research methodology. The authors intend to unlock the behavioural elements of eco-efficiency in manufacturing in order to bring deeper understanding at the mechanisms that evidently support eco-efficiency and continuous improvement. In section 5, the authors make a discussion on the possible applications of this framework for eco-efficiency in production facilities.

PRIORITISATION OF ACTIONS CUBE FOR ECO-EFFICIENCY (PACE)

In addition to the CAGE, the authors have developed another tool to help them engage with practitioners on a decision level for eco-efficiency (later steps in research plan). In Figure 3, the authors present the "prioritization of actions" cube for eco-efficiency (PACE). PACE belongs to type 1a matrices according to (Phaal et al., 2006) but uses 3 dimensions instead of two. A similar design is utilised by BASF with a wider spectrum of application ("BASF," 2014). The dimensions are Ease of Implementation, Benefit from implementation and Cost of implementation. All three dimensions could take values of 1, 2 or 3 as 1 being the smallest and 3 being the largest (the scale will be decided at initial trial tests). This tool is designed specifically to visualise various improvement options that can lead to improved eco-efficiency and engage with the practitioners in action research.

By acknowledging that more than one solution or action can be economically viable, the authors intend to develop PACE further for research into options that improve the environmental performance of a production facility. The aim is to focus in actions that are relatively easy to implement, highly beneficial and the cost is kept as low as possible. The arrows in Figure 3 that represent the various solutions start from the same starting point (which is the current system status). However, by taking into account eco-efficiency as the ratio of economic output vs environmental output (Kuosmanen and Kortelainen, 2005), the arrows do not reach the same eco-efficiency levels (represented by the end of the arrow). Ideally the authors expect to identify actions that move the system to the top-left corner of the cube in the front (highlighted).

This visualization tools is inspired by the of work (Levente L. et al., 2007), (Simon et al., 2008) and the BASF methodology for life-cycle analysis (Saling et al., 2002) and the BASF Seabalance visual output ("BASF," 2014). It is presented in the paper to provide an overview of the participatory research work in progress

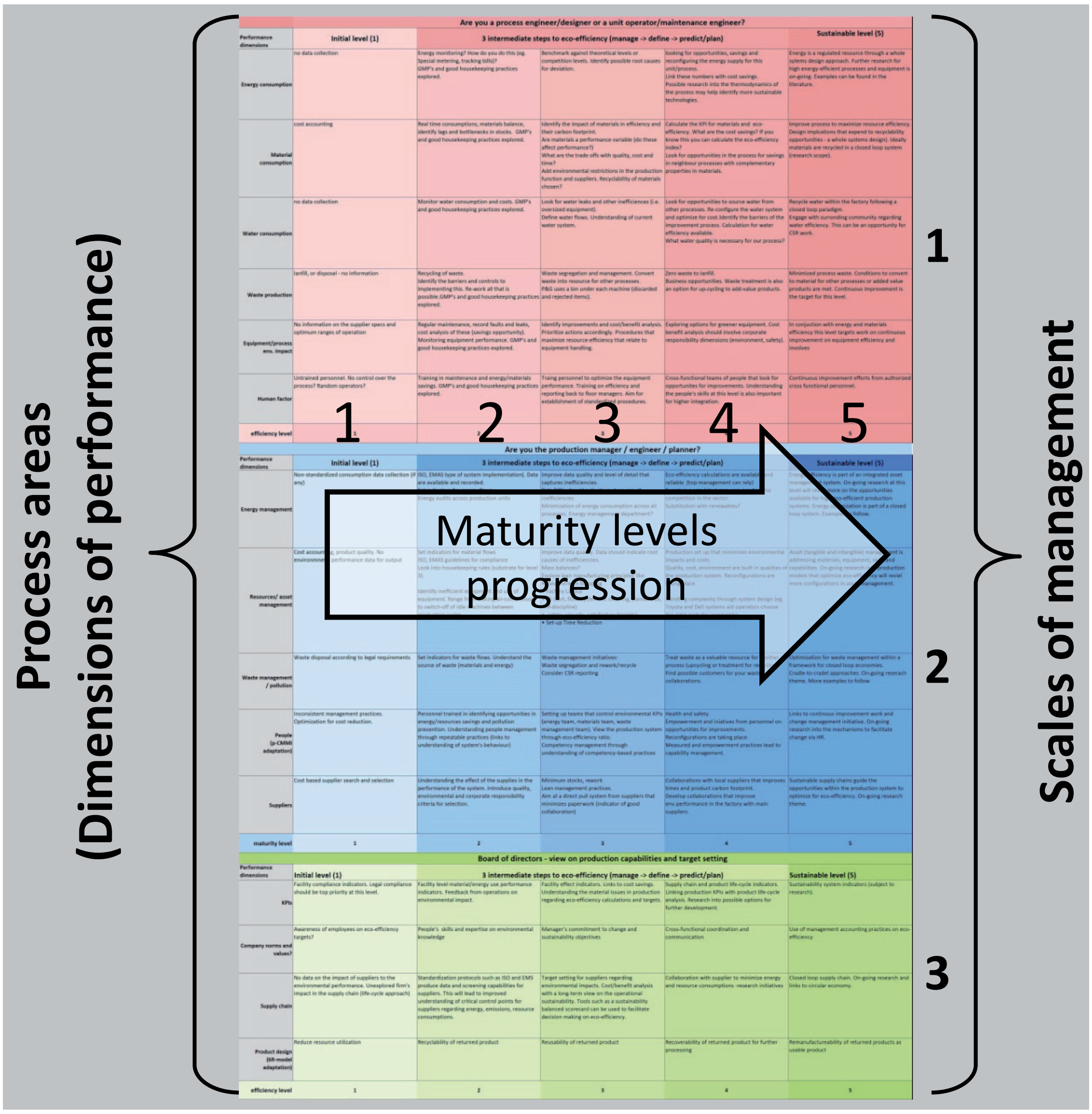

Figure 1. Presentation of the CAGE (process areas, maturity levels, fields [scales] of application).

Resources	Cost accounting, product quality. No environmnetal performance data for output	Set indicators for material flows ISO, EMAS guidelines for compliance Look into housekeeping rules (substrate for level 3). Identify inefficient equipment and use of equipment. Range from leaking air-compressors to switch-off of idle machines between production cycles.	Improve data quality. Data should indicate root causes of inefficiencies. Mass balances? Explore lean manufacturing principles like • Value Stream Mapping • Factory Layout • 5S (sort, flow, systematic cleaning, standardize, self-discipline) • safety, security, satisfaction (targets) • Set-up Time Reduction	Production set up that minimizes environmental impacts and costs. Quality, cost, environment are built in qualities of the production system. Reconfigurations are taking place. Handling complexity through system design (eg. Toyota and Dell systems aid operators choose the right parts for assembply)	Asset (tangible and intangible) management is addressing materials, equipment, skills and capabilities. On-going research into production models that optimize eco-efficiency will reviel more configurations in asset management.

Figure 2. Magnification on the grid's resource dimension on 2nd scale of management (levels 1 to 5, from left to right) for readability.

by the authors. Gaps and opportunities identified via the maturity grid will be further studied and prioritized having a strong focus on the cube visualization. The authors assume that this representation of actions will create a degree of confidence in the action research team that is working on this.

In the following section the authors provide more information on the development and underlying design principles of the first module of the toolkit (CAGE). This tactic is not presented for the second module as it still under investigation and has not been tested yet in the industry.

Discussion

The toolkit (CAGE and PACE) has been developed to facilitate data collection in participative research. The authors till this date have used only the CAGE in order to collect data from industrial practitioners and more work is expected in the future with organizations that are interested in making improvements in environmental performance. In this section the authors provide early evidence of the applicability and usefulness of the framework constructed in three different situations: self-assessment of current status in a factory, case study research and as

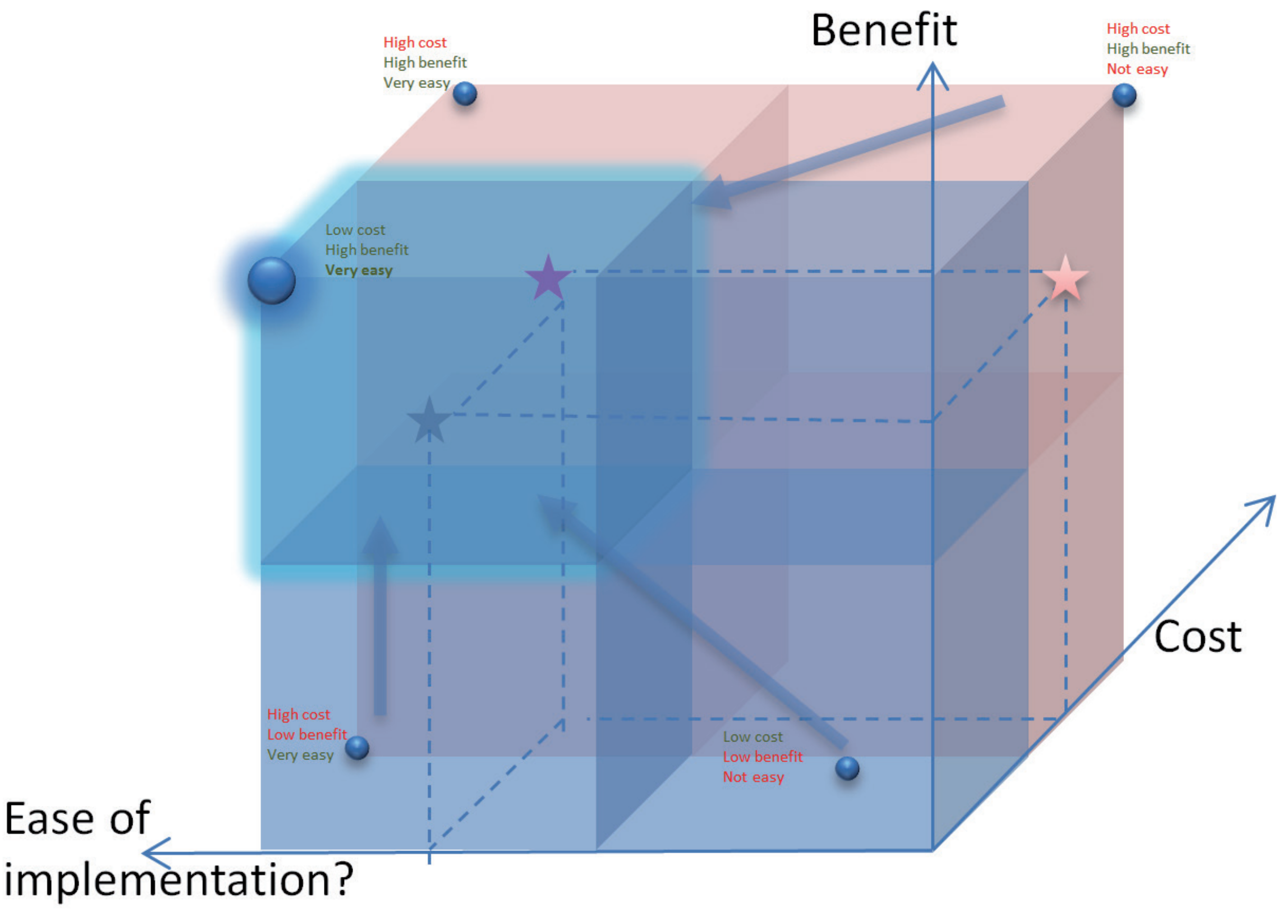

Figure 3. PACE. Prioritization of actions that improve the system's eco-efficiency.

a workshop with practitioners. The authors are applying the framework in multiple environments in order to understand where this tool is more effective in: raising discussion of the sophistication of current practices (along five levels of maturity) and awareness regarding the dimensions of eco-efficiency in factories and mapping of current and future status.

A) AS A RAPID SELF-ASSESSMENT TEST

The CAGE conceptual framework has been tested in three different modes. The purpose was different in each case (Table 3). First of all it served as a rapid self-assessment tool for eco-efficiency for two companies. The practitioners (one in each case) were employed in production and quality management respectively. They provided the self-assessment of their production facilities with regards to their environmental performance in a Likert-type scale of 1 to 5 while in parallel viewing the framework printed in A1 (poster size). In Figure 4 the authors provide the performance profiles of these two companies.

However, this approach in using this framework is not producing data other than the assessment profile. The quality of information that the authors are interested in will be pursued through workshops and similar activities. Using the grid as a checklist will be considered as a research option, once the dimensions (vertical and horizontal) have been validated through workshops and there is wider acceptance of this framework. On that basis, it can be part of survey type of research activity (positivistic). However, at this research stage, it is used to attract attention from practitioners and receive a quick self-description of the organizational competence and performance.

B) CASE STUDY RESEARCH (SEMI-STRUCTURED INTERVIEW GUIDE)

The framework has been tested so far in one case study to facilitate the interview process. The authors have used the framework as an interview guide with a manufacturer in the food and drink industry to describe and explore the environmental practices already installed in the factory. The practitioners (the production manager and the maintenance manager) were introduced to the research agenda and the tool (populated grid) was sent via e-mail a few days prior to the interviews. During the interviews the practitioners were asked to produce evidence of practices they use to manage environmental output along the dimensions of the framework (as applicable). A walk around the facilities was also performed after the interview so that the authors can have an overview of the facilities and talk to personnel in site (not interviewed). The walk was necessary to raise questions about the current environmental output of the facility that were communicated later to the interviewees for additional feedback. The practitioners were keen to learn about best available practices (BAP) and expressed their desire to contribute to the population of the framework with their own BAPs. The authors had the opportunity in that walk to relate the content of the interview with the on-going activities in the factory and ask for details from personnel in site. In this case study (it is still under development) the authors observed the high degree of automation in the factory. Very few workers

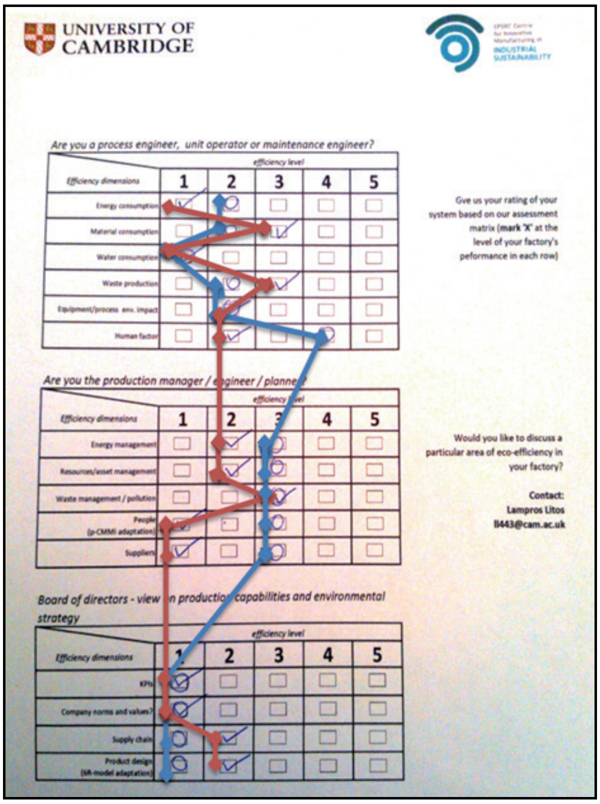

Figure 4. CAGE as a rapid self-assessment tool for eco-efficiency in production facilities.

had an active role in the production area as production lines were fully automated from raw materials to palettes for fork-lifts. This observation initiated some thinking as to how opportunities for improvement on environmental performance could be implemented with minimum participation from the personnel. However, this case study is still under development and more information will be gathered in the future.

C) IN A WORKSHOP WITH INDUSTRIAL PRACTITIONERS

The toolkit, as previously mentioned, has been designed to facilitate participatory research. Running a workshop with industrial practitioners can produce a lot of data that are content-specific to eco-efficiency (learning about best available practices from practitioners) but there can also be learning outcomes regarding the perception of maturity of these practices in industry. Furthermore the authors have the chance to study the practitioners in their effort to cluster BAPs into maturity levels.

The workshop on CAGE is designed to inform the grid with BAPs on eco-efficiency similar to the workshop objectives (current practices and future goals) presented by (Routley et al., 2013):

1. Help understand how lessons learned in the past may be applied to future challenges.
2. Provide better visibility of the current situation and the journey.
3. Provide a common understanding and visual representation across different functional areas.

The authors summarized the three different operational modes of the grid in Table 3 in order to make a clear statement of the expected outcomes of this methodology and express their concerns in each case.

In regards to the PACE module, this has been designed to follow up the use of CAGE within organizations that are interested to explore opportunities to improve on eco-efficiency. PACE is intended to help various managers provide their feedback on proposed actions and prioritise depending on the contribution to eco-efficiency. The researchers aim to collect information about drivers of transformational change in the manufacturing environment and use this module initially as a mean to align manager's ideas. More work on this concept is on-going and should be discussed in the future by the authors.

Conclusion and future research plans

This study is part of a research plan focusing in eco-efficiency for factories. The authors are conducting research in collaboration with industrial practitioners and collect data regarding environmental performance and best practices that enhance production targets like cost, quality etc. In order to conduct research in that participatory methodology the authors have developed theoretical constructs or tools that help them engage with their audience.

The authors present in this paper the design properties of the toolkit they created for research. The toolkit consists of two modules: a capability assessment maturity grid (CAGE) and a prioritisation of actions visualisation to be used in that sequence. The authors did not have the opportunity to test the second module in field research yet and therefor it is presented briefly to provide an overall view of the research methodology. The maturity grid has been applied so far in three different settings: as a self-assessment form, a semi-structured interview guide and a workshop.

The design of the grid was assessed according to the design principles of maturity grids that have been developed in the study of Maier et al. (2012). In maturity grids the design principles and the underlying assumptions that the research makes in order to model a specific condition are found to have common characteristics. The framework of Maier et al. offers the opportunity to study the compliance of CAGE to these common features that underpin maturity grids.

Finally, the authors' early experiences on the application of grid are presented in the three settings mentioned above. There is not a direct comparison of the outcomes of these applications as the audience and purpose is different in each case. Overall, this multi-purpose approach is a mean of achieving wider impact in the industry, collect different qualities of data from the field and make an assessment at a later stage about the effectiveness of the framework in regards to the setting of application.

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Table 3. Summarizing the use of CAGE.

Using CAGE to facilitate data collection in:	Who is using it (audience)?	Expected outcomes from the method application	Concerns about the method of application
Rapid-self assessment	Practitioners in industry in various roles of production, maintenance, environmental management or operations. Individual contributions from one company or more.	1. Understanding the alignment of performance and effect of management practices across the three scales of management (process, production floor and manufacturing level). 2. Visualizing, in terms of benchmarking, the opportunities for improvement in certain underperforming areas. Identify strong and underperforming areas of environmental performance. 3. In the future it can evolve into a tool to facilitate and overview the improvement areas in their factory. 4. A mature example of this approach is give in lean manufacturing by (Goodson, 2002).	Data collection can be limited. The practitioners provide their own view of their production system performance. Therefore there is no direct comparability with other companies in terms of scale and common language on eco-efficiency. It has a restricted case sensitive usage.
Semi-structured interview guide	Practitioners within a manufacturing site in various roles. Single companies that can have multiple production sites.	Emphasis is given to understand the company's evolutionary steps in managing environmental performance. The interviewers can collect historic information as well as quantitative data about environmental performance. They also need to thoroughly investigate the data for comparison with sector's best practices in the literature. Aim to make numerous case studies so that the authors can me generalizations about common behavioural patterns and use that information for action research in later stages of the research with companies willing to explore change initiatives.	It is case and sector specific. It is not safe to compare maturity profiles in terms of performance (quantitatively).
Workshop	Various practitioners from various manufacturing companies.	Aiming to disseminate best practices and understand what future improvement aims and actions can be. This environment can produce valuable data that can shape the grid's dimensions and content for further use. Aim to capture the interaction between the workshop delegates and record their views on eco-efficiency.	Unpredictable audience. Data on eco-efficiency may be hard to process.

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