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# Integrating sustainability in the development and operation of high-volume production lines

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## Abstract

Three key aspects influence the sustainability of high volume production: The available production technology, its integration and, finally, the operation of the production line. The differing contexts require the manufacturer to assess each aspect independently, which, in addition to common decision structures, hinders the holistic sustainability assessment of a technology and its performance in the use stage. Based on an industrial collaboration, this study addresses the development and integration of a methodology combining quantitative and qualitative methods to assess technologies, their implementation, and their operation.

Results indicate that the simplicity of the chosen methods is the key factor enabling their integration into the decision-making processes. An initial review of ongoing case studies indicated positive results and an increased environmental awareness of decision makers as well as high potential for beneficial integration of a Green Lean concept.

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**Keywords:** Technology development; Green Lean; Sustainability assessment; Mass production

## 1. Introduction

The strive towards progress in environmental performance has become any organization's daily business to remain competitive. Stakeholder expectations, brand reputation, regulatory compliance and economic performance are all related to sustainability, thus creating a strong argument for the integration of sustainability metrics in the decision-making processes for production technology development and operation. Various concepts and tools have been developed to assess environmental sustainability on product level, yet, they usually exclusively evaluate a specific section of the production chain.

This study suggests a methodology how a technology can be assessed as it progresses from an early stage of exploration, to

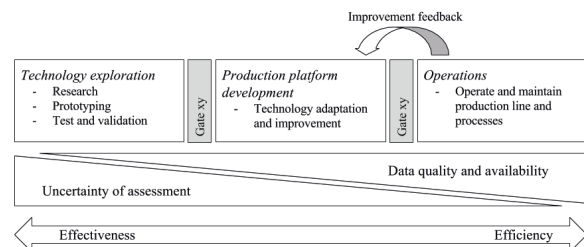


Fig. 1. The stages of technology integration composed of technology exploration, production platform development, and operations separated by decision gates. Early-stage assessments are characterized by a high uncertainty due to lack of data, respectively low data quality. As technologies progress through the stages, the data quality increases to the extent that quantitative assessments become feasible at later stages.

production platform development, and the subsequent implementation in operations (Fig. 1). The three stages are closely linked with each other, yet the decision context, as well as potential implications on the environmental performance of the production line, differ significantly. *Technology exploration* focusses on novel innovations or emerging technologies which have the potential of altering the way production processes and technologies are employed today. *Production platform development* aims to adapt and improve equipment and technologies in an existing production line. *Operations* drive and maintain the production line with a high focus on resource efficiency (human, physical and financial resources).

The scope was limited to in-house activities and does neither include transportation nor storage of semi-finished or final products. Further, over-heads such as heating and ventilation are not included, unless they are relevant for a given production process (e.g. stable level of temperature and humidity in the printing process).

The project was set up in collaboration with a large Danish manufacturing company. The project group behind this study consisted of stakeholders representing each of the three stages, in addition to experts in environmental and facility management.

## 2. Theoretical background

The here proposed methodology integrates three complimentary tools, which address the individual challenges at each stage of the technology integration. This section introduces the tools that are adopted for environmental decision making along the technology value chain.

### 2.1. Qualitative assessment for technology exploration

It is crucial to adopt an early awareness of potential environmental implications of a technology in order to avoid negative surprises later on.

A major challenge of technology exploration is the low availability of data [1]. Either the technology is not mature, i.e. its real-life performance is unknown, or supplier collaboration has not reached a level to facilitate data exchange to create best estimates for comparison to current production technologies. For cost reasons, extensive sustainability assessments, such as Life Cycle Assessment (LCA) are currently not an option for application in daily business. As consequence, tools like the Product Life Cycle Check (PLCC) have been developed to integrate Life Cycle Thinking in the early stages of technology exploration [1]. Based on a matrix, structured into the four life cycle stages materials, production, use, and end-of-life, a layperson is able to investigate and estimate in what way each stage contributes to environmental impacts. The latter is categorized by the MECO principle into impacts related to raw *M*aterials, *E*nergy, *C*hemicals and *O*ther sources, such as social or work environmental circumstances. The assessment follows an iterative approach, in which each iteration adds further information, gathered from suppliers, databases or the Internet. Even though the PLCC is primarily a qualitative assessment tool, it encourages to integrate quantitative

indicators as its results increase in detail from one iteration to the next. The assessment and its associated process thus sets environmental evaluations on the agenda of both the manufacturer and the supplier and paves the way for subsequent assessments within production platform development.

### 2.2. Quantitative assessment for production platform development

As opposed to technology exploration, production platform development typically occurs in close collaboration with the supplier(s). Data of potentially new production equipment becomes readily available and can be compared to the existing production line. However, it is rarely the case that an organization bases a decision exclusively on environmental performance. With cost as a main driver, the assessment has to reflect economic aspects in order to make a firm case for implementation of any modification.

The Eco-Care Matrix [2] has been developed to facilitate the integrated assessments of both environmental and cost dimensions relative to a reference (base-) scenario (Fig. 2). The results enable not only a ranking of scenarios, but allow identification of the aspect (i.e. environmental or economic performance) that has to be improved to increase the competitiveness of a technology.

The environmental performance is assessed with a streamlined LCA, while the calculation of the economic performance is based on a Life Cycle Costing (LCC) tool [3].

### 2.3. Green Lean for operations

Once a production line is up and running, the focus shifts to efficiency gains through continuous improvement. By nature, changes in production efficiency may alter the environmental performance. A common misconception is that ‘wastes’ (or ‘muda’ in Japanese) removed by lean initiatives are in any case leading to decreased environmental impact [4]. For example, many efficiency initiatives decrease production scrap, hence

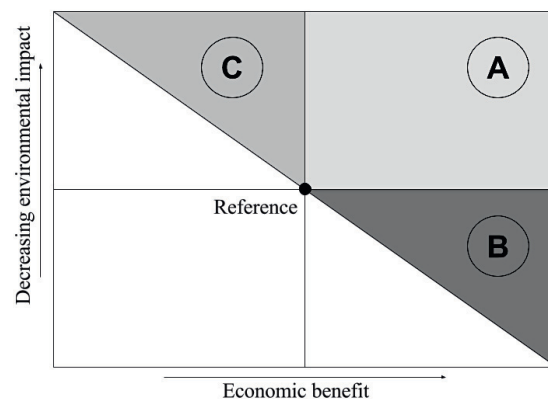


Fig. 2. Eco-Care Matrix as suggested by Wegener et al. [2]. Solutions in quadrant ‘A’ have a superior sustainability performance compared to the reference point (center black). Solutions in area ‘C’ and ‘B’ should focus on economic and environmental improvements respectively

reduce the amount of required raw material to produce the same output, however, they might generate processes that are for example more energy intensive, require chemical treatment or are more labor intensive. Consequently, the overall sustainability might be compromised, if the focus is set too narrow.

Several recent publications describe frameworks to link continuous improvement to environmental performance in order to avoid above-described pitfall [4]–[8]. In taking advantage of the existing concepts Six Sigma and Lean [9], the frameworks aim to integrate sustainability into these quality- and efficiency-focused concepts. Principally, they follow the five subsequent steps [7]:

1. *Definition of the project* including scope and relevant stakeholders
2. *Measurement* of the current performance of the production line
3. *Analysis* of the results
4. *Implementation* of improvements
5. *Control* the new processes by suitable monitoring mechanisms

Setting relevant environmental indicators is crucial to gauge the effects resulting from the elimination of root causes and can consequently create benefits on the other manufacturing indicators (e.g. quality, cost). Further, it enables clear communication to all stakeholders along the value chain ranging from operational to management levels. Rödger et al. [10] suggest for this purpose the Sustainability Cone, a framework developed to define indicators for sustainability and manufacturability, to support consistent decision making on individual levels within a production platform (e.g. per equipment, per cell, per line) and in relation to the produced product (e.g. parts, modules, final product).

#### 2.4. Data baseline as foundation for quantitative assessment and Green Lean

A sound data baseline is crucial in order to determine hotspots and benchmark improvement scenarios against the current performance. As the manufacturing industry currently moves towards digitalization, an increasing amount of high-quality data becomes readily available to create a relative benchmark for comparison. Consistency in the data collection is crucial, and hence, standardization of the data collection should be one of the goals when implementing this methodology across various organizational functions.

### 3. Practical implementation

For two reasons, simplicity was considered a key criterion for the design of the conceptual methodology: Firstly, it requires only a minimal change in the organizational structure, hence can be implemented without major interference in the business as usual. Secondly, it allows the staff to conduct those assessments as part of their regular business procedures, without extensive training.

Next to the technicalities of the tools, their implementation in the decision making process was considered in close

collaboration with each of the three internal stakeholder groups throughout the technology value chain.

The *qualitative assessment*, as described by Wenzel and Caspersen [1], has been restructured and enhanced with guiding questions to support the project management in conducting the assessment during technology exploration. Rather than listing potential impacts along the Life Cycle in a matrix structure, the new assessment design focuses on the strategic environmental focal points of the case company (being carbon emission reduction and reduction of waste generation). This is to ensure a given technology's compliance with the organizational goals, which consequently discourages investments in solutions with an inferior environmental performance.

As the lifetime of the equipment in this context is generally long (i.e. 10-15 years), the stages prior and subsequent to the use stage typically become insignificant i.e. the environmental impact caused by the manufacturing of the equipment is dwarfed by the impacts resulting from its use. Compared to the original PLCC, this constitutes a shift in focus towards the expected application of the technology. Further, impacts within the social or work-environmental dimensions have been excluded, as the procurement department and the health and safety department address those independently. The assessment concludes in a summary of findings and becomes an integral part of the technology documentation, which is forwarded to the production platform developer.

As described above, the *quantitative tool* assesses the environmental perspective by means of a streamlined LCA. As this is – due to time and cost constraints – not feasible for each project, the project group determined a number of hotspots based on internal expert opinions and literature research. The resulting focal areas included all types of production waste (scrap and quality excl. excess inventory, as this is a result of the planning strategy rather than equipment technology) in addition to electricity consumption. In order to ensure performance comparability between the scenarios and the reference, the indicators are calculated as amounts per kilogram of product produced. This enables the user to compare initiatives, which alter the production performance at various stages, and builds the foundation to aggregate the results into a total performance of the production line. Waste is measured in kilograms (i.e. as is usually the case), whereas electricity is expressed as Global Warming Potential (GWP in kg CO<sub>2</sub> eq) to reflect the location-specific electricity grid mix. The two indicators can be assessed independently or, if relevant, aggregated in a combined indicator, expressed in GWP (i.e. kg of waste multiplied with emissions resulting from the raw material production).

Two economic indicators are considered in the quantitative assessment. The Full Manufacturing Costs (FMC) are used to multiply the waste indicator. This results in a weighted environmental performance (y-axis in Fig. 2) in order to determine how an initiative at the beginning of the production line compares to one altering the line further downstream. The Net Present Value (NPV) was selected as the second and central economic indicator to benchmark various scenarios (represented on the x-axis in Fig. 2). Prime reasons are i) its widespread application for many investments, hence not

requiring any additional calculation of a scenario-specific economic performance and ii) the inclusion of both capital and operational expenses. The major advantage over LCC is the integration of the Weighted Average Cost of Capital (WACC). LCC focuses generally on the costs of a product throughout its lifecycle, but does not include the costs arising from different ways of financing those costs. The WACC in NPV however, operationalizes the organization's minimum benchmark for required return by including the interest rates of a variety of financing tools.

The *Green Lean* adaptation emphasized the need to define relevant indicators to capture environmental aspects of efficiency initiatives. As opposed to the focus on the environmental performance of a specific technology, Green Lean seeks to increase overall efficiency of the entire production line. Consequently, the perspective changes from the individual waste or energy indicator to manufacturing performance, enhanced with environmental impacts. Only initiatives that indicate a positive impact on all indicators are considered for implementation. As continuous improvement is to some extent already embedded in the organizational structure, the focus of Green Lean was to enhance the existing way of doing things environmentally. Consequently, the steps *measuring* (2) and *controlling* (5) were redesigned to accommodate for economic, environmental and output quality indicators.

#### 4. Current results

At the time of writing, selected elements of the concept were introduced in the case company. The qualitative assessment has been tested by the end-users, and the respective feedback was included in order to strengthen its applicability. Current work focuses on embedding the tool in the decision process, educating the prospective users in addition to establishing the hand-over to the technology development. The quantitative tool has been developed and completed for two business areas and is currently tested on pilot projects. Similar to the qualitative tool, it still lacks a clear description of its integration in the decision process (i.e. who should conduct the assessment when, and how are the results communicated to whom?). The standardization of data collection is ongoing and is, due to the multinational locations of the organization, a major task in itself. The Green Lean approach will be tested as part of a larger continuous improvement initiative, which is currently planned and to be rolled out in winter 2017/18. First results are expected by June 2018.

#### 5. Discussion

##### 5.1. Defining relevant indicators

The choice of indicators is primarily driven by the company's sustainability strategy. In the given case, this led to a focus on waste (i.e. process/material efficiency) and electricity (i.e. global warming potential). Other environmental impact categories such as acidification, eutrophication or human toxicology are not addressed. Hence, the assessment is subject to the risk of burden-shifting, which results from

initiatives with one-dimensional focus without elaborating on the full breadth of potential environmental impact categories. One can argue that the company's focus is to some extent guided by public awareness and the national policy agenda, both of which have pinpointed climate change resulting from carbon emissions as environmental issue no.1.

Another question that currently goes unanswered concerns the ideal indicators for the quantitative assessment. The here suggested aggregation of GWP to compare waste and energy results in an arbitrary weighting, dependent on the chosen energy mix and the emission generated in the production of the processed raw materials. Here, a dedicated analysis regarding the form of desired indicator would lead to an improved decision support. However, such an additional normalization or weighing step would add complexity to the assessment, where it is least desired.

This reflects the generic dilemma of any attempt to simplify a complex context to a single indicator, which, however, is a key requirement for a successful integration and application in business. Due to the negative correlation of simplicity and thoroughness, a company in a competitive environment will choose simplicity to enable a claim on 'sustainability', but will not take the necessary steps to investigate the full spectrum of environmental impacts arising from its operations.

The economic dimension however, could be covered sufficiently in the here suggested methodology to the degree that the applied indicators are already widely used throughout the organization and hence fully satisfy the end user's requirements.

##### 5.2. Assessment

As argued above, the simplification led to a loss of quality compared to state-of-the-art environmental assessments. This is true for both the qualitative and the quantitative tool. The qualitative assessment is limited in the availability of data and is filled out by a non-expert, which bears the risk that significant environmental impacts are overlooked. Yet, it is positive that the assessment could be anchored in the decision process regarding the technology and hence can be frequently refined as the technology progresses through the stages of platform development and its subsequent use in operation. As the data quality continues to improve, more detailed assessments can be considered as an option.

The quantitative assessment as defined today would certainly benefit from an integration of other impact categories to verify a true environmental benefit of an alternative scenario. It might be discussed whether this should be the case for projects involving a certain level of investment to avoid having to conduct extensive assessments of even the slightest change in the production line.

The delimitation of the scope turned out to be correct insofar as the stakeholders are asked to assess aspects they have the power to influence directly. Hence, the decision to exclude transport, storage or auxiliaries (where not contributing to the process) is partly responsible for the simplification in data requirements and assessment method.

### 5.3. Efficiency vs. effectiveness

Awareness that a focus on efficiency is not sufficient to reach sustainability has increased in the recent years and gave rise to alternate assessments and concepts such as science-based targets [9] or absolute sustainability [10]. Those novel methods set targets by assigning upper limits (or safe operating spaces) within which an organization should remain, if it were to be considered 'sustainable'. Yet, the manufacturing industry seems to be stuck in the efficiency paradigm originating from the effort to increase the revenue by lowering production costs i.e. increasing efficiency. This fact is reflected in the here suggested methodology, which benchmarks the performance of an initiative relative to the current performance. Gains in effectiveness however are most likely achieved at the stage of technology exploration, from where the most radical changes in the production system are triggered. Hence, it may make sense to strengthen the here suggested qualitative method with a dedicated sustainability assessment such as LCA, to capture the full scope of the potential environmental impacts and set ambitious targets which are likely to be unachievable by the current production setup.

### 6. Conclusions

The study served the purpose to embed environmental considerations in the exploration, development and operation of production technologies. The developed methodology has been operationalized by combining and adapting existing tools.

The company's environmental strategy and the need for simplification have been the main driver in the definition of the relevant focus areas of each part of the methodology. Although the environmental strategy does address the most important environmental hotspots and are as such considered in the methodology, it does neither include other relevant impact categories nor puts the impacts in perspective of the finite system of 'planet earth'. While this project very likely leads to an improvement in the environmental performance, since it supports selecting more sustainable technologies, and to some extent puts environmental issues on the staff's radar in day-to-day development work, it remains stuck in the efficiency paradigm, hence hindering a development to de facto sustainability.

### 7. Future research

Future research will have to address shortcomings in the quantitative assessment and how it has to be anchored in the organizational management processes. The former includes the standardization of the data baseline and a review of the indicators that are to support the decision making process. The latter will be addressed by advancing research into the management processes supporting the application of the methodology. This will expand beyond the case company to include general barriers in the implementation of sustainability in the organizational context.

Further, the study aims to create a closer link of the here proposed methodology in order to seamlessly integrate qualitative and quantitative tools in the green lean approach.

The Green Lean initiative itself will be focusing on the integration of relevant environmental indicators for all levels and is conceptualized in parallel with a pilot project that has been initiated in fall 2017.

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