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Design for Sustainable Public Transportation: LCA-Based Tooling for Guiding Early Design Priorities

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Abstract: Environmental sustainability is an increasingly important subject for public transportation organizations. For passenger train operators, modernization projects provide key opportunities to improve the environmental impact of their rolling stock by making informed design decisions at the midpoint of the life cycle of their trains. Life Cycle Assessment (LCA) is widely adopted as the main instrument for evaluating environmental impact. However, in the past LCA was rarely used in the earlier design stages, where it is most effective, due to constrained access to data, information, and LCA-specific expertise. To this end, a purpose-built streamlined LCA tool for train modernization is developed and demonstrated, following a Design Science Research approach. The developed tool simplifies the application of LCA employing four main design principles: (1) sacrificing the declarative function of LCA, (2) the use of Input–Output-based Life Cycle Inventory, (3) the inclusion of 'shadow costs', (4) the limitation of the included environmental impact categories. By streamlining the application of LCA in this way, it becomes possible to introduce LCA-based principles and ways of thinking into a process that would otherwise be inaccessible to performing LCA in: the early design stages of modernization projects.

Keywords: public transportation; train modernization; environmental sustainability; life cycle assessment; railways

1. Introduction

Environmental sustainability is increasingly important in the management of transportation systems as Europe moves towards a 100% renewable transportation system for climate, energy, and sustainability reasons [1]. This topic is being addressed in all major modes of transport, including road transport [2,3], air transport [4], maritime transport [5–7], and railway transport [8]. Even though railway-based transportation has a relatively low environmental footprint in Europe when compared with other modes of transportation [9], there are still many opportunities to improve (electric) railway travel concerning sustainability, for example by improving energy conversion [10].

Train modernization projects are critical points halfway through the life cycle of rolling stock. These projects offer opportunities to learn from years of experience with an existing train series and to implement improvements to the existing design. In the building sector, for example, the refurbishment of existing constructions is generally seen as a favorable alternative for new buildings from an environmental point-of-view, though sometimes at the expense of lower utility or higher costs, depending on the pre-existing condition of the building [11]. Similarly, train modernization offers an interesting opportunity to improve the environmental sustainability of rolling stock. Assessing sustainability in these projects, however, can be a complex challenge, demanding a proactive consideration of environmental sustainability aspects from project managers and project-related stakeholders [12].

1.1. Front-Loading of Environmental Improvements

The earlier phases of product development offer the most potential for improvement, but also offer the least knowledge about the product [13,14] (see Figure 1). An effective approach to deal with this knowledge trade-off can be found in front-loading, "a strategy that seeks to improve development performance by shifting the identification and solving of problems to earlier phases of a product development process" [15]. This strategy makes it possible to address problems before they become too costly or difficult to solve. The effectiveness of front-loading can be improved by transferring knowledge and problem-specific information from previous projects, as the information from the existing train can be used to support the redesign of the modernized train. For this reason, the research focuses on train modernization, where rolling stock receives a mid-life update.

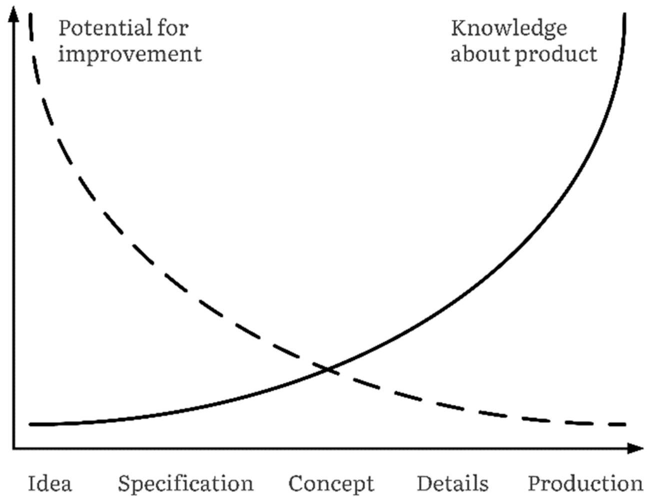

Figure 1. The trade-off between improvement potential and knowledge about a product [13].

An important limitation of applying the 'front-loading' strategy to sustainability-focused measures is that it can often be unclear to what extent these measures are effective. To evaluate the potential of environmental improvements for specific (re)design propositions, there needs to be a tangible way to evaluate their efficacy.

1.2. Life Cycle Assessment

Academic interest in life cycle sustainability assessment has seen a rapid rise in the last decade, covering a broad range of methodological discussions as well as focused topics [16,17]. Although the exact understanding of environmental sustainability and its assessment varies per company, the use of Life Cycle Assessment (LCA) to facilitate more sustainable decision-making is widely recognized as the main approach and the most suitable basis to evaluate environmental sustainability [18–20]. The ISO 14040 [21] and 14044 [22] standards provide internationally recognized principles and guidelines required for performing an LCA. This enables a commensurable quantitative assessment of all emissions of harmful substances, depletion of finite resources, and resulting damages to the environment of a product life cycle.

LCA is commonly applied to assess the cumulative potential environmental impact of the life cycle of a product or process. This can be done for various purposes, for example, for communication and marketing aims [21]. Many LCA reports and publications adopt this declarative style of LCA, as they are intended to be shared with professional or academic audiences. This declarative purpose is reflected in LCA-based reports and regulations such as Product Environmental Footprint (PEF) and Environmental Product Declaration (EPD) which require transparency and have set guidelines for their documentation. EPDs communicate the impacts of material extraction, energy use, and waste treatment and standardize the quantification of several environmental impacts of a specific product. Each product category has its specific regulations, summarized in its Product Category Rules (PCR). For example, for rolling stock the product category rules *PCR 2009:05 for Rolling Stock Version 3.02* applies, belonging to the product group classification of *UN CPC 495* [23]. The PEF aims to increase the comparability between environmental impact assessments of similar products, which in the past, proved to be too difficult in communication with the customer [24]. PEF aims to improve comparability and communicability to various stakeholders by limiting the flexibility of methodological choices for these product categories, thus reducing the flexibility that LCA is known for [25]. Its implementation is not without its challenges, especially concerning (1) the expected policy outcome, (2) difficulties in application, (3) added value compared to regular LCA, (4) maturity of the underlying impact assessment methods, (5) a fair comparison of products [26].

Besides its declarative function, LCA can also be used to investigate environmental improvements, focusing on the aspects that are affected by decisions about certain products or processes [22]. An improvement-focused LCA is facilitated by linking processes in the product life cycle to environmental damages by tracking all material, energy and waste flows in the life cycle. However, the improvement analysis in LCA often receives little attention, despite its usefulness in actually lowering environmental burdens [27]. During product development, when design decisions are still flexible and typically confidential, there is a lowered burden of proof for the organization concerning claims about environmental impact. This allows for much lower requirements of LCA concerning certainty, transparency, and documentation than declarative applications such as eco-labeling or foot-printing [28].

1.3. Streamlined Life Cycle Assessment

The requirements for regular LCA applications lead to high cost, time, and issues of data confidentiality and verifiability, even to the point that some consider it to be a flawed tool that cannot deliver what it promises [29]. The application of LCA in early design stages can be difficult because of its tedious, expansive, and time-consuming nature [30]. The practical use of LCA methods and software tools in industry, therefore, reveal the need for streamlined life cycle assessment methods that are derived from experience with the complex's full methods [31]. Streamlined LCA aims to provide essentially the same type of results as a full LCA, i.e., covering the whole life cycle, but superficially (e.g., using qualitative or generic data), followed by a simplified assessment, thus significantly reducing the expenses and time expended [32]. Streamlining draws parallels with the As Low As Reasonably Practicable (ALARP) approach [33] which was originally intended for risk management. The core concept of ALARP is to set tolerable risk levels, instead of attempting to eliminate risk at all costs. This approach can also be applied to the evaluation of environmental impact, where the goal is not to perfectly evaluate impact but to choose a form of evaluation that is reasonably practicable.

Three levels of LCA can be distinguished, separated by an order of magnitude in the typical work required to perform them in decreasing order [28]: (1) full LCA, (2) streamlined LCA (or screening LCA), and (3) matrix LCA (see Figure 2). Full LCA is understood as an ISO 14040/14044 compliant application, fit for communication with the general public, and places high demands on aspects such as data quality, interpretation and requires a critical review from a third party. Full LCA is thus usually conducted by environmental specialists and rarely by designers during the design phase [34]. Streamlined (or screening) LCA is a simplified version of LCA that is usually not ISO-compliant, but can be used to identify 'hotspots' in a product life cycle and are best suited to comparative studies where data limitations are likely shared by both options. Matrix LCA is the simplest form of assessment, providing only brief and mainly qualitative or semi-quantitative information at a basic level.

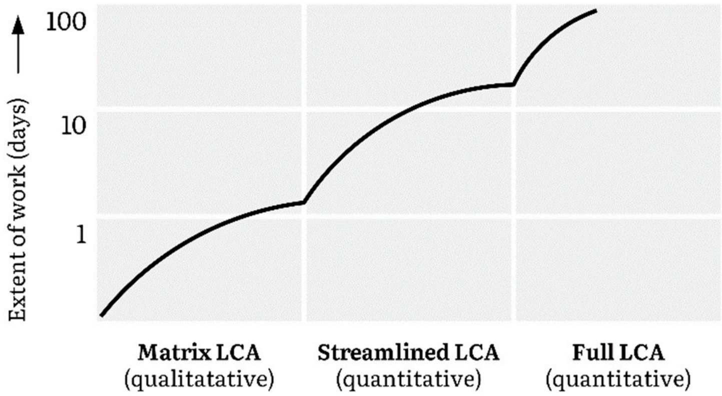

Figure 2. Three levels of LCA, indicating the typical extent of the work required (adapted from [28]).

Qualitative LCA approaches such as matrix LCA are unable to capture all the results of a full LCA, which may lead to a loss of important insights [35,36]. Streamlined LCAs are also subject to a high degree of uncertainty when compared to a full LCA. An important distinction to make when talking about uncertainty in LCA is the difference between accuracy and precision, which are often perceived as synonyms, but are not [32]. Accuracy describes the closeness of a measured value to its 'true' value, whereas precision represents the spread of these measurements. In consequence, the accuracy of a model's result may be high while its precision can be low, meaning that the average of such model results will still represent meaningful information even though the results' spread (i.e., the standard deviation) may be large [32]. As simplification is required to allow the application of LCA in the earliest design stages, the focus of this research is positioned in this domain of high accuracy and low precision.

1.4. Research Aim

Overall, the limitations of LCA mean that the method is rarely used as an improvement instrument by designers, especially in the most crucial early design stages. LCA typically relies too strongly on the expertise of the assessor, the availability of time, and availability of appropriate information and data, making its application in this early stage unfeasible. The research described in this article therefore aims to develop and present a streamlined LCA-based software application that is specifically designed for assessing early design decisions in train modernization projects. The results of the research indicate that it is possible to trade precision in the application of LCA in exchange for much lower reliance on the aforementioned data, information, and expertise. In this early stage, generic Life Cycle Inventory data can be applied to use LCA as an internal improvement analysis instrument, lowering the burden of proof that is typically associated with declarative uses of LCA, such as the PEF. This streamlining process lowers the barrier of applying LCA to the extent of making its application feasible in the earlier design stages, as demonstrated in the modernization process of a double-decker train used as a case study.

2. Materials and Methods

2.1. Methodology

To explore the problem that has been stated in the introduction, this article follows a Design Science Research (DSR) approach, which can be operationalized in various ways [37]. This article builds on an iterative DSR approach for producing and presenting DSR [38], as illustrated in Figure 3.

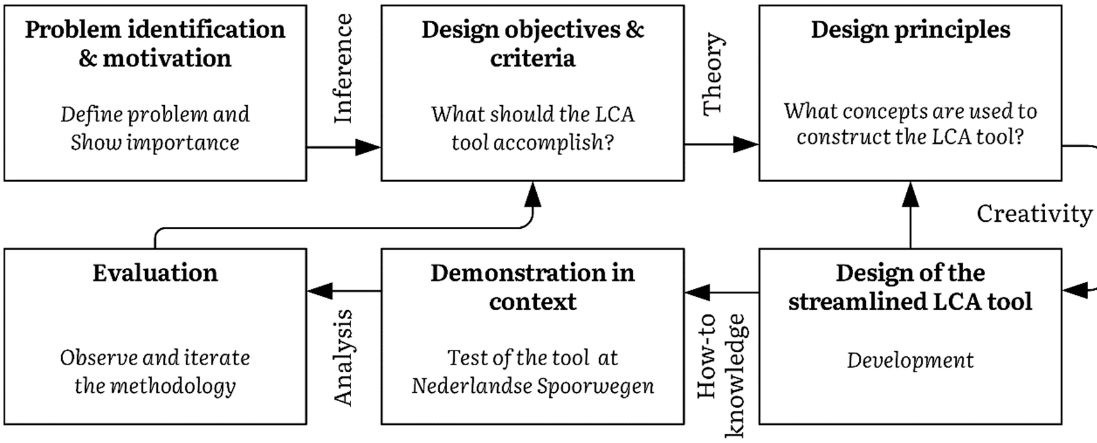

Figure 3. Structure of the Design Science Research approach (modified from [38]).

2.2. Design Criteria

In this section, the design objectives and criteria are introduced, indicating what a successful streamlined LCA tool should be able to accomplish. To ensure the rigor of the design evaluation process, it is structured using a mostly formative, ex-ante, and naturalistic evaluation strategy [39,40]. The validity of the adopted DSR approach mainly stems from requirement validity, criterion validity, and theoretical validity [41]. The design criteria for streamlined LCA concern relevance, validity, compatibility with computational procedures, reproducibility, and transparency [42]. These principles are adapted into five design criteria that a streamlined LCA model for use in asset procurement should meet (see Table 1). These criteria are evaluated together with a focus group within the train modernization department at Nederlandse Spoorwegen, including the (ex-post) evaluation of the first working design of the tool in a real environment.

Table 1. Criteria for the streamlined LCA-based tool [42].

Criterion	Description
Relevance	Compatibility in regards to the decision to be supported by the LCA. In this application this relates to the design decisions of train modernization.
Validity	The streamlined LCA should show similar insights as a more detailed study would have, though a lower resolution is acceptable.
Compatibility (with computational procedures)	The streamlined tool should be able to be integrated alongside other design criteria and into existing databases and existing information technology environments related to modernization.
Reproducibility	The tool should be designed so that different practitioners arrive at the same LCA score or ranking result, given identical asset characteristics (and goal and scope definitions).
Transparency	In order to be credible and to identify improvement potentials, it should be easy and feasible for a practitioner to understand the calculation of the final result and origins of the main environmental issues.

2.3. Design Principles

In this research, three techniques are combined and incorporated into the design of the tool. (1) The use of streamlined Life Cycle Assessment, (2) the application of Input–Output-based Life Cycle Inventory, (3) the use of 'shadow costs' to express environmental impact in financial terms. The first of these techniques have already been discussed in the introduction. The latter two will be briefly explained.

2.3.1. Input-Output Based Life Cycle Inventory

Streamlining efforts within LCA mainly focus on the Life Cycle Inventory (LCI) analysis, which is typically the most time-consuming phase. LCI involves modeling all energy and material flows in the life cycle of a product. As this activity requires modeling of all relevant processes and their flows, streamlining efforts at the LCI phase have the greatest potential for savings, as it is the most time-consuming phase of LCA [42]. Missing data place an additional and considerable limitation on LCI concerning uncertainties and the speed of conducting a process-based LCI study [43,44]. When LCI data for specific materials are missing, relying on a generalized impact of a broader material group can be used to make suitable estimates [45]. The use of generic data over specific data can be used to save time in developing the LCI, but also increases the possibility of errors in the conclusion of that LCA.

An alternative for process-based LCI exists in the form of the Input–Output (IO) method, where the life cycle impact is modeled for specific industries and economic sectors. Using economic allocation, these direct impacts are then combined into embodied impacts for each produced good or service (i.e., how much impact is caused by the whole upstream processing of a good or service) [32]. IO tables reveal what each sector spends on the goods and services of another, making it possible to allocate the environmental impact of a single industry's flow based on the overall impact of a specific sector, or national and global economies [42]. Compared to process-based analyses, methods that utilize IO analyses generally show smaller data requirements [46]. An IO-based approach is both fast and comprehensive as it has the whole economy as its system boundary, negating the need to make difficult system boundary choices [32].

There are also drawbacks to the use of IO methods. It is more challenging to fit specific data into the generic data structure for IO matrices compared to process-based LCI, due to the self-referencing and recursive nature of IO tables [47]. Additionally, the used economic sectors mainly encompass the upstream and core processes, related to the production phase of the product life cycle, adopting a cradle-to-gate scope. Downstream processes (related to the use and end-of-life phases) are not commonly considered by the economic sectors. Lastly, it also requires a comprehensive, recent, and localized IO-based dataset that contains all metrics related to multiple environmental impacts.

2.3.2. Shadow Costs of Environmental Impact

Natural capital is one of the six aspects that are required to be reported about in Integrated Reporting (IR), a reporting framework that proposes the integration of financial and non-financial information in a single report [48]. LCA normally relies on normalization to aggregate multiple environmental impacts using a recognizable outside reference and to make sense of the magnitude of the impact. Many impact assessment methods (CML, ICLD, ReCiPe, TRACI, etc.) use Person Equivalents (PE) to normalize, expressing the calculated impact in terms of the average yearly impact of a person at the national, continent, or global level.

Even though the use of PE-based normalization is common in LCA, it is not common in corporate reporting. In recent years, industries have begun to show major interest in the use of environmental prices, mainly in the context of Corporate Social Responsibility (CSR) to quantify progress on certain sustainability issues [49]. These 'environmental' or 'shadow' costs are approaches that aim to express environmental impact in monetary terms, usually based on abatement or damage costs. Even though these costs are expressed using financial units (e.g., € or $), they can be seen as prices for something for which there is no market, having no actual financial value.

Conceptually, the use of shadow costs is similar to that of normalization to personal equivalence (see Figure 4). Both approaches use an outside reference to allow for the aggregation of multiple environmental effects and making sense of the magnitude of the impact.

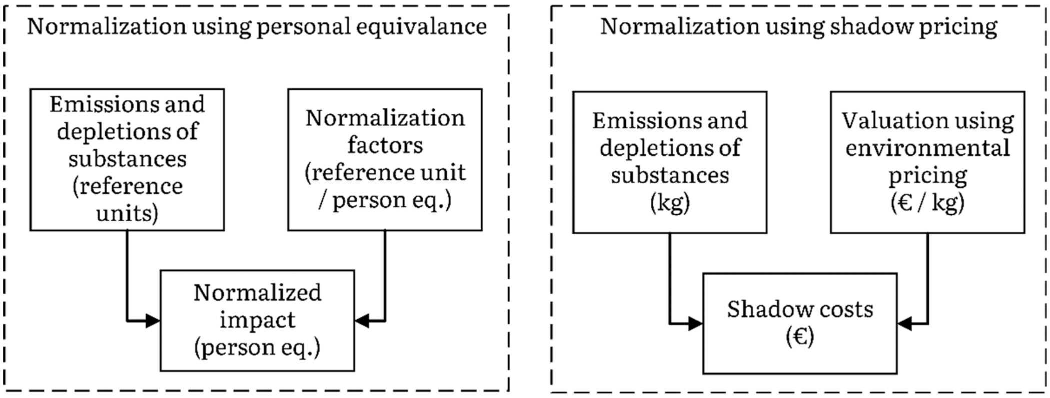

Figure 4. Relationships in conventional normalization and normalization using shadow costs.

The main difference between personal equivalence and shadow costs is that shadow costs are already expressed in monetary terms, making interpretation, decision-making, and communication of the results easier, as people are likely to have a better understanding of the value of money than of the average environmental impact of a single person. By expressing environmental impact in financial terms, it becomes easier to evaluate the two side-by-side (compatibility criterion). Furthermore, streamlined LCA and shadow costs can be effectively combined to evaluate the environmental impact of products in the early design stages of a product, but cannot be used as a substitute for full LCA [50] (which is not the aim of the design).

2.4. An LCA-Based Tool for Guiding Early Design Priorities in Train Modernization

A computer-assisted streamlined Life Cycle Assessment tool was developed to evaluate the environmental efficacy of various design decisions during the early stages of train modernization. The LCA tool supports the identification of environmental impact 'hotspots'. The tool takes the form of a standalone software application specific to this goal, which is intended for internal audiences within the Train Modernization department of Nederlandse Spoorwegen.

2.4.1. Goal and Scope of the Streamlined LCA Tool

The goal and scope of the application have been predetermined, to ensure that it is appropriately focused on the train modernization process (as required by the relevance criterion). By purposefully predetermining this first phase, the professionals who need to use the tool can skip this phase, further streamlining the LCA-based evaluation process. An overview of the characteristics associated with the 'goal and scope' phase of this LCA application is provided in Table 2.

Table 2. Overview of the goal and scope characteristics of the streamlined LCA tool.

Element	Description
Goal	To identify the 'hotspots' of environmental impact associated with early design decisions in train modernization to improve these design decisions.
Intended audience	The internal staff of the Train Modernization department of the Nederlandse Spoorwegen (NSTM). The outcome is not to be shared with external audiences.
Functional Unit	Passenger·kilometer
System boundaries	Economic system level (as determined by the IO-table based inventory of the Exiobase v3 database)
Allocation method	Economic partitioning (following the economic nature of using IO-based LCI, based on economic proportion in each industrial/economic sector)
Environmental impact categories	The impact categories have been chosen by Nederlandse Spoorwegen and enable future compatibility with EPD: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP)
Main assumptions & limitations	▪ Only the remaining useful life of a modernized train is included in the scope. The lifespan before modernization is excluded. ▪ The application is considered a streamlined LCA which does not comply with ISO 14040/14044 norms.

2.4.2. Inventory of the Streamlined LCA Tool

The source for the IO-based inventory is the open-source database called Exiobase [51]. Exiobase v3 contains inventory data on 164 economic sectors for 97 countries. It not only depicts the IO matrices of individual countries, but also takes into account the interconnections between them. Furthermore, it contains data on the five environmental impact categories included in this application, enabling future compatibility with EPD. It thus allocates and specifies the emissions of harmful substances for multiple economic sectors in various regions.

A user interface is used to link the data of the IO database to the life cycle of trains. A screenshot of the inventory window of the computer application is shown in Figure 5.

The LCI model for the modernized train is built by modeling individual components of the train which are treated as an average item from a corresponding economic sector, as found in the IO database. For example, the inventory data for seating is represented by the average item from the furniture sector. The remaining life cycle of the modernized train (including the modernization process itself) is thus modeled in an item-by-item way. The aspects that are used to build the LCI of the modernized train are summarized in Table 3. Information about the train's usage profile and remaining lifespan (years of use) is used to automatically calculate the environmental impact per functional unit for each user input. This not only simplifies the LCI process, it also ensures that different users should arrive at similar results, as the same data is used and the goal and scope have been fixed (reproducibility criterion).

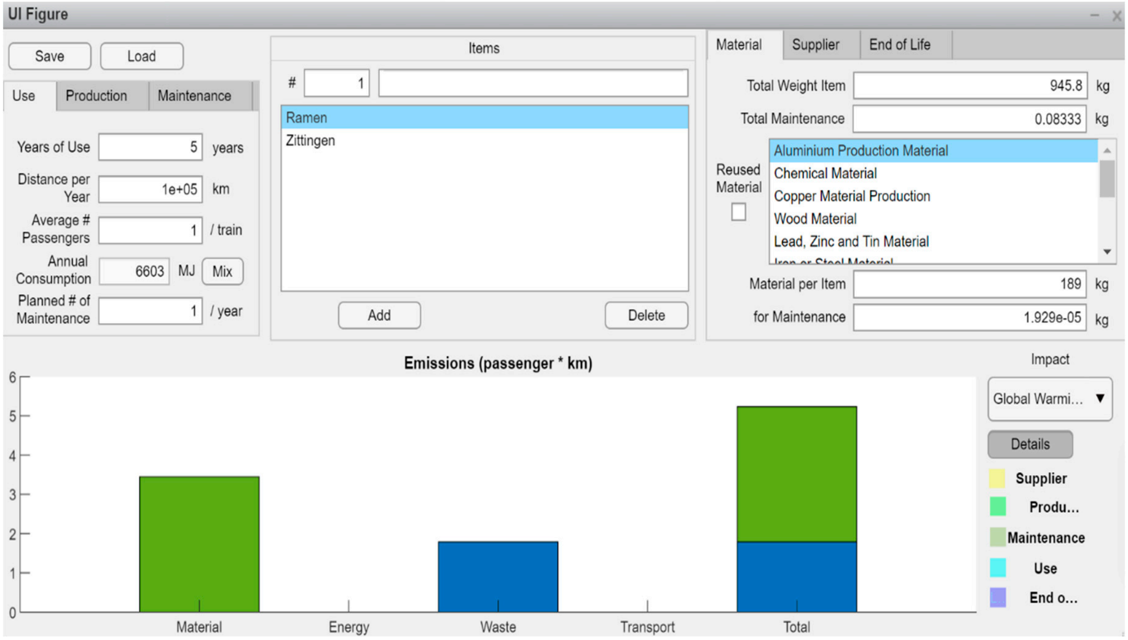

Figure 5. Screenshot of the streamlined LCA tool showing the inventory screen for train modernization.

Table 3. User input for the LCI of the modernized train.

Life Cycle Phase	User Input
(Raw) materials	Material composition and weights of the parts and components that comprise the train.
Supply chain	▪ Energy consumption and waste production at suppliers. ▪ Transportation from suppliers to the modernization facility.
Production (train modernization)	Energy consumption and waste generation during the process of modernizing the train.
Maintenance	Maintenance is treated as requiring additional components and is modeled in the same way as (raw) materials.
Use	▪ Component lifespan, expressed in years of use (time) ▪ Average daily use (time) ▪ Energy consumption (power) ▪ Source of (renewable) energy
End-of-life	▪ Selection of end-of-life treatment options such as landfill, incineration, bio-gasification, recycling, re-manufacture, and re-use. ▪ Transportation to waste treatment facilities.

3. Results

This section shows the results of the design process in the form of an LCA-based tool for evaluating environmental sustainability in train modernization. The application of the designed LCA-based tool is demonstrated by means of a case study at Nederlandse Spoorwegen.

3.1. Profiling in the Streamlined LCA Tool

The design of the tool allows for the inclusion of multiple environmental impact categories. However, in line with the aim of simplification, only the environmental impact categories that were dictated by the EPD for the assessment of trains were included in the initial design of the LCA tool. The result is a selection of only five environmental impact categories at the midpoint level (see Table 4).

Table 4. Environmental impact categories included in the streamlined LCA tool (PEF-compatible).

Impact Category	Unit	Environmental Effect (Midpoint Level)
Global Warming Potential (GWP)	kg CO_2 eq.	The contribution to global warming by the emission of greenhouse gases.
Ozone Depletion Potential (ODP)	kg CFC-11 eq.	The reduction of ozone concentration in the stratosphere.
Acidification Potential (AP)	mol H + eq.	The acidification of water and soils that is caused by the emission of acidic substances.
Eutrophication Potential (EP)	mol N eq.	The eutrophication of water that is caused by the emission of specific substances (discharge of phosphoric, nitrogenous, and organic matter).
Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq.	The formation of tropospheric ozone (summer smog), caused by the discharge of specific gases that have an oxidizing action under the effect of solar radiation.

An important limitation of this narrow selection is that the overall environmental impact profile of this application will be incomplete and lower overall when compared to other commonly used impact assessment methods that take into account a wider range of environmental impacts.

As discussed in Section 2.3.2, shadow costs are used to normalize the results of these five midpoint environmental impact categories. The shadow cost valuation used for this step is already used by Nederlandse Spoorwegen to report on environmental impact in their annual reporting [52] and follows the Handbook on Environmental prices [49]. This valuation approach uses the valuation of emission at the midpoint level, for the Netherlands (the geographical region of the case company) in the year 2015.

3.2. Interpretation Using the Streamlined LCA Tool

The tool is used to find the weak points and hotspots for the existing train design, identifying improvement opportunities for the design of the modernized train. Using the LCA tool, it is possible to trace back five (EPD oriented) environmental issues to specific components in the train design or specific life cycle phases (transparency criterion). The use of shadow costs is used for normalization, allowing a direct comparison between different environmental impact mechanisms as well as aggregation into a single (total) impact score that can be used to indicate the preferred design options. Nederlandse Spoorwegen already makes use of shadow costs in its annual reports, facilitating its inclusion in the streamlined LCA tool.

3.3. Demonstration of the Tool at Nederlandse Spoorwegen

The LCA tool is demonstrated and evaluated in a real-world train modernization project at the Nederlandse Spoorwegen. As the main passenger operator of the Dutch railway network, the company plays a vital role in providing sustainable mobility in the Netherlands. The NS Train Modernization (NSTM) is the branch of Nederlandse Spoorwegen in charge of the overhaul of part of the rolling stock fleet. Its long-term vision is to improve the environmental sustainability of the rolling stock that needs to be modernized to face the second part of their useful life.

The VIRM train series is the current backbone of the intercity fleet of NS. In this article, the VIRMm1 train (see Figure 6) is used to demonstrate the streamlined LCA tool. The modernization project for the VIMRm1 train series has already been completed. However, the other two trains in the rolling stock series (VIMRm2/3 and VIMRm4) are technically similar, enabling the use of the LCA-based tool for identifying future improvements.

Figure 6. VIRMm1 train during modernization at NSTM, extending its life another 18 years.

The information required for the LCI is derived from the bill-of-materials of the pre-modernized train using the material composition of each item that is considered within the scope of the modernization project. In this application, it is assumed that the new items have the same composition as the removed items. The production and maintenance phase are excluded from this train LCA, as insufficient data on these life cycle phases were available.

The application of the streamlined LCA tool allows for determining the overall environmental impact per functional unit (passenger · km) for the various components of the train. The 'shadow cost normalized' impact results show that the seats especially have a big environmental impact, followed by the doors and windows (see Figures 7 and 8). These impacts are primarily related to the weight of these parts, as they need to be accelerated and decelerated during the daily operation of the train using traction energy. The outcome of this assessment made the areas the attention of the re-design efforts should focus on clear.

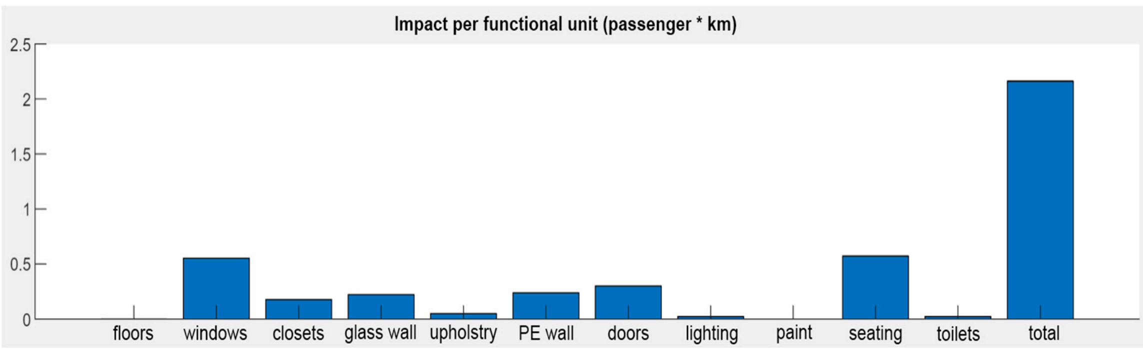

Figure 7. Screenshot of the streamlined LCA tool, showing 'shadow cost normalized' impact results.

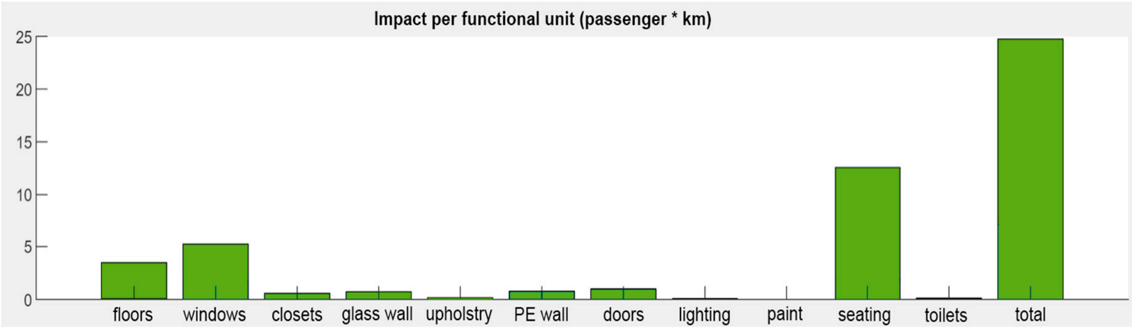

Figure 8. Screenshot of the streamlined LCA tool, showing the global warming impact results.

3.4. Evaluation of the Streamlined LCA Tool

The tool was evaluated together with the focus team of the train modernization department at Nederlandse Spoorwegen, demonstrating that is practically applicable and allows integration into the design stage of the train modernization process of a real-world railway operator. Furthermore, the resulting design meets the intended design criteria for streamlining (see Section 2.2) and the intended goal (see Section 2.4.1). Only the validity criterion proved to be difficult to fully evaluate without performing a full LCA (see Section 4.5), for which neither time nor resources were available in these early design stages. Instead of judging the validity of the LCA tool against a full LCA, it is more appropriate to judge the validity of not performing an LCA at all. Without the simplifications included in the design of the tool, LCA would not have been practically feasible in the first place. Compared to a lack of LCA, the tool was able to provide useful insights into the life cycle. With this tool, it is possible to identify and prioritize early design development directions, albeit at a low level of fidelity.

The ability of the LCA tool to support the assessment of various alternative design options was further evaluated by the staff from multiple departments of case company NS. These users had different levels of experience with train design and LCA applications. During these user tests, the users were asked to assess the impact on different environmental impact categories, thereby introducing the users to the full breadth of environmental impacts in the LCA tool. The users reported that the tool itself is useful for supporting the assessment of environmental impact, but that the ease-of-use of the interface of the LCA tool could be improved.

4. Discussion

The design of the LCA-based tool was guided by the question of how to simplify LCA in such a way that the reliance on limited information, data and expertise is as low as reasonably possible. These simplifications are achieved by employing four main design principles, which are briefly discussed. Even though the designed LCA tool is intended as a proof of concept, its application in a real-world setting and subsequent evaluation does allow for a reflection about its underlying principles.

4.1. Sacrificing the Declarative Function of LCA for Improvement Analysis

The first design principle that was applied is sacrificing the 'declarative' function that is typically associated with LCA. Sacrificing the declarative function means that the developed tool is not intended for external audiences and should not function as a means to report or to communicate about environmental impact. Instead, the tool emphasizes an internal application of LCA for improvement purposes based on sensitivity analysis and the comparison of design options. In this context, it can be used as a rough, but accessible basis for the identification of 'hotspots' in the environmental impact profile of the modernized train. A low-precision improvement analysis can already be useful in this context for determining key areas [53] for (re)design, as long as the accuracy of the assessment is adequate. Furthermore, the reliance on data, information, and expertise can be much lower for improvement analyses than it is for declarative purposes, lowering the barrier to using LCA.

Additionally, the streamlined LCA tool can also help familiarize staff with the concept of LCA in an approachable way, the lessons of which can also be used in later project stages where declarative LCAs such as PEFs are required, but require expertise to perform well [26].

4.2. Lowering Data Requirements Using Input-Output Based Life Cycle Inventory

The suitability of streamlined LCAs not only relies on the objectives of the study but also greatly depends on the databases that are incorporated [54]. The second design principle that was incorporated into the design of the streamlined LCA tool was, therefore, the application of an IO-based Life Cycle Inventory. This allows for a fast but comprehensive way to model the LCI. This generalized approach not only needs less data input, but it also reduces the chance of missing critical datapoints when compared with a process-based LCI, where information about each material flow and process step can be critical. Furthermore, the use of an IO-based inventory negates the process of making system boundary choices, a process that requires a high level of LCA expertise to perform well. The trade-off that is being made by using an IO-based LCI is that the results are also generalized to the level of national sectors or industries, resulting in an imprecise but accurate outcome of process-based LCI. This means that the quality of the database becomes critical, especially with respect to the level of detail, completeness, and its geographical and temporal validity of the database.

4.3. Lowering Interpretation Expertise Requirements Using Shadow Costs

The third design principle that was used in the design of the streamlined LCA tool was the use of 'shadow costs' for normalization, instead of the more common practice of using person equivalence. This design decision serves two main functions. Firstly, for non-experts of LCA, the concept of 'shadow costs' is arguably easier to understand than personal equivalence as it uses the universally familiar language of money. This is especially useful for judging the magnitude of environmental impacts. Secondly, the use of 'shadow costs' makes it easier to evaluate the less tangible 'soft' environmental impact alongside the 'hard' financial criteria of design, as it already uses the same unit (in this application it was the €). This combination of functions makes it possible to use 'shadow costs' both as the basis for normalization within the scope of the LCA application (substituting person equivalence) as well as the basis in which to harmonize the financial and environmental impact performances within the design requirements (which lie outside the scope of the LCA). This fosters an intersubjective discussion about how to prioritize design decisions. An important limitation of this approach is that the use of 'shadow costs' is more subjective than the use of personal equivalence, making it unsuitable for declarative purposes (see Section 4.1).

4.4. Simplified Profiling Using a Limited Set of Environmental Impact Categories

The fourth and last principle that was applied in the design of the streamlined LCA-based tool was to limit the number of environmental impact categories that were included in the application. The limited set of environmental impacts made it easier to interpret the result and to identify improvement areas, as there are not that many different types of impact to consider. Current demands on the breadth of environmental impacts that are included in LCA are often limited. For example, the EPD used to report on train modernization only requires reporting on five environmental mechanisms (the ones that were included in the designed tool), incentivizing organizations to focus mainly on these environmental factors.

This approach does carry a high risk of leaving blind spots in the evaluation of the environmental impact. Additionally, these blind spots may also result in burden-shifting to environmental impact mechanisms that are not included in the scope, potentially leading to a design that is only more sustainable 'on paper', as other environmental impact categories are not included. This characteristic, however, is not inherently part of the design of the tool but can be attributed to the current requirements of environmental reporting norms and ambition levels of the organization concerning environmental sustainability. To allow for future improvements in this regard, the tool can be easily extended to include other environmental impact mechanisms, provided the relevant data are available in the LCI database.

4.5. Limitations and Future Research

A discussion about the application of the tool with the staff of Nederlandse Spoorwegen did result in an additional insight about ownership and responsibility. The sources of expertise, data, and even environmental impacts could be traced to different departments within the organization of Nederlandse Spoorwegen. The use of the tool LCA not only required (and thus stimulated) collaboration between these departments, but also left an open question about the organizational level at which the responsibility for environmental impact and its assessment should be assigned in future modernization projects. A promising future development to address this challenge is to integrate sustainability into a digital twin of the system [55].

Another avenue for future research is to further evaluate the magnitude and sensitivity of the uncertainty introduced by the streamlining approach compared to a full LCA. This could be studied by performing an exhaustive, peer-reviewed LCA of the same modernized train upon completion, comparing this outcome to that of the streamlined LCA tool, and subsequently judging to what extent the identified environmental 'hotspots' are similar. Alternatively, the results of the streamlined LCA can be compared with a sufficiently large and representative sample of existing rolling stock PEF reports.

5. Conclusions

Environmental sustainability is an increasingly important subject for public transportation organizations. Measuring the type and extent of environmental impact is crucial, as it is difficult to improve something if you cannot 'measure' it. LCA is widely adopted as the main instrument for evaluating environmental impact. However, LCA is rarely used for improvement analysis in earlier design stages due to limitations concerning access to data, information, and LCA-specific expertise. In earlier design phases, it is easy to make changes, but less information is available, whereas late in the process there is more information, but it is difficult to make meaningful changes. This knowledge trade-off is especially apparent in the application of LCA [56].

Intent on breaking this trade-off, a streamlined Life Cycle Assessment based tool is proposed that, aimed to take sustainability into account in the earliest development stages. This is achieved by purposefully trading-off the precision for the sake of making LCA accessible and usable in the early stages of train modernization while ensuring high accuracy by using an IO-based LCI. By limiting the goal and scope, impacts, and associated system boundaries, to only a single predetermined and archetypical application [57], the LCA expertise and information requirements are lowered. The sum of these simplifications makes it possible to apply a rudimentary but focused form of LCA where it would otherwise be impossible to use.

By lowering the barriers of applying LCA, it becomes possible to make more informed decisions concerning environmental impact, as an assessment with low precision is arguably better than having no assessment at all. The quantitative nature of the tool helps with comparing and judging the magnitude of environmental impact and the efficacy of design options, finding hotspots in the rolling stock life cycle, and integrating the result alongside other design criteria, such as life cycle costs. This stimulates a different way of thinking during the design process by bringing more awareness of environmental impact and by linking engineering decisions with environmental improvement analysis as early as possible when it offers the most leverage. As indicated earlier, the proposed tool is not intended to replace full LCA, but to exist alongside it, albeit at a much earlier stage of the design process and a much lower fidelity. Errors made in the earliest phases of assessments can be quickly corrected once more information and data become available during the development process. Furthermore, this information is not wasted, as it can still be used to perform a full LCA in later stages. Metaphorically, this tool is to full LCA what a quick sketch is to a carefully crafted painting: A quick, but conscious effort to provide the broad strokes for the improvement of environmental impact. Even though the design explored in this article has been directed towards train modernization, the principles themselves may also be generalizable to other, physical-asset-oriented applications, both within and outside of the public transportation domain, as long as the goal and scope of the application are adjusted accordingly.

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