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Project implementation scenario selection for sustainable project and product lifecycle management. Application of network data envelopment analysis

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Abstract

A method has been proposed to select one of several project implementation variants in the context of sustainable project management. The method should be applied in the phase of the project definition. The projects are viewed across the entire lifecycle of the project and its product. In all the phases, the sustainability aspects should be addressed in a balanced way. The sustainability context implies that different stakeholders will have conflicting opinions on the weights of different variables. The proposed approach is based on network Data Envelopment Analysis that does not require the weights of individual variables as input. Consequently, the proposed method is the first approach allowing users to select a project implementation variant in the context of sustainability and the entire project and product lifecycle, without imposing the weights of individual variables. The proposal is designed for organisations using project sustainable management.

Keywords: *network DEA, sustainable project management, desirable inputs, undesirable outputs*

1. Introduction

Today, project management cannot be detached from sustainability [4, 57]. Organisations are increasingly motivated to adopt a sustainable approach to their projects. The motivation may be a consequence of legal regulations, but also of the conviction that a sustainable approach to management is profitable for the organisation – even if the profits do not always mean a quick and easy-to-achieve increase in the firm's cash account balance.

Regardless of the definition used, sustainability is based on multiple perspectives and goals, often conflicting. These perspectives and goals do not appear in a void but rather arise from real humans – people, groups, institutions, etc., with their expectations, limits, needs, strengths, weaknesses, emotions, lifestyles, and preferences. They all have to be taken into account in sustainable project management.

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Conflicting views and goals occur in all management situations, but they constitute the very substance of sustainable project management and the conflicts are especially strong. In sustainable management, goals concerning profit, the planet, and people have to be addressed in a balanced way, and this simply cannot be achieved without conflicting views. The method proposed here is a non-parametric one, which means that – in contrast to similar methods proposed in the literature for sustainable project management – it can be used to avoid discussions about variable weights. Accordingly, even if the approach proposed here can also be applied to other projects, it fills a gap that is especially important for sustainable project management, where the differences in the perception of variables' weights are especially significant.

This gap has been revealed in literature reviews: there exists no method allowing users to select a variant of project implementation in the project definition phase that would ensure a required level of sustainability would take into account the whole project and the project product lifecycles, and would not impose weights or target values of individual variables. And in sustainable project management, the problem of selecting project implementation variant is an inherent part of the methodology. The goal of this paper is to propose such a method. It will also be possible to apply it to sustainable project portfolio selection.

The proposed approach is based on an extension of the DEA method, called network DEA. It is a non-parametric method that allows for the treatment of objects containing stages. It is the non-parametricity of the method that allows users to avoid the necessity of imposing weights or target values of variables.

The outline of the paper is as follows: In Section 2, the problem of sustainability in organisation and project management is discussed. In Section 3, the state of art on evaluation of projects or project realisation alternatives in sustainable project management is presented. In Section 4, real-world case studies of projects are analysed, with the lifecycle of the project and product and sustainability perspectives. In Section 5, one-stage and network data envelopment analysis are presented. In Section 6, the proposed application of network DEA to project scenario selection in sustainable project management is proposed. Section 7 contains a computational example. The paper terminates with conclusions and some research perspectives.

2. Sustainability in organisation and project management

Sustainability and sustainable development have been used since the late 1980s. These were first applied to organisations and later extended to projects [57]. According to one definition, sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs [48]. Other authors refer to sustainable development as adopting business strategies and activities that satisfy the organisation and its stakeholders today but do not lose sight of the needs of humans in the future [35]. In this definition, "needs" encompass financial, human, and environmental resources. It is common to distinguish between three pillars of sustainability, such as people, planet, and profits [56], or economic prosperity, environmental quality, and social justice [50]. To be sustainable now means not only taking into account the economic and environmental aspects of an issue but also fulfilling people's cultural, material, spiritual, and intellectual requirements [60]. However, the economic aspect is not redundant, as increasing an organisation's competitiveness and thus its chances for survival through innovative solutions is also seen as a sustainability practice [47]. Tharp [63] lists the following aspects as elements of sustainability in project management: human rights, labour practices, the environment, fair operating practices, consumer issues, and community evolvement and engagement.

To summarise, the author of the present paper agrees with Williams and Millington [70], who state that it is difficult to define sustainability in a precise way. The understanding and perception of sustainability varies enormously from one person or group to another. Moreover, an interest in sustainability issues will not be equally strong among groups or persons who share the same definition of this notion. Tambulasi and Kayuni [60] present the notion of a sustainability matrix that represents the individual points of view of what sustainability should be. This matrix has four dimensions:

1. Weak versus strong sustainable development: Weak sustainability accepts losses or damage to the environment if they are outweighed by social and economic benefits, whereas strong sustainability involves the primacy of environmental protection over social and economic benefits;
2. Egalitarian versus non-egalitarian sustainable development: An egalitarian approach aims to increase the welfare of poor people, and to ensure that no development results in a decrease in the quality of life for poor people. A non-egalitarian approach protects the environment while seeking to maintain the living standards of the rich;
3. Bottom-up versus top-down sustainable development: In a bottom-up approach, the participation of all stakeholders is crucial. On the other hand, in a top-down approach participation of the project stakeholders is limited, or even avoided where possible;
4. Narrow versus broad sustainable development: In a narrow approach, environmental protection is an end in itself, while in a broad approach, other perspectives (economic, social, etc.) are also important.

The sustainability matrix, which may of course be modified and expanded, highlights the fact that each project stakeholder may have a very different view of project sustainability, and these views additionally may vary in their intensity.

Sustainability forms the foundation of product and project lifecycle management (PLM) and product and project lifecycle assessment (PLA), which have been extended to sustainable PLM and PLA [24, 59]. These terms refer to managing and/or evaluating projects and products while taking into account all the stages of product production or project implementation, from the point of view of sustainability. In the context of projects, a sustainable lifecycle approach means considering all the phases of the project in the context of sustainability, as well as the lifecycle of the project's product. The phases will vary from one project to another, but will always include (possibly under different names) initiation, planning, execution, closure, the usage and maintenance of the product, and possibly its disposal.

Sustainability is achieved through a balance between objectives related to profit, the planet, and people. This balance has to be defined in each case by the project sponsor or project owner. A useful way to calculate and ensure such a balance is to use the so-called P5 approach (P5 Standard) used by the PRiSM (projects integrating sustainable methods) project management methodology [4]. The P5 (people, planet, prosperity, process, and product) approach is a selection of aspects that have to be taken into account in sustainable projects. The aspects are grouped into three categories, as presented in Table 1 where the first three 'P's from the *P5 Standard* can be found) and further subdivided into finer sub-categories. Further categories, both the process of project implementation (in all its phases) and the project product viewed across its entire lifecycle, have to address all the sustainability aspects from Table 1 in a balanced manner.

Table 1. Main aspects and categories of the P5 standard

Category	Aspects
Society (people)	labour practices and decent work society and customers human rights ethical behaviour
Environmental (planet)	transport energy water consumption
Economic (prosperity)	return on investment business agility economic stimulation

An important part of the PRiSM methodology is the analysis of project stakeholders. Each stakeholder will represent one or more aspects from Table 1. The project owner should assign weights to the stakeholders assuring that each phase of the project's implementation and the project's product lifecycle will equally address the aspects in Table 1. For example, if there are five stakeholders interested in the economic aspects of the product and only one interested in its environmental aspects, the weight of the latter should be higher. Similarly, if more stakeholders are more interested in the sustainability of the process than those interested in the sustainability of the product, the weight of the former should be higher. A similar balance has to be given to the relation between the present and the future. If necessary, additional stakeholders representing the missing aspects should be included or the project owner themselves should take on the role of the supporter of an underrepresented sustainability aspect.

Each stakeholder should identify the aspects from Table 1 that are of interest to them, define the project or product lifecycle phase(s) that they are most important for them and define the inputs and the outputs of these phases using the detailed description of the respective aspects from the *P5 Standard*.

Another important aspect of the PRiSM methodology is that it requires multiple project delivery scenarios (called in the following also realisation or implementation alternatives) to be considered at the project definition stage. Thus, the problem of selecting one project implementation option from among many, with the project being seen across its lifecycle and that of its product, occurs in the case of every project implemented according to the PRiSM methodology.

3. Evaluation of projects or project realisation alternatives in sustainable project management – state of the art

The selection of projects or project realisation scenarios before project initialisation is a problem encountered in everyday practice of project management. It is performed in at least two situations:

A. Selection of project portfolio by an organisation [37]: Not all project candidates can be implemented within a given project budget if they exceed what is available. Thus, a multicriteria problem of project candidates' evaluation has to be solved, leading to a project ranking. The first projects from the ranking list are selected for implementation until budget exhaustion;

B. Selection of project implementation alternatives [4]: Before the initiation of a project, several alternatives for its implementation are often considered. A multicriteria problem then has to be solved; this is essentially similar to the one considered in the previous case. The result is a ranking of project implementation alternatives. Here, only the highest-ranked candidate is selected. The solution to this type of problem is required by some project sustainable management methodologies.

In both cases, the mathematical programming problem to be solved has a similar structure: a set of evaluation functions (maximised, minimised, or assigned a target value) and a set of constraints. In each case, a multicriteria optimisation method has to be selected. If sustainable management is applied by the organisation in question, the objective functions and possibly the constraints have to take sustainability into account.

The library search engine Primo VE (*Primo*) was used to identify the present state-of-the-art concerning project or project alternatives selection in the context of sustainability. Eight significant papers have been identified. The approaches used in those papers are summarised in Table 2.

Table 2. Summary of the state of the art of project or project scenario selection problems in the context of sustainability

Project evaluation criteria groups	Multicriteria method used	Reference
Economic, social, environmental	AHP	[27]
Economic, social, environmental	multicriteria group decision making	[21]
Economic, social, environmental	trade-off objective function	[28]
Economic, social, environmental, technical	goal programming	[1, 2]
Economic, financial, social, environmental, governance	multicriteria group decision making	[14]
Economic considering the cost of sustainability	Single weighted objective programming	[34]
Economic, strategic alignment, operational planning, proper cooperation of human resources, production components, environmental, social	fuzzy best-worst method, fuzzy robust stochastic programming	[51]
Weighted total of productivities of consecutive stages	network DEA	[38]

In all the identified papers – except for that by Li [38] – the considered projects are seen as one phase. This means that either various phases were not analysed or the entire project and product lifecycle was not considered. Both approaches have severe drawbacks. If a long-term project is viewed as a whole, it is not possible to take into account its intermediate effects or the outputs of individual phases, which may be harmful to the environment or wider society, even if this negative effect is temporary. On the other hand, if a project is considered in isolation from the whole project and product lifecycle, its overall effect cannot be evaluated and may even be falsified. For example, a project product may be harmless and useful to the users for a while, but after disposal and decomposition, it could become extremely harmful.

The other drawback of the existing approaches (Table 2) is the need to provide certain parameters that are typically difficult to agree upon. In all the identified cases (except for [38]) unique target values, coefficients, or weights for the objectives from Table 2 have to be given. There is no room for modelling conflicting interests between different stakeholders that are normal in sustainable project management. The stakeholders are not referred to at all.

The paper aimed to cover the problem of project or project scenario evaluation in the context of sustainability across the entire project and product lifecycle, with clearly isolated project and product lifecycle phases. The extant scientific literature has been consulted to identify the existing descriptions (case studies) of projects with distinguished phases. It follows from the literature review that the problem of evaluating such a project is still up for debate. Li [38] discusses one project type seen in phases and proposes a specific solution, although it is far from general (as subsequently discussed). In the next section, the case study review aims to identify information or parameters based on when such an evaluation might be performed.

4. Analysis of real-world projects across the lifecycle of the project and product with sustainability perspective

Tambulasi and Kayuni [60] describe a harvesting project whose aim was implemented in Malawi over the period 1987–2001; its goal was to respond to the issue of accelerating deforestation and the resulting energy crisis. Fundamentally, it consisted of two stages, followed by the usage of the project's product:

Stage 1. Planting and protecting the plantation;

Stage 2. Handing over the plantation to local communities;

Usage. Use of the plantation by the local community to provide fuel wood.

The primary stakeholders were local community members who were interested in having access to the wood, the environmental organisations that aimed to ensure the sustainable consumption of the wood and prevent further deforestation, and a financing organisation interested in not exceeding a certain budget and achieving a plantation characterised by a fairly sufficient surface and a fairly good survival capacity. Table 3 describes the inputs and outputs of individual phases that can be concluded from the description of the project.

Table 3. Inputs and outputs for the project phases [60]

Stage	Inputs	Outputs
Stage 1	Budget	Plantation quality
Stage 2	Salaries for the local workers Plantation quality Plantation surface	Plantation surface Harvesting schedule
Usage	Harvesting schedule Plantation quality Plantation surface	Energy production Plantation quality Plantation surface

The units of measurement for the individual inputs and outputs in Table 3 are not always clear. The budget and salaries will be measured in monetary units, and the plantation surface in units of area; however, plantation quality is a notion that needs to be further clarified. From the point of view of the local community, the quality of the plantation will be equivalent to the energy provided per surface unit of the plantation. By contrast, for environmental organisations, the same notion will probably mean the degree of robustness (the survival capacity) of the plantation. Certain tree species may determine the robustness and thus the quality of the plantation. The harvesting schedule may be measured by its degree of liberality: local communities would prefer a liberal schedule, allowing them to harvest any quantity of wood at any time, whereas both the environmental and funding organisations will be interested in more limited harvesting possibilities. Energy production will be measured using energy-specific measures.

Resorting to a certain simplification and generalisation, it can be said that from the point of view of local communities, the budget is rather neutral, but the salaries of the local workers (due to a work shortage and poverty in the region, the egalitarian approach is preferred), the plantation surface and the energy production should all be as high as possible. Similarly, the harvesting schedule should be as liberal as possible and the plantation quality should be measured in the energy provided per surface unit and should also be as high as possible. For the environmental organisations, the budget and the salaries will be neutral, and the surface area and quality of the plantation should be as high as possible; the latter should be measured by its degree of robustness. Furthermore, the harvesting schedule should be as scant as possible and the energy production as high as possible. The funding organisation will aim to minimise the budget and the salaries paid to local people, and to maximise the surface area of the plantation and its quality (in the sense of robustness), in addition to maximising the the energy produced (a rather narrow approach will be represented).

The importance of the phases will also vary. In the initial phase, local communities may attribute the highest weight to the first stage and possibly to the second, which will determine the harvesting policy, as they will be interested in a near-term agenda of creating jobs. In contrast, the funding agency will assign the highest weights to the performance indicators on which the project will be evaluated, and it is common knowledge that such indicators sometimes have little to do with the importance of the stages as perceived by the stakeholders [44]. The environmental organisations will probably assign the highest value to the usage stage, as it will have the strongest long-term consequences.

Li [38] describes a biogas project in China, and more precisely its final phases: biogas production and biogas consumption. The goal of the project is to motivate as many rural households as possible to install equipment using biogas in their houses. The inputs and outputs are defined as shown in Table 4.

Table 4. Selected inputs and outputs for the stage of the project described by Li [38]

Stage	Inputs	Outputs
Biogas production	biogas investment rural population subsidy for installing the necessary equipment quantity of biogas service stations	biogas production
Biogas consumption	biogas production	number of rural household biogas digesters reduction in the emission of CO_2 effect on soil quality average per capita net income environmental benefits

The most important variable in this example is biogas production, which is an output in the first stage and an input in the second. A solution to the conflicting situation is based on the introduction of an intermediate variable in an attempt to strike a balance between biogas production as both output and input. However, this is done without referring to the project's stakeholders, who should be responsible for determining this balance; otherwise, it will be purely theoretical. For example, the production of biogas should be maximised from the point of view of policy-makers (who follow political decisions) and for environmental organisations but should probably be minimised according to the preferences of electricity and natural gas producers (for whom it will mean a market decrease).

Several papers presented projects involving the use of solar energy by individual households or neighbourhoods. Snegirjovs et al. [58] describe a general project for an individual customer, but solar systems may also be installed in specially designed neighbourhoods, as in the Civano project described by Nichols and Laros [46], where the solar system is only one element of the environmentally friendly solutions applied. Such projects pass through several stages, from proposal, through design and installation, to maintenance. The inputs and outputs of the individual phases of such projects are shown in Table 5.

Table 5. Selected inputs and outputs for the project described by Snegirjovs et al. [58]

Stage	Inputs	Outputs
Proposal elaboration	initial data customer needs	proposal
Design	initial data from proposal	design results of analyses full documentation for the installation team
Installation	design results of analyses full documentation for the installation team workload of the installation company	installation of the solar energy system
Maintenance	installation of the solar energy system workload of the maintenance company	number of breakdowns

The inputs and outputs in Table 5 once again illustrate the difficulty and the complexity of defining the inputs and outputs in the context of sustainable project management and the strong dependence of such definitions on stakeholders. For example, the number of breakdowns will simply be considered as a variable to be minimised, but the maintenance company will be interested in a high number of breakdowns if a profit can be made from each repair. The workload of the installation company will also have a double nature: the users will want to minimise it while the installation company would normally prefer to maximise it. However, assuming that the installation company adopts a sustainable perspective, that is, thinking not only about today but also about the future, they may treat the workload as an input to attract future customers with an attractive price.

Furthermore, the units of measurement will again depend on the stakeholder. For example, the initial data variable can be measured based on the cost incurred to obtain the data or by its quality, as judged on a given scale by an adequate stakeholder. Another measurement possibility linked to this variable is mentioned by Snegirjovs et al. [58] in the form of an opinion of one of the stakeholders: *It is beneficial to avoid initial on-site visits*. On-site visits increase the data quality but result in a proportional increase in the administrative cost. This stakeholder was willing to accept lower data quality, as the cost of obtaining initial data using on-site visits would be an input.

Tongo et al. [66] describe a building construction project in Nigeria through all its stages of development (pre-design, design, pre-construction, construction, and postconstruction) in the context of waste generation. For all the stakeholders except waste management companies, waste is an undesirable output. However, the study shows that the measurement of waste differs according to the phase; most stakeholders attribute a higher weight per 1 t of a specific type of waste in the construction and post-construction stages than in previous stages. In addition, waste is not perceived by the stakeholders as a uniform stream; some attach more value to 1 te of, for example, glass waste, whereas others attach more value to concrete waste. Thus, the measurement of waste will strongly depend on both the project phase and the stakeholder.

Additionally, Thabrew and Ries [62] discuss the problem of the conflicting interests and different perceptions of the various stakeholders of the variables and their measurement in the context of project sustainability and various project phases. The project they examine is a post-tsunami well and water storage reconstruction project in Sri Lanka. The inputs and outputs for the case study project phases are shown in Table 6.

Table 6. Selected inputs and outputs for the project, as described by Thabrew and Ries [62]

Stage	Inputs	Outputs
Well construction	work of the local community members	reduction in water treatment cost free, safe water for the community
Water collection preparation	cost of cans	number of people benefited convenience of access to safe water
Water storage preparation	cost of storage tanks	number of people benefited reduction in wastewater careful consumption

As previously, there is a striking difference in the stakeholders' perceptions of the variables in Table 6. In the eyes of the local population, the more cans and storage tanks there are, the better. On the other hand, the variable reduction in wastewater is not of such high importance to them. The institution providing the financing may see the situation differently, especially if it is an environment-oriented organisation.

A literature review of projects related to sustainability and implemented based on clear cut-off phases leads to two conclusions:

- The inputs and outputs for each stage may be seen differently by each stakeholder, both concerning the choice between minimisation and maximisation and concerning the measurement unit.
- The parameters needed by the methods listed in Table 2 would be very difficult to determine for projects considered in the context of sustainability and in their consecutive phases. The weights of the individual variables and the target values of the objective function are not even mentioned in the case studies analysed in this section or, if they are, their strong dependence on the key stakeholders of the project is emphasised.

It is important to note that the stage weights are not addressed in the existing papers in this literature review. The most important conclusion is that a non-parametric approach to the problem of the evaluation of projects with phases in the context of sustainability would be useful, particularly one where no target value of the objectives nor weights of the variable would be imposed. Each stakeholder may have a different view on this problem and their view has to be taken into account according to the importance of the stakeholder, with no unique values of the parameters being introduced by a single decision maker. A non-parametric approach to the evaluation of various units, as well as projects, is offered by the Data Development Method (DEA). Its network version is appropriate for units composed of stages, in addition to projects composed of stages. The DEA forms the basis of our proposal and is summarised in the next section.

5. One-stage and network data envelopment analyses

5.1. One-stage data envelopment analysis

Data envelopment analysis or DEA [7] is used to evaluate the relative efficiency of the members of a set of entities (called decision-making units, or DMUs) that utilise similar inputs to produce similar outputs. Efficient and non-efficient DMUs in the given set are distinguished as a result of the method's application. The collection of DMUs may be composed, for example, of schools, hospitals, for-profit or non-profit organisations, countries, regions, etc., and various types of efficiencies can be considered. In the most basic approach, the inputs are the quantities or purchase prices of the resources used for production, and the outputs will be the quantities or selling prices of the products that are manufactured. However, DEA can also be used to handle efficiencies in a broader sense, where inputs are defined as bads (the magnitudes that should be minimised) and outputs as goods (the magnitudes that should be maximised) in the activities performed by the DMUs. From this perspective, it is also possible to consider immaterial inputs and outputs. For example, DEA has previously been used to choose the best site for a Japanese company in a process where one of the inputs was susceptibility to earthquakes, and one of the outputs was the ability to recover from earthquakes [7]. In a case such as this, the unit of measurement may be a subjective scale. In this paper, inputs and outputs will be understood in this broader sense.

One-stage and network DEA are distinguished. Let us start with a one-stage DEA and assume that there are N DMUs in the evaluated set, each of which is evaluated in a separate step. The DMU evaluated in the first step is numbered with the index 0, as DMU_0, with the other DMUs denoted as $DMU_i,\ i = 1, \ldots, N-1$. For DEA to be applied, the inputs and outputs of all $DMU_i, i = 1, \ldots, N$ must be of the same type. One can then define the set of inputs $In_j, j = 1, \ldots, J$ and the set of outputs $Out_l, l = 1, \ldots, L$ that are common to all the DMUs under consideration. The amount of a given In_j or its value applicable to a $DMU_i, i = 0, \ldots, N-1$ (expressed in the units selected for In_j) will be denoted as $x_j^i, j = 1, \ldots, J$, and the respective values of the outputs as $y_l^i, l = 1, \ldots, L$. For each $DMU_i, i = 0, \ldots, N-1$, a virtual input $VIn_i = \sum_{j=1}^{J} v_j x_j^i$ and a virtual output $VOut_i = \sum_{l=1}^{L} u_l y_l^i$ are defined, where the weights (also called multipliers) $v_j,\ j = 1, \ldots, J$ and $u_l,\ l = 1, \ldots, L$, respectively, are selected from the point of view of DMU_0 to give it the chance to present itself in the best light. If, despite this possibility, the DMU scores worse than the other DMUs, one can assume that it is, in fact, worse.

The following mathematical programming problem is solved:

$$Eff_0 = \frac{\sum_{l=1}^{L} u_l y_l^0}{\sum_{j=1}^{J} v_j x_j^0} \to \max \tag{1}$$

subject to

$$\frac{\sum_{l=1}^{L} u_l y_l^i}{\sum_{j=1}^{J} v_j x_j^i} \leq 1, \quad i = 1, \ldots, N-1$$
$$v_j \geq 0,\ j = 1, \ldots, J \tag{2}$$
$$u_l \geq 0,\ l = 1, \ldots, L$$

When all the steps have been performed, the values $Eff_i,\ i = 0, \ldots, N-1$, defined as:

$$Eff_i = \frac{VOut_i}{VIn_i} = \frac{\sum_{l=1}^{L} u_l^i y_l^i}{\sum_{j=1}^{J} v_j^i x_j^i} \tag{3}$$

will have been calculated, where $v_j^i, i = 0, \ldots, N-1;\ j = 1, \ldots, J$ and $u_l^i,\ i = 0, \ldots, N-1;$ $l = 1, \ldots, L$ are weights determined by solving (1) and (2) with each DMU_i in the role of the selected DMU_0. The values $Eff_i,\ i = 0, \ldots, N-1$ are called the relative efficiencies of the respective DMUs.

5.2. Network data envelopment analysis

The one-stage DEA does not consider the internal structure of the the process by which the DMUs transform inputs into outputs. If this process consists of more than one stage and the individual stages and their efficiencies are of interest to the decision maker, network DEA should be applied [10, 12, 29, 40]. Here, T stages for each $DMU_i,\ i = 1, \ldots, N-1$, will be considered (where is the same for all the DMUs considered) for the transformation of the inputs $In_{j,}\ j = 1, \ldots, J$ into the outputs $Out_l, l = 1, \ldots, L$, which are denoted as $St_t, t = 1, \ldots, T$. The inputs $In_j, j = 1, \ldots, J$ are inputs to St_1, and the outputs $Out_{l,}\ l = 1, \ldots, L$ are the outputs from St_T. The outputs of $St_t,\ t = 1, \ldots, T-1$ are denoted as $Out_{l_t}^t,\ l_t = 1, \ldots, L_t$, and the inputs to $St_t,\ t = 2, \ldots, T$ as $In_{j_t}^t,\ j_t = 1, \ldots, J_t$. Some of the $Out_{l_t}^t,\ l_t = 1, \ldots, L_t$ will belong to the set of $In_{j_t}^{t+1},\ j_t = 1, \ldots, J_t, ,\ t = 1, \ldots, T-1$, but not necessarily all. Similarly, the set of $In_{j_t}^t,\ j_t = 1, \ldots, J_t\ ,\ t = 2, \ldots, T$ may contain some elements that do not belong to the set $Out_{l_t}^{t-1},\ l_t = 1, \ldots, L_t$. The inputs $In_{j,}\ j = 1, \ldots, J$ are also denoted as $In_{j_1}^1,\ j_t = 1, \ldots, J_1$ and the outputs $Out_{l,}\ l = 1, \ldots, L$ as $Out_{l_T}^T,\ l_T = 1, \ldots, L_T$. The values of each $In_{j_t}^t$ used or the values applicable to the stages St_t in $DMU_i,\ i = 1, \ldots, N-1$ (expressed in a unit selected for $In_{j_t}^t$) are denoted as $z_{j_t}^{i,t},\ j_t = 1, \ldots, J_t, t = 1, \ldots, T$, and the respective values of the outputs $Out_{l_t}^t$ as $w_{l_t}^{i,t},\ l_t = 1, \ldots, L_t, t = 1, \ldots, T$.

It should be noted that the network DEA is sometimes called two- or n-stage DEA [10, 11]. It can be also mentioned that these terms may also refer to the use of several stages that lie not within the DMU process but in the DEA calculation algorithm [39, 67, 69], which falls outside the scope of this paper.

Through the use of network DEA, it is possible to consider both the overall efficiency of each DMU_i, $i = 1, \ldots, N-1$, denoted as $OvEff_i$, $i = 0, \ldots, N-1$, and the efficiency of the individual stages $Eff_i^t, t = 1, \ldots, T$, $i = 0, \ldots, N-1$. The following definition is introduced:

$$Eff_i^t = \frac{\sum_{l_t}^{L_t} u_{l_t}^{i,t} w_{l_t}^{i,t}}{\sum_{j_t}^{J_t} v_{j_t}^{i,t} z_{j_t}^{i,t}} \tag{4}$$

where the weights $v_{j_t}^{i,t}$, $j_t = 1, \ldots, J_t$, $t = 2, \ldots, T$, $u_{l_t}^{i,t}$, $l_t = 1, \ldots, L_t$, $t = 1, \ldots, T-1$ will be selected in the individual steps (each of which is linked to one selectedDMU) from the point of view of the selectedDMU. In the case of network DEA, however, the determination of these weights is not as unequivocal and straightforward as in the case of one-stage DEA. The same is true for the definition of $OvEff_i$, $i = 0, \ldots, N-1$.

In network DEA, several approaches are considered. In the first place, multiplicative and additive approaches are distinguished. In the additive approach [6], the overall efficiencies $OvEff_i$, $i = 0, \ldots, N-1$ of DMU_i, $i = 1, \ldots, N-1$ in each step are defined as weighted sums of the efficiencies of the individual stages:

$$OvEff_i = \sum_{t=1}^{T} \lambda_t^i Eff_i^t, \quad i = 0, \ldots, N-1 \tag{5}$$

The weights λ_t^i are non-negative decision variables, and may be required to sum to one. In the additive approach to network DEA, (5) is applied to DMU_0 to form the objective function in the mathematical programme equivalent to (1) and (2). In the multiplicative approach [5], which will not be considered here, (5) is replaced with:

$$OvEff_i = \prod_{t=1}^{T} Eff_i^t, \quad i = 0, \ldots, N-1 \tag{6}$$

In network DEA, one can also distinguish between the composition and decomposition approaches [10]. In the composition approach, the efficiencies of the individual stages in (4) are first determined and then aggregated into the overall efficiency in (5) or (6), whereas in the decomposition approach the overall efficiencies in (5) or (6) are first calculated and then decomposed into (4). The respective mathematical programming models are analogous to the models in (1) to (3), with an adequate objective function as in (5) or (6). In this paper, the decomposition approach will be used. The reason is that in the problem formulated here the overall evaluation of the project is the most important information that can be decomposed if necessary into the evaluation of the individual stages. Hence, the objective function in (5) will be used in the first place. The multiplicative approach with objective function (6) does not seem suitable in the context of sustainable project management, because, in the context of sustainability, it is necessary to differentiate the weights of the phases (e.g., the remote future and the present will rarely have the same weight).

5.3. Other developments of DEA

Other variants of (1) and (2) are also considered in the literature [7, 8, 17, 19, 45]. In addition, more constraints or objectives can be added to (1) and (2) (e.g., to the weights [26, 49] or objectives [41]).

Another issue worth mentioning and covered by the DEA approach involves so-called undesirable (minimised) outputs, which are especially important in the context of sustainability. Similarly, desired (maximised) inputs may occur, too. These notions, which are nonexistent in the original version of DEA, arise when it is necessary to avoid or dispose of certain substances by consuming them in a process. There are diverse approaches to treating the desired inputs and undesired outputs in the DEA [20, 22, 23, 25, 64, 65, 71]; for example, using a minus sign in the formulae in (1) and (4), or applying slacks in these expressions to represent the difference between the given value and a threshold value. In this paper, the most straightforward approach will be used, which is consistent with the definition of inputs as bads and outputs as goods, as mentioned previously. Undesired outputs will be treated as inputs and desired inputs as outputs. Although this approach has been criticised in the context of manufacturing processes, it seems to be suitable for project management; often, for example, an input like the work of a certain group of people will be desired by some stakeholders of a sustainable project and should be avoided in the eyes of other stakeholders.

5.4. DEA in project evaluation and the context of sustainability

DEA has already been applied to the concept of sustainability (cf. [75] for a review). The simplest approach involves determining the efficiency of each DMU for each of the sustainability perspectives selected, and then defining the ultimate efficiency as their arithmetic mean [18]. The specific uses of DEA in sustainability-related problems primarily relate to the importance of the undesirable outputs and desirable inputs. The problem of so-called weak disposability [43] is also considered in the literature, where some of the inputs (or outputs) are interrelated, and a decrease or increase in one influences others. Wu et al. [72] applied DEA to a production system with a pollution treatment. Subsequently, the short- and long-term perspectives were differentiated and each user was asked about their subjective preference, as expressed by a coefficient $\alpha \in [0, 1]$, where values closer to one indicate a short-term preference and values closer to zero a long-term preference. This coefficient is used in the network DEA formula in (5).

One-stage DEA has been applied to project evaluation in several publications, concerning the problem of project selection and for the evaluation of a project after its completion [16, 32, 33, 36, 69, 73]. The inputs to the models consist of the project cost, the workload, the size of the project team, and the project team's competencies. The outputs include the financial benefits to the organisation, cash flows, patents, improved processes, increased customer satisfaction, and new skills acquired.

Both material and immaterial outputs are taken into account, including stakeholder satisfaction. Stakeholder satisfaction forms the foundation of the modern understanding of the success of a project [9], and success and failure are multi-criteria concepts [54]. Indeed, Kuchta et al. [30] proposed that the evaluation of a project should be based on an equivalent of efficiency (1), in which the inputs are the values of the failure criteria of the project and the outputs are the values of the success criteria. In this context, DEA is used not so much to evaluate the efficiency of a project, but rather to forecast its chances of success.

One-stage DEA has been used to evaluate project performance in the context of sustainability in only a few papers, either for projects from specific industries [42, 61, 68, 69] or in combination with other approaches, like AHP and fuzzy decision making [52].

The need to consider various project phases in sustainable project management would imply that network DEA will be a suitable tool for the assessment of sustainable projects. Surprisingly, it has rarely been used in this context. There is one study in which network DEA has been applied to project assessment [31], but this does not consider the aspect of sustainability. The only work in which network DEA has been applied to the evaluation of sustainable projects is that of Li [38], as previously mentioned. Li [38] points out that the variable of biogas production is an output (and thus a good) in the first stage, and an input (and thus a bad) in the second stage. An intermediate variable is introduced for modelling purposes and is detached from any stakeholder analysis.

There exists no general approach to evaluating projects in the context of sustainability, with the distinction of inputs and outputs of individual phases. Additionally, the goal of this paper, resulting from the analysis of the cases studied in Section 4, is to develop a non-parametric approach to projects or project scenarios in the context of sustainability, in which the stakeholders would not impose the weights of individual variables. The only parameters imposed would be the weights of the stakeholders, which should reflect their importance for the project and ensure the project's sustainability, and project phases. No such approach has been identified in the literature. A proposal for filling this gap is presented in the next section.

6. Proposed application of network DEA to project scenario selection in sustainable project management

A specific project at the definition stage is considered. The variant in which it is to be implemented needs to be selected. $DMU_i,\ i = 0, \ldots, N-1$ represents the feasible implementation variants. In each scenario, it is assumed that the project has T stages.

In the first step, all stakeholders that are considered to be important for the project are placed in a set. This set of stakeholders should cover all the aspects of sustainability discussed in Section 2 and be seen as important by the project owner. The number and strength of the stakeholders selected for each aspect of sustainability should reflect the weight attached to the given aspect by the project owner. The selected stakeholders are denoted as $H_p,\ p = 1, \ldots, P$. The project owner will determine the weight for each stakeholder, $h_p,\ p = 1, \ldots, P,\ h_p \geq 0$, s.t. $\sum_{p=1}^{P} h_p = 1$.

In the second step, the set of all candidate values for the inputs and outputs of all the stages will be presented to the stakeholders (the *P5 Standard* should be used here). The candidates will initially be defined neither concerning their nature (whether it is an input or an output and of which stage) nor concerning their measurement (for example, so-called the documentation candidate can take on various roles and can be measured in various ways, depending on the stakeholder, as explained previously).

In the next step, each stakeholder will be asked to define the measurement for each element on the list that is not neutral to them, to indicate the stage of the project to which they connect the element, and to declare whether this element is a bad (an input) or a good (an output) in connection with the chosen measurement. In other words, the inputs $z^{i,t}_{j_t,p}$, $j_t = 1, \ldots, J_t$, and the outputs $w^{i,t}_{l_t,p}$, $l_t = 1, \ldots, L_t$, $t = 1, \ldots, T$, $p = 1, \ldots, P$ will be defined. Some of the inputs of stage t will undoubtedly be identical to the outputs of the previous stage $t = 1, t = 2, \ldots, T$ and this equivalence will be reflected in the input data.

The following definition of the efficiency of the t-th stage, according to the p-th stakeholder, $t = 1, \ldots, T; p = 1, \ldots, P$, will be adopted:

$$Eff^{t}_{i,p} = \frac{\sum_{l_t}^{L_t} u^{i,t}_{l_t,p} w^{i,t}_{l_t,p}}{\sum_{j_t}^{J_t} v^{i,t}_{l_t,p} z^{i,t}_{l_t,p}} \tag{7}$$

where the weights $v^{i,t}_{l_t,p}$, $j_t = 1, \ldots, J_t, u^{i,t}_{l_t,p}$, $l_t = 1, \ldots, L_t, t = 1, \ldots, T$, are decision variables and will be selected in the individual steps (where each step is linked to one selected DMU_i, thus one project implementation variant), for the inputs and outputs selected by the p-th stakeholder, by solving the analogous mathematical programming problem in (1) to (3). The objective function is:

$$OvEff_{0,p} = \sum_{t=1}^{T} \lambda^0_t Eff^{t}_{0,p} \tag{8}$$

with each project implementation variant playing the role of DMU_0 in turn. The weights of phases in (8) are decision variables on which certain constraints may or may not be imposed. Additional constraints concerning the weights of the respective stages can be imposed by their respective stakeholders or by the project owner. Finally, the following is defined:

$$OvEff_{i,p} = \sum_{t=1}^{T} \lambda^i_t Eff^{t}_{i,p}, \quad i = 0, \ldots, N-1, \ p = 1, \ldots, P \tag{9}$$

representing the evaluation of the pth stakeholder of the variant DMU_i, $i = 1, \ldots, N$. The overall evaluation of the variant, according to the concept of sustainability, is calculated as:

$$SEff_i = \sum_{p=1}^{P} h_p OvEff_{i,p}, \quad i = 1, \ldots, N \tag{10}$$

The quality of (10) will naturally depend on the selection of stakeholders therein. If it is assumed that the selected stakeholders represent all the important aspects of sustainability to an adequate degree, then the project scenario selected from among those for which the evaluation in (10) is the highest will represent a compromise that takes into account all the sustainability requirements imposed by the project owner.

7. Computational example

A project whose aim is to revitalise an existing railway connection in a picturesque mountain region that has been unused for over 30 years is considered. Several other projects of this type have been implemented in Europe and across the globe [74]. Here, a fictitious, simplified example based on real-world cases is analysed.

The considerations will be limited to the last two stages, i.e., construction (Stage 1) and service (Stage 2), and omit the design stage for simplicity. Let us suppose that there are several scenarios for the implementation of the project that differ in terms of the type of trains used, the utilisation degree of local workers, the services offered in the revitalised stations, and the duration of the project. Let us also limit our study to these parameters, although many more would have to be taken into account in a real-world application. Again, for reasons of simplicity, merely three stakeholders are discussed: the construction company, the local community, and an environmental organisation. The choices made by the stakeholders (simplifying the situation to limit the number of inputs and outputs) can be defined, beginning with Stage 1 (construction), as shown in Table 7.

Table 7. Stage 1 inputs and outputs and their measurements selected by the stakeholders for the example project

Stakeholder	Type of train	Utilisation degree of local workers	Services at the stations	Project duration
Construction company	measured based on the cost of railway traction required: output	measured based on salaries: input	measured based on the construction cost: input	neutral
Local community	measured based on comfort: output	measured based on salaries: output	measured based on the number of services: output	input
Environmental organisation	measured based on the damage caused to the environment: input	neutral	measured based on the number of services: input	neutral

It is worth noting that additional types of measurements may be required by each stakeholder for each parameter and the same element may be seen as an input (a bad) by one stakeholder and an output (a good') by another. For example, the services offered at the revitalised station may be measured based on their number by the local community and the environmental organisation. However, the local community would be interested in maximising this number (which would offer more job opportunities to the local community), whereas the environmental organisation would be interested in minimising this number (to minimise waste, tourist presence, and other elements that would damage the environment). The cost of the railway traction required is an output for the construction company if it is assumed that the subvention received by the company from the government depends on this value. Furthermore, the environmental organisation does not see any "goods", i.e., any inputs, at this project stage; thus, the respective evaluation will be zero. A listing such as that in Table 7, however, would serve as a basis for discussion during meetings including all the stakeholders, as recommended, for example, by Eckersten et al. [15]. Such meetings are indispensable in sustainable project management, which requires the respectful treatment of human resources and an open approach to seeking a compromise. These may lead to some modifications to Table 8.

Table 8. Stage 2 inputs and outputs and their measurements selected by the stakeholders for the example project

Stakeholder	Utilisation degree of local workers	Services at the stations	Project duration
Construction company	neutral	neutral	neutral
Local community	measured based on the maintenance cost: input; measured based on the reliability degree: output	neutral	measured based on the number of services: input; measured based on the profit: output
Environmental organisation	measured based on the reduction in car traffic: output	neutral	measured based on the number of services: input; measured based on the waste produced: input

Stage 2 (service) can be treated similarly, as shown in Table 8. Here, an element that is typical of network DEA should be pointed out; for the local community, the number of services offered at the revitalised stations is an output of the first stage (Table 7) and an input to the second stage (Table 8). This is because what is ultimately important to the local community is not the number of services *per se* (as this is only an intermediate variable) but the profit to the community, measured arbitrarily; for example, based on additional tax incomes. The degree of local worker utilisation is neutral at this stage, as construction workers are referred to here, and these will not participate in Stage 2 of the project.

The following scenarios are considered to be feasible (Table 9). For all the inputs and outputs, the measurement is based (for simplicity) on a scale from one to five, where one represents the lowest value and five the highest. The scales may be defined objectively (representing intervals of, for instance, monetary units) or subjectively (expressing a subjective opinion on the presented aspect).

Table 9. Scenarios for project implementation

Scenario 1	cost of railway traction	comfort	damage caused to the environment	maintenance cost	reliability	reduction in car traffic
	2	1	2	2	3	1
	salaries of local workers	number of services	profit	waste created by the service	time	
	3	4	3	3	3	
Scenario 2	cCost of railway traction	comfort	damage caused to the environment	maintenance cost	reliability	reduction in car traffic
	5	3	1	4	5	2
	salaries of local workers	number of services	profit	waste caused by the service	time	
	4	2	1	4	2	
Scenario 3	cost of railway traction	comfort	damage caused to the environment	maintenance cost	reliability	reduction in car traffic
	1	2	4	1	2	1
	salaries of local workers	nmber of services	profit	waste created by the service	time	
	1	2	3	2	5	

EXCEL Solver was used to solve the corresponding problem in (2) and (3), with the objective function in (8) used for each scenario. No restrictions were imposed on the weights of the phases, and in each case, Stage 2 was selected as the most vital. The results are presented in Table 10. The total score for each scenario is based on the assumption of equal weights for the three stakeholders.

Table 10. Evaluation of project implementation scenarios

Number of scenario	Construction company	Local community	Environmental organisation	Total evaluation
1	1.18	0.74	0.79	0.9
2	1.42	1.99	2.49	1.96
3	0.54	2.49	0.88	0.3

Scenario 2 can be viewed as the best; more precisely, it is the best for both the construction company and the environmental organisation. The local community prefers Scenario 3, mainly because it gives a higher profit than Scenario 2. However, Scenario 2 is the second-best scenario for the local community. Thus, a compromise can be reached on which form of implementation should be selected for the project. Of course, in a real-world case, there are likely to be further discussions and iterations, and the final decision may still vary. In any case, the decision can be reached without having to discuss and negotiate variables or the weights of the respective stages.

8. Conclusions

An approach has been proposed that can be applied in the early stages of project definition for projects that should be managed sustainably nowadays concerning a large proportion of all projects. The proposed method aims to evaluate various project implementation scenarios or formulae, but the method can also be applied to select the optimal portfolio from a group of similar projects. The novelty of the approach concerning the literature is the fact that it takes into account all the stages of the project and its product lifecycle. It does not require any coefficients or target values for the optimisation criteria apart from the weights of the stakeholders, as assigned by the project owner to ensure the project meets the required sustainability level. This is especially important in sustainable project management, where the entire lifecycles of the project and its product need to be treated holistically, taking into account clearly conflicting interests and views of project stakeholders. In addition, in the sustainable project management methodology PRiSM, in the project definition stage, it is required to consider various project implementation scenarios.

The proposed method is based on the network DEA, which is a non-parametric method originally used to calculate the relative efficiency of similar entities that transform certain inputs into outputs in a series of consecutive stages. The non-parametricity of the method is an important advantage, because in sustainable project management the weight and target values of individual parameters depend strongly on the stakeholders, who often have conflicting views in this respect, to the point that the same value may be desirable for one decision-maker and undesirable for another. The approach proposed in this paper allows stakeholders to avoid conflicts in this respect.

Our framework is solely a proposal and needs further verification and development, as follows:

- The prerequisite for the usage of the proposal is the possibility to collect information from numerous stakeholders on the desirable and undesirable inputs and outputs of consecutive phases of the project and project product lifecycle. A communication method consisting of suitable questionnaires and checklists should be developed and tested;

- Various examples of the measurement of sustainability-related inputs and outputs need to be developed for real-world case studies, so that a set of example measurements can be proposed to facilitate the choices of project stakeholders;
- The mathematical programming problem considered here is not linear, and several computational issues require a solution, especially where there are numerous stakeholders and project implementation scenarios;
- The model needs to be developed further and should incorporate various methods of project and product lifecycle assessment [24], including models that allow for a combination of the two, as the result of a project, is usually a product [3]. It should also include different ways of measuring the degree of sustainability [13, 55]. The approach based on the *P5 Standard*, as described in Section 2, was merely an example;
- The issue of the weights of the project stages needs to be addressed, and should take into account the (not always visible) importance of decisions taken in the early stages of a project, which are often irreversible or extremely costly to reverse in later stages. The the problem of constraints potentially being imposed on the weights of different phases should thus be analysed.

In short, the proposed method still needs extensive research before being developed into a mature approach, and should be supported by suitable software that would help users to make better decisions at the definition stage of sustainable project management. One thing is clear, however: there is a need for such a method, due to the omnipresence of multistage projects in all aspects of human life [53] and the inseparability of project management from the modern, broad understanding of sustainability.

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