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APPLYING SUSTAINABILITY THEORY TO TRANSPORT INFRASTRUCTURE ASSESSMENT USING A MULTIPLICATIVE AHP DECISION SUPPORT MODEL

Marie Ridley Pryn*, Yannick Cornet*, Kim Bang Salling

Dept of Transport, Technical University of Denmark, Denmark

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Abstract. It is generally expected that the three dimensions of the economy, society and the environment must be included in any measurable sustainability pathway. However, these do not provide much guidance as to how to prioritize impacts within and between the dimensions. A conceptualized approach to sustainability based on the nested model is therefore presented seeking to provide an alternative approach to sustainable transportation assessment, namely the SUSTAIN Decision Support System (DSS) model. This model is based on a review of basic notions of sustainability presented by the Brundtland Commission report, which is used to validate the nested model of sustainability for countries operating under the paradox of affluence. This provides a theoretical rationale for prioritising longer-term ecological integrity over shorter-term economic concerns, in line with the stronger conceptualisation of sustainability supported by ecological economists. This conceptualisation is operationalized by the use of Multi-Criteria Decision Analysis (MCDA) and a multiplicative version of the Analytic Hierarchy Process (AHP). The planning and decision-making process related to a new connection across the Roskilde Fjord in Frederikssund, Denmark, is used as a case study. It is found that the SUSTAIN DSS model results provide a type of benchmark for connecting to the essence of sustainable development as well as to integrate sustainability more explicitly into the planning and assessment practice.

Keywords: sustainability; transportation; assessment; MCDA; multiplicative AHP/Rembrandt; Brundtland; Frederikssund.

Introduction

The transport area in Denmark is subject to massive investments in these years and from an official hold, there is a great focus on sustainability, green technology and modal shift towards active and public transportation as a means to reduce the level of CO_2 emissions. Accordingly, planning for sustainability has become a global trend and is becoming an integrated focus when assessing new initiatives (EC 2011). However, this focus is often lost along the process between visioning and implementing. Many policies attempt to reduce the externalities of transport, but despite this, initiatives taken tend to be isolated rather than holistically oriented and sometimes fail in meeting the visions presented (Pryn 2013). Planning for sustainable transportation has faced tremendous barriers in the form of path dependencies established by large institutional, corporate, cultural and discursive incumbents (Voß *et al.* 2009). Banister calls these planning attempts *schizophrenic paths*, since it is '*clear that action is needed but no effective action is taken to remedy the situation*' (Banister 2008).

Despite these difficulties, the three dimensions of social, economic and environmental sustainability have become a de facto starting point to conceptualize and operationalize sustainable development in transport and elsewhere (Connelly 2007; Munasinghe 1993; Lélé 1991). However, there is no common guidelines for which criteria to assess and how to balance them. The Cost-Benefit Analysis (CBA) approach has provided a way to translate impacts into comparable monetary units, although it has been found to hold certain limitations when incorporating and assessing attributes such as environmental or social issues (Banister 2008; Joumard, Nicolas 2010; Beukers *et al.* 2012). The methodology of Multi-Criteria Decision Analysis (MCDA) provides a possibility for incorporating such factors that are not easily quantifiable (Beukers *et al.* 2012).

This paper presents the SUSTAIN Decision Support System (DSS) model, which is based on an MCDA approach combined with the concept of the nested model of sustainability. This concept is proposed in the ecological economics literature, which places the three well-

Corresponding author: Marie Pryn
E-mail: *mapry@transport.dtu.dk*

*Both authors contributed equally to this paper (co-first authors) known dimensions in a certain order of priority and thereby expresses a stronger understanding of sustainable development (Joumard, Nicolas 2010).

The background for the paper is a Danish research project on national sustainable transport planning called SUSTAIN. This research is conducted in close collaboration with a defined 'user group' representing national agencies and consultancies in the practice field. The DSS model presented here is intended as direct guidance for practitioners enabling a type of sustainability benchmark when planning and assessing transportation infrastructure projects.

The following section introduces the basic notions of sustainability and the nested model. Then the DSS model is presented and tested on the case study of a new fixed link connection crossing Roskilde Fjord in the municipality of Frederikssund, Denmark. The discussion section analyses the results with regards to their implications and suggests potential improvements to the methodology. Finally, the conclusion confirms the potential of the proposed approach in setting a type of sustainability benchmark in transportation infrastructure assessment.

1. Theory

This section briefly presents the theoretical understandings of sustainability, and revisits the Brundtland report entitled 'Our Common Future' in order to provide the theoretical underpinning for prioritising the various notions of sustainable development (World Commission on Environment and Development (WCED) 1987). This review provides a basis for presenting the nested model and informing on its assumptions and potential limitations.

1.1. Sustainable Development

The three dimensions of sustainability – also sometimes called the three pillars of sustainability, or the triple-bottom line (Elkington 1999) – often consists of representing the economy, society and the environment as three equal and intersecting circles. Although interpretations for each of the three dimensions vary, at its most simple level, it is understood that addressing all three dimensions will support a process towards sustainability.

In practice, the three dimensions do not provide much guidance to planners and policy-makers as to how to prioritize between the conflicting and interacting factors that can often emerge. This concept has been criticised both for encouraging trade-offs and overlooking the interdependence of these factors (Gibson 2006). In practice, the issue of trade-offs can lead to the default prioritization of effects that can be quantified and monetized, often to the detriment of more complex and long term impacts that often characterize the social and environmental dimensions (ibid.). In order to address these limitations, the nested model is proposed as an alternative approach to conceptualising the three dimensions. The nested model, as opposed to the intersected model, depicts the three dimensions of sustainability as three nested spheres, where the economic circle is nested within the social circle, and the resulting socio-economic circles are in turn nested within the environmental circle. The two models are shown in Fig. 1.

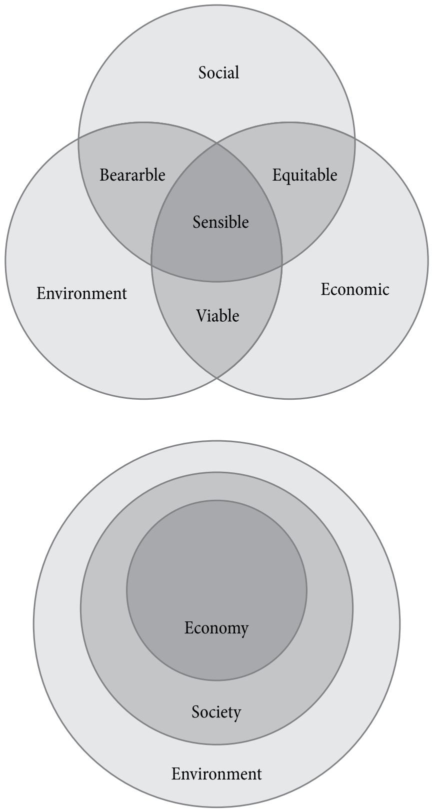

Fig. 1. Intersected and nested models of the three dimensions of sustainability

In the following sections, the nested model is demonstrated to be an improvement over the intersected model by revisiting the Brundtland report. The defining elements of the Brundtland report are reviewed here in order to analyse the nested model from a theoretical perspective.

1.2. Revisiting the Brundtland Report

The Brundtland report was adopted by the United Nations General Assembly in 1987 and it is remembered for formulating the oft-quoted one-line definition of sustainable development: '*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (WCED 1987). Beyond this definition, the report also provides an exhaustive attempt at clarifying the concept of sustainable development as well as dealing with issues of trade-off.

The sustainable development definition above (together with the report's title) sets the normative ambition to satisfy needs and aspirations of both current and future generations, thus clearly putting the anthropological needs at its core. However, the report makes a clear distinction between what could be termed the paradox of poverty versus the paradox of affluence. For countries within the paradox of poverty, the report gives overriding priority to meeting the essential needs of the poor and to provide for minimum consumption standards. This is justified on the basis that poverty generally contributes to a vicious cycle of environmental degradation, health impacts and general vulnerability. Yet, past a certain point of income-per-capita, Brundtland warns about increasing environmental impacts, often of global scale and long-term nature (such as climate change or biodiversity loss). This can be termed the paradox of affluence. For countries within the paradox of affluence, the primary concern shifts to preserving nature's life support systems.

As a result, Brundtland is clear on the need for more affluent populations to bring their lifestyles, values, patterns of behaviour, levels of consumption, energy and resources use in line with the planet's ecological means with regard to long-term sustainability. Thus preserving the basic overall integrity of natural systems that support life is concluded to be a minimum for sustainable development, what Langhelle calls Brundtland's proviso of sustainability (Langhelle 1999).

About the economic dimension, Brundtland is prescriptive on the role of economic growth and technological development to combat poverty and meet human needs. In the paradox of affluence, quantitative economic growth is replaced by a type of growth and development that takes full account of environmental and social factors, what is termed the 'quality' of economic growth. Conceptualizing economic growth and technological development as a means to an end within social and environmental constraints also fits well with the nested model that depicts the economic dimension nested within the social and environmental circles.

Assuming Denmark is generally beyond the basic concerns of ensuring that essential needs and minimum consumption standards are met, it can be said to be operating within this paradox of affluence. The Brundtland understanding of sustainable development is summarised in Fig. 2.

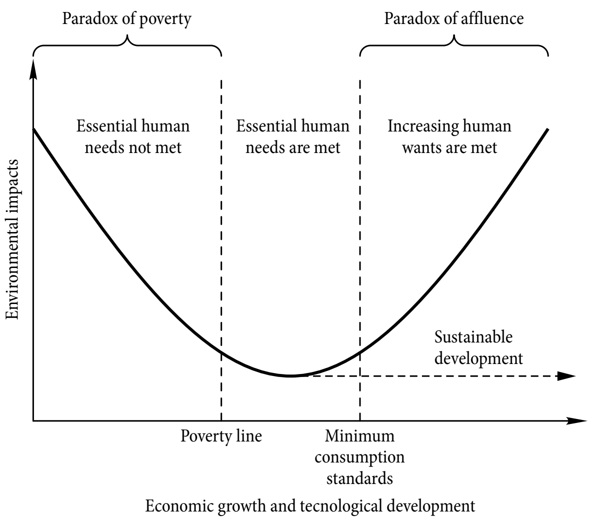

Fig. 2. Sustainable development by Brundtland, adapted from Cornet, Gudmundsson (2015)

1.3. The Nested Model of Sustainability

The nested model is a simple visual representation of the tenets presented by ecological economists such as Daly and Costanza (Daly 1990; Costanza *et al.* 1997), who distinguish between weak and strong sustainability. Weak sustainability assumes that three types of capital – natural, human and economic – can be substituted. The weak position matches the commonly used intersected model of the three equally important dimensions of sustainability, where performance in one dimension can offset reduced performance in another. The strong position on the other hand suggests that some types of natural capital – such as the ozone layer or biodiversity – cannot be substituted by man-made capital. Because such ecological systems are vital to human existence, they in fact cannot be called natural 'capital', but rather should be accounted for separately and in their own right (Daly 1990; Giddings *et al.* 2002; Hopwood *et al.* 2005). This approach brings forth the concept of irreversibility, where a small impact may in fact become very penalizing in the long term if it is irreversible (such as a species loss or an ecosystem collapse).

Consequently, rather than viewing the three circles as three distinct but complementary dimensions of sustainable development, the nested model adopts the premise that a sustainable environment is a necessary condition for a sustainable society, and that a fair and equitable society is also a necessary condition for sustaining economic activity. In other words, the model is based on the strong sustainability understanding that society and its economy can only exist within the limits and carrying capacity of natural systems, and both depend on the integrity and proper functioning of these systems. This understanding also offers a consideration of the three dimensions as operating on different temporal and geographical scales, where for example environmental impacts are considered to generally operate over longer time scales while economic impacts tend to be of shorter-term nature. Based on this, the nested model assigns a default hierarchy between the three dimensions.

The nested model has been proposed for use in both practice and academic literature, see e.g. Joumard and Nicolas (2010), The Natural Step (2014), Griggs *et al.* (2013). At a general level, the nested model can be seen as an adequate representation of the concept of sustainable development elaborated by Brundtland. The Brundtland prioritisation of ecological integrity in the paradox of affluence corresponds well with the nested model placing the environment as an outer boundary to the socio-economic circles. However, the nested model introduces simplifications that the Brundtland report can also help illuminate. The next section presents some of the assumptions behind the nested model.

1.4. Assumptions of the Nested Model

By bundling together all environmental impacts under the environmental dimension, the nested model assumes all impacts to be equally relevant, while Brundtland distinguishes between different types of natural capital. Not all-environmental capital is critical or irreversible, which implies that not all environmental criteria should receive the same treatment or priority. On this matter, Brundtland shares the views of ecological economists: *regeneration* of renewable capital, *substitution* of non-renewables, *compliance with thresholds* on wastes and emissions, *precautionary principle* for irreversible capital, and consideration for system-wide effects and *integrity*. This lack of precision in the nested model may lead to an overall over- or under-prioritisation of the environmental dimension compared to what a more fine-grained analysis would suggest.

The same argument applies to time scales. Although the nested model attempts to prioritize a longer-term horizon, not all environmental impacts belong to long-term natural processes of concern to future generations. Noise is a good example of a non-economic, yet short-term and local impact, which may not be of particular relevance to future generations or to maintaining environmental integrity.

A third related concern is the lack of 'veto' power. Although impacts on nature are given a higher priority, the fundamental assumption that the dimensions can be traded remains. If the perceived economic or social benefits of a new infrastructure project are high enough, critical or irreversible capital that contribute to the Earth's life support systems may be sacrificed nevertheless. This implies that the nested model is in fact 'weaker' than what strong sustainability and the Brundtland report call for. One way to overcome this would be to set a requirement that all three dimensions must improve for a project to be allowed to go ahead, or to give critical and irreversible capital a category of their own, as was done by Joumard and Nicolas (2010).

A last potential weakness of both the intersected and the nested models is that they only explicitly cover three dimensions of sustainability while leaving other areas implicit or external. The time dimension and the interrelationship of the dimensions are implicit in the models, while issues of governance and processes of change are considered external. For these reasons, the nested model in itself is not enough, it is meant as a tool that needs to be inscribed within a strategic planning and policy-making process. Table 1 summarises the strengths and weaknesses of the nested model of sustainability.

This section illustrated that the nested model is a useful representation of sustainability. However, similarly to the common intersected model, it is a rather simplistic representation of the full complexity of sustainable development. For this reason, the model's assumptions and potential weaknesses need to be kept in mind when operationalising it. Nevertheless the nested model brings the advantage of providing general guidance on the difficult issue of prioritisation of impacts based on a stronger understanding of the precepts of sustainability. The next section shows how the nested model can be operationalised for transportation assessment.

2. Method

This section presents the methodology for supporting decision-making adopted in this paper. The DSS model is first presented, and then three approaches for prioritising assessment criteria are elaborated before being applied to the case of an existing transportation infrastructure project.

2.1. Decision Support Model

The decision support model illustrated in Fig. 3 is designed to expand the foundation for decision-making by allowing for the systematic inclusion of impacts that are not easily quantifiable or monetized. The model introduces MCDA, which is based on value measurement using qualitative input from a ratifying group to overcome this issue.

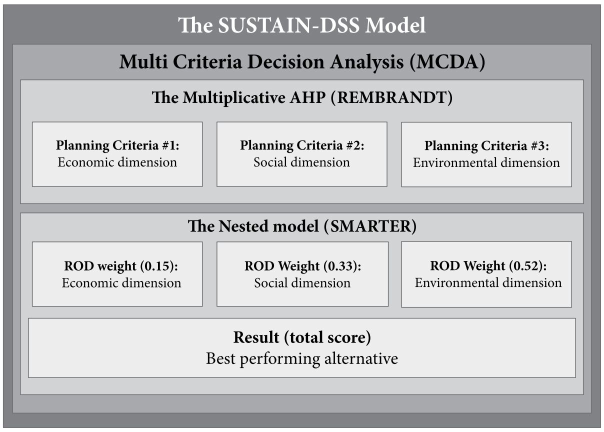

Fig. 3. A schematic overview of the SUSTAIN DSS model – here with the nested model prioritisation using Rank Order Distribution (ROD) weights, adapted from Salling, Pryn (2015)

Table 1. Nested model strengths and weaknesses

Strengths	Weaknesses
Prioritising environmental integrity is in line with Brundtland and is applicable for a rich country.	Different types of environmental capital are not explicitly considered, e.g. critical, irreversible, non-renewable or renewable.
Long-term impacts are implicitly prioritised, giving a voice to future generation concerns.	Not all environmental impacts are long term or relevant to keeping natural systems intact. Not all social or economic impacts are short term.
The existence of global or local environmental thresholds suggests an overriding priority for some environmental impacts.	Limits may still be crossed. There is no explicit 'veto' in the model. Gains between dimensions may still be traded.
All three dimensions economy – society – environment are addressed, providing a more holistic picture.	Issues of governance and change process are considered external.

The MCDA methodology extends information from a multiplicative version of the Analytic Hierarchy Process (AHP) by Saaty (2012), also known as the REMBRANDT technique, which has been proven well suited for group decision making (Lootsma 2011). As in the original AHP, the REMBRANDT technique is based on a procedure of pairwise comparisons of alternatives. The comparisons are performed by stating the preference for one alternative over another according to a semantic scale going from indifference to very strong preference expressed on a scale from 0 to 8 where 0 indicates indifference. The scale and associated preferences can be found in Appendix. For example, Alternative 1 and 2 are evaluated against each other for the first criteria, and then Alternative 1 and 3 are compared, and so on. The process is complete when all possible comparisons are made. Combining the evaluations from a range of stakeholders or experts allows building an objective evaluation of how each alternative performs with regards to each criterion.

2.2. Case-Based Prioritisation of the Criteria

A standard MCDA approach for providing a contextual ranking of the criteria is to involve stakeholders in weighting criteria against each other for their relative importance. This is done by using the same process of pairwise comparisons described above. In this way, it is possible to determine the case-based prioritisation, taking the perspective of the main stakeholders of the project (for e.g., the municipality responsible for a new transport infrastructure project implementation).

2.3. Nested Model Prioritisation of the Criteria

To align with the priorities sustainability theory suggests, the model applies the Simple Multi Attribute Rating Technique Exploiting Ranks (SMARTER), which provides a means of assigning direct weights to criteria based on an importance ranking. Predetermined surrogate weights can then be assigned directly to this ranking thereby simplifying the process for decision makers. In this paper, the Rank Order Distribution (ROD) weights are used (Roberts, Goodwin 2002).

One caveat in using ROD weights is that as the number of criteria grows, the weight given to the lowest ranked criteria becomes marginal. For this reason, the criteria within each of the three dimensions of sustainability are given equal weights in this paper, while ROD weights are applied as a whole to each of the three dimensions of sustainability. The ranking of the dimensions reflects the hierarchy suggested by the nested model presented earlier. The corresponding ROD weights are given in Fig. 3.

The main purpose of this approach is to provide a rational and objective way of weighting criteria according to the understanding of sustainability. However, for this approach to be valid, the relative *importance* of each of the criteria needs to be comparable. For example, a negligible impact on air pollution would by default be ranked higher than, say, a very large impact on costs due to the default prioritisation of environmental impacts in general. Thus, applying top-down weighting of each sustainability dimension based on sustainability theory may be considered too context insensitive. This implies that the nested model prioritisation can be used as a type of sustainability 'yardstick', but some adjustments on the default ROD weights could be permissible depending on the actual context. Alternatively, contextually relevant weights could be assigned to criteria *within* each dimension to compensate for this.

An important extension of this argumentation is that the choice of criteria needs to be representative and relevant in the given context. The process of criteria selection is explained in more detail in the case study below.

2.4. Sustainability Advocate Prioritisation of the Criteria

In order to create a comparison to the nested model, an alternative prioritisation can also be produced by returning to the standard MCDA approach of eliciting preferences from a group of stakeholders or experts, who, this time, would be taking an explicit 'sustainability advocate' perspective (Jeppesen 2009). This sustainability advocate view can be produced by answering the pairwise comparison of the criteria, this time not by taking the 'here-and-now' perspective of current stakeholders as in the case-based prioritisation above, but by taking a 'future generations' perspective. This can be informed by explicit sustainability theories or be based on experts' own understanding of sustainability.

The methodology presented here requires first that project alternatives have been determined, and second that a list of contextually relevant yet comprehensive assessment criteria exist. The section below elaborates on the case study concerning a new fixed link across Roskilde Fjord in Frederikssund. It presents the four alternatives that are considered as well as the set of planning criteria that were extracted from the original project documentation.

3. Case Study

In order to test the applicability and effect of the DSS model, it is applied on a case study concerning the decision process of constructing a new connection crossing Roskilde Fjord in the municipality of Frederikssund, Denmark. The planning of the connection has been an on-going project since the 1960's, until March 2013 when the government provided the legislative framework for a high level bridge crossing south of Frederikssund, to be funded mainly through user charges (Pryn 2013).

The current bridge has faced increasing congestion for several decades, but due to a location within a Natura 2000 protected area (*http://www.natura.org*), the construction of a new bridge has not been so straightforward. The bridge forms a local and regional link, but is not of national importance, and raising the money for a new connection has therefore been difficult (Pryn 2013). Furthermore, the growth of the city of Frederikssund

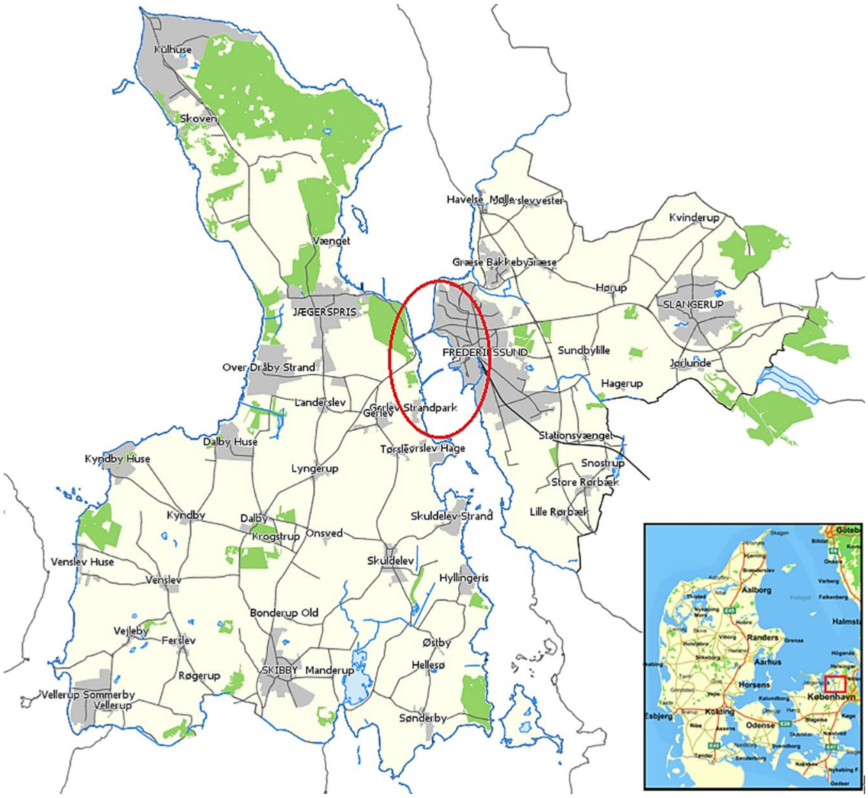

Fig. 4. Map of Frederikssund (sources: *http://infokort.frederikssund.dk/borger/kort.htm*; *http://www.krak.dk*)

over time has resulted in the bridge being situated in the very city centre, putting restraints on the possibilities for expanding the current connection. The type of solutions listed in the Environmental Impact Assessment (EIA) report are found to be similar to those proposed when the problem was first acknowledged in the 1960's (Vejdirektoratet 2010a). The case study shows that no alternatives to building a new link have been seriously considered e.g. solutions that are not car-oriented or other traffic-reducing measures. This calls for a wider set of alternatives to be considered.

3.1. Alternatives

In this paper, four alternatives are evaluated. The first two alternatives are based on the EIA and follow the conventional 'predict-and-provide' approach (Owens 1995). The final two alternatives are proposed by the authors in order to evaluate options that would support a shift to other modes than the car. The alternatives are:

- *Alternative 1* is identical to the officially decided solution and consists of a high level bridge located south of the city centre and funded through user charge;
- *Alternative 2* is an expansion of the current bridge in the city centre, also funded through user charge;
- *Alternative 3* is a light rail link established on a new bridge exploiting an existing dam construction, connecting the western peninsula with the train station in Frederikssund;
- *Alternative 4* is a service of free shuttle busses on the existing connection funded through user charge applied to other modes using the bridge.

Since Alternative 1 has already been selected for implementation, the case thereby serves to exemplify the assessment procedure of the DSS model.

3.2. Criteria

The set of assessment criteria to be used in the model intends to reflect the context as well as mirror the considerations that took place in the various stages of the planning process preceding the actual decision for the new connection. The criteria have been extracted and formulated directly based on the background literature of the case study, as well as through a coding of current trends in planning as described by Owens (1995). This combined inductive and deductive approach resulted in an explicit set of eight assessment criteria presented below.

In this case study, the assessment criteria have been particularly difficult to extract due to the various stages in the decision process. The first stage concluded with the first EIA and resulted in a recommendation for the southern high level bridge connection from the Road Directorate. The second stage of the process built upon this recommendation but was of a more economic kind. Accepting user charge as means of funding became a condition for the new connection, which led to a problematic undermining of many of the assessments made in the first stage (for e.g. due to changed forecasts in terms of expected traffic). This also meant that the criteria planned for in the first stage changed importance in the second. The traffic-related impacts and the extent of environmental impacts would naturally change under the new conditions, but no new assessment was conducted to investigate the scale of this change.

However, it seems without doubt that both the increased mobility and the economic viability of the project received high priority throughout the planning process and constituted main elements in the basis for decision. They are therefore included in the set of assessment criteria, where the economic viability is assessed based on the infrastructure and operations costs.

Based on the EIA and public hearings, the impacts of major concerns to both residents and politicians were noise and air pollution (Vejdirektoratet 2010a, 2010b). They are therefore included in the set of assessment criteria. In relation to air pollution, impacts on the climate and global warming are conspicuous by their absence in the assessment. Increases in CO_2 levels are stated in the EIA, but no actions to reduce the levels are suggested. Consequently, it becomes clear that immediate, short-term impacts with a direct incidence on the local population were of a much higher concern than the distant, global, less tangible impacts like climate change. For this reason, 'CO_2 emissions' is not included as an explicit criterion, but because it is likely to be highly correlated to air pollution, one can consider this criterion to act as a valid proxy for climate change impacts in general.

Due to the very unique and characteristic nature of the fjord and its surroundings which constitute a significant part of the identity of the area, any harm done to nature was not only of general environmental concern, but also of local concern. Local biodiversity impacts are thus included as well as a criterion about 'built aesthetics and identity'. The project was expected to meet and if possible enhance these characteristics as a part of the local identity. This was an important argument presented by contractors, which was adopted by local politicians (Roskilde Fjord – Ny fast… 2005).

The technical characteristics of the project (such as road capacity and speed) are part of meeting expected road traffic demand and thereby future proofing the project. This criterion supports the notion of speed and private motoring being desirable objectives, but also reveals the paradox and conflicts between some of the planning objectives: increasing speeds and relieving congestion can be considered to benefit time savings for car users, but it also constrains future mobility choices (Owens 1995).

Finally, accessibility within the municipality has been a strong and stated argument for increasing road capacity, and should be seen in the context of achieving a coherent municipality. On the other hand, this type of accessibility is limited to those able or willing to drive and own a car, while other socio-economic groups may not benefit directly.

Based on this review process, the final set of criteria used for the assessment of the four alternatives are summarised in Table 2.

These eight criteria reflect the foundation for the decision-making done in the case study. The assessment of each alternative used here as well as the weighting of the criteria for the case-based and the sustainability

Table 2. Final set of assessment criteria

No	Criteria	Description
C1	Transportation and mobility	This criterion relates to the expected mobility improvements for the current users as well as co-benefits for goods transportation. It includes the expected time-saving gains, reachable distances (such as 30 min isochrones), and potential to relieve congestion. It should also consider users' travel costs, which in this specific case include potential user charges where applicable.
C2	Infrastructure and operations costs	This criterion includes the direct costs consisting of the construction costs, vehicles costs (in the case of a public transport alternative), operation and maintenance, and decommissioning. The criterion also considers risks related to the feasibility or complexity of the project, whether new technology is required etc.
C3	Noise exposure	This criterion is concerned with annoyances from noise arising from the use phase of the project. This criterion does *not* include noise as an impact to wildlife.
C4	Air pollution	This criterion refers to perceivable local air pollution such as fine particulates and other health-related emissions.
C5	Local biodiversity impacts	This criterion encompasses all damages on nature with particular focus on the risk for irreversible damages to the local fjord ecosystem. This includes impacts on water flow, bird life, wildlife, the marine environment, underground water, soil etc.
C6	Built aesthetics and identity	This criterion refers to the contribution of the project to creating a sense of identity to the region as well as adapting aesthetically to the surrounding built environment.
C7	Traffic demand and future proofing	This criterion relates more specifically to the project's expected ability to absorb expected future growth in *vehicular traffic* based on current forecasts and modelling practices. In this case future proofing may include meeting expected demands from the development of the city of Frederikssund.
C8	Coherence with in municipality	This criterion is concerned with local coherence in the transport network in terms of connecting various parts of the municipality. Accessibility to services, to jobs and to recreation is implicit in this criterion. In this case, the municipality is physically split by the fjord where the congestion experienced on the current bridge increases disparity in accessibility levels.

Table 3. Categorisation, ranking and weighting of the criteria

No	Criteria	Sustainability dimension	Case-based		Nested model		Sustainability advocate	
			Rank No	Weight	Rank No	Weight	Rank No	Weight
C1	Transportation and mobility	Economic	1	0.28	3	0.05	4	0.05
C2	Infrastructure and operations costs	Economic	2	0.19	3	0,05	7	0.04
C3	Noise exposure	Social	6	0.08	2	0.11	3	0.12
C4	Air pollution	Environmental	4	0.12	1	0.26	1	0.56
C5	Local biodiversity impacts	Environmental	5	0.08	1	0.26	2	0.15
C6	Built aesthetics and identity	Social	8	0.03	2	0.11	8	0.01
C7	Traffic demand and future proofing	Economic	3	0.14	3	0.05	5	0.04
C8	Coherence within municipality	Social	7	0.07	2	0.11	6	0.04

advocate assessments have been done by a user group of 16 professionals with a background in transport engineering and planning. The weights and rankings for each of the three assessments appear in Table 3, while the assessment of the alternatives for each criterion can be seen in Appendix.

4. Results

4.1. Case-based Municipality Prioritization

The four alternatives are assessed by the user group in an MCDA using the eight criteria described above. The criteria are compared against each other from a municipality perspective and thereby ranked and assigned weights (see Fig. 5 and Table 3). This analysis forms a basis for using the model by representing the standpoint of one of the main stakeholder group in the planning process.

The assessment results in a very close scoring of the four alternatives and gives no clear recommendation as to which solution is favoured by the municipality (Fig. 5). Despite an actual decision process resulting in the recommendation of Alternative 1, this fictive reconstruction of the municipality preferences points to indifference between the four alternatives, which cannot be concluded from the actual process. However, the actual process only considered Alternative 1 and 2 along with a range of other similar alternatives and thereby the conditions for assessment have been changed for this experiment. In addition to this, this experiment only tries to reproduce the position of the municipality, while the final decision was taken at a national political level and included recommendations from several stakeholders as well as other political considerations. For these reasons, the assessment performed by the user group is still considered valid for exemplifying the use of the nested model in this paper.

4.2. Nested Model Prioritization

To test the effect of the nested model, the same set of criteria is applied to the DSS model. The assessment of each alternative within each criterion remains the same, but the weighting is altered according to the nested model based on the affiliation of the criteria to each dimension. Within the dimensions, the criteria are assigned equal weights summing up to the weight assigned for each dimension (see Fig. 6 and Table 3).

Interestingly, the preference of the alternatives shifts to the favour of Alternative 3 and 4 following this

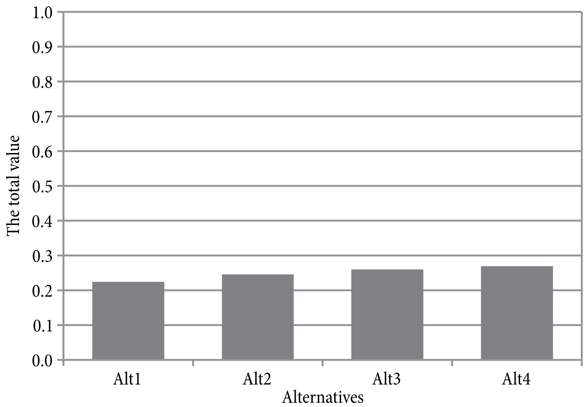

Fig. 5. Resulting graph of the case-based municipality assessment

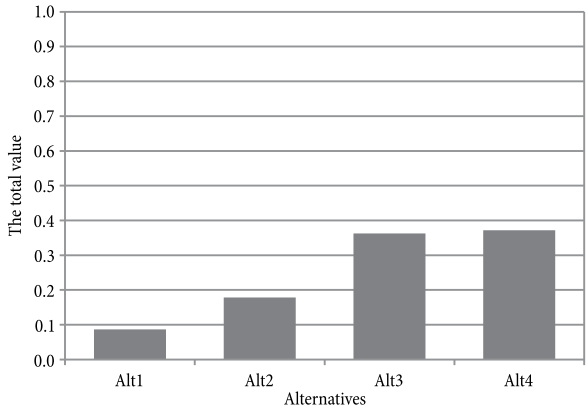

Fig. 6. Resulting graph of the nested model assessment

change in weighting. This is so since the criteria where Alternative 4 performs well now receive a higher weighting, while, on the other hand, the criteria weights where Alternative 1 performs well are diminished (Fig. 6).

4.3. Sustainability Advocate Prioritization

The assessment using the sustainability advocates priorities results in an even more distinct scoring of the four alternatives separating the car based alternatives from the non-car based alternatives. This can be explained by the underlying understanding of sustainable development as a mainly an environmental problem and thus causing the very high weights given to the environmental criteria. The fact that the light rail alternative (Alternative 3) now overtakes the shuttle bus alternative (Alternative 4) compared to the nested assessment could indicate a local context where the solution should be seen in connection to the already existing high class public transportation system (Fig. 7).

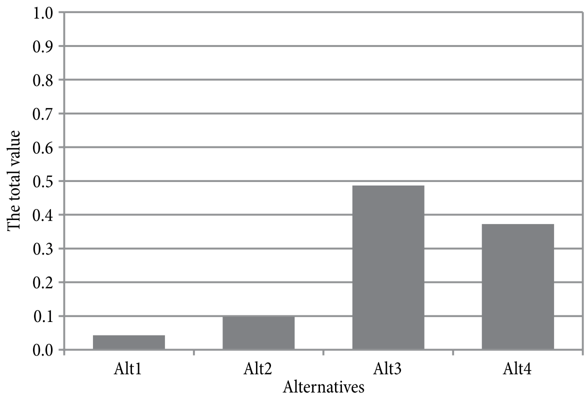

Fig. 7. Resulting graph of the sustainability advocate assessment

5. Discussion

From the results above, it is clear yet unsurprising that a different set of priorities changes the outcome of the planning process, even when the set of criteria and their individual assessment remain unchanged. In this case, applying the nested model of sustainability leads to a higher preference for the light rail as well as the free shuttle bus alternatives as the 'more sustainable' options. This should be compared to the sustainability advocate prioritisation, which provides a contextual and more distinct ranking of the four alternatives.

The three assessments present an insight on how new weighting can affect the preferred alternative. However, different results may occur if a new set of criteria is used for assessing the alternatives. The municipal assessment is indicative of an underlying car-based mind-set, while the nested as well as the sustainability advocate assessments illustrate the potential for a new paradigm in assessment. The sustainability ranking or the division and prioritisation of the existing eight criteria into the three dimensions do not provide a guarantee per se of meeting sustainability demands. Furthermore, the eight criteria secure no special attention to a number of wider sustainability issues, as they are rather a reflection of the current and contextual planning objectives.

This conceptual difficulty suggests the need for new and if possible, standard set of criteria for assessing sustainable transportation altogether. This ideal set of criteria would ensure a more holistic approach that could include more multi-modal and long-term considerations. For example, Banister elaborated in some depth what a wider understanding of sustainable mobility could include (Banister 2008). Such criteria could also address some of the limitations that were raised concerning the nested model approach, namely the lack of consideration for different types of natural capital affected and concepts such as irreversibility.

Nevertheless, it was shown that the nested model of the three dimensions of sustainability is conceptually accurate as well as simple to understand and operationalize into an MCDA process. However, it must also face the tough question: is it useful in driving change?

On one hand, a stronger conceptualisation of sustainability implies a basic reframing of the ethics behind the planning for sustainable transport. Using the nested model may at the very least '*contribute to shape knowledge and/or introduce new ideas*' (Gudmundsson, Sørensen 2013). Compared to the more traditional approach consisting of producing a CBA analysis complemented by an EIA report, the MCDA approach provides the opportunity to integrate both monetized and non-monetized effects into one common tool. This alignment of effects may contribute to an earlier and more holistic assessment of all impacts. In addition to this, the very process of MCDA requires an early engagement with experts and stakeholders in assessing the various alternatives against all possible impacts, which may help build a sense of ownership and gain acceptance for the project. Finally, the process requires explicitness on the criteria used as well as their prioritisation. Such transparency provides clarity to all stakeholders involved in the decision-making process.

On the other hand, although the tool is intended for instrumental use rather than just inspirational, it cannot replace decision-making. In suggesting a 'more sustainable' alternative, it is limited by the set of criteria that are considered. As it was already highlighted in the theory about the nested model, factors falling outside of the three dimensions of economy – society – environment are not explicitly considered. In a context of governance, such factors may include strategic fit with existing goals and visions, agency knowledge and capacity, the presence of effective leadership, or the barriers posed by norms and public expectations (Cornet, Gudmundsson 2015). However, based on the assumption that a decision departing from the results provided by the tool would require proper justification, the process may help increase accountability and thereby avoid *symbolic* use – where the assessment process is used as a means to justify a decision that has already been taken (Gudmundsson, Sørensen 2013).

Naturally, validating the process presented here in a real planning context could inform further on its potential and limitations in enabling 'more sustainable' alternatives to come through.

Conclusions

This paper uncovered some of the conceptual and analytical limitations of the planning approach illustrated by the case of a new connection across Roskilde Fjord in Frederikssund, and it proposed some pathways to overcome them. At a conceptual level, a stronger and more fine-grained understanding of sustainability is suggested as a starting point, and at the analytical level, the use of weights based on the nested model of sustainability is exemplified as a way to operationalize this.

Although the nested model is simplistic in that it does not accurately reflect the numerous complexities that compose sustainability theory, it was shown that this simplicity also renders its operationalization possible and provides valuable insights to the challenge of planning for more sustainable transportation. More particularly, it was shown that the reprioritisation of the environmental dimension above the socio-economic dimensions is consistent with the definition of sustainable development endorsed by the Brundtland report of 1987. Whereas the model bundles different types of natural capital into one and does not prevent critical thresholds to be crossed, it allows concerns for long term environmental integrity to supersede more narrow and short term considerations that traditional methods allegedly fail to do. This future generations' perspective embedded in the protection of long-term environmental integrity is the basic of the new ethics proposed by Brundtland that is deemed applicable for developed countries such as Denmark.

For the case of a new bridge connection across the Roskilde Fjord in Frederikssund, it was shown that applying the model leads to a clearer conclusion on the preferred alternative from a sustainability perspective. Overall, the alternative of a free shuttle bus service operating over the existing connection and the alternative of a light rail reusing existing infrastructure crossing the fjord are considered 'more sustainable' than the officially decided solution of building a new southern high level bridge for car-based traffic. When weights based on a stakeholder defined 'sustainability advocate' are used, the overall preference for the light rail alternative becomes clearer. However, while this approach may be more contextually relevant, it is also more dependent on stakeholders own understanding of sustainability.

This paper thus demonstrates the value of revisiting in more detail sustainability theories in order to beat the *schizophrenic paths* revealed by Banister (2008). The overall challenge raised is to arrive at a more precise understanding of sustainability that can inform prioritisation of often-conflicting issues and integrate that knowledge into existing processes of governance. The Brundtland report was selected for its wide acceptance and universal adoption, and it was found that, when reviewed beyond its one line definition, it can serve as useful guidance for such prioritisation.

Thus, the nested model approach proposed here is meant as a method, on one hand, for reaching further and connecting better to the essence of sustainable development, and on the other hand, to integrate this understanding into real planning and assessment practice. Because of its simplicity, the nested model serves as this 'bridge' between conceptualisation and operationalization of sustainable transportation planning. Although its results are not expected to be used 'as is', they can inform practitioners in taking a more explicit sustainability perspective – a type of benchmark – for comparing with decisions based on more traditional methods. However further research is needed to demonstrate whether the SUSTAIN Decision Support System model can also serve as a bridge to its strategic utilisation in a complex, democratic political process where paths dependencies and myopic interests may form serious barriers to change.

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APPENDIX

Assessment of Project Alternatives per Criterion by User Group

REMBRANDT assessment scale

Intensity of preference	Definition
0	Indifference
2	Weak
4	Definite
6	Strong
8	Very strong
1, 3, 5, 7	Compromise between

Criterion 1: Transportation and mobility

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	2.31	2.75	5.67	0.77
Alternative 2	–2.31	0.00	0.75	2.04	0.13
Alternative 3	–2.75	–0.75	0.00	0.74	0.07
Alternative 4	–5.67	–2.04	–0.74	0.00	0.03

Criterion 2: Infrastructure and operations costs

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	–4.35	0.34	–5.89	0.02
Alternative 2	4.35	0.00	1.01	–1.83	0.21
Alternative 3	–0.34	–1.01	0.00	–3.01	0.05
Alternative 4	5.89	1.83	3.01	0.00	0.72

Criterion 3: Noise exposure

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	–2.01	–3.76	–1.97	0.05
Alternative 2	2.01	0.00	–0.48	–0.38	0.21
Alternative 3	3.76	0.48	0.00	–0.03	0.47
Alternative 4	1.97	0.38	0.03	0.00	0.72

Criterion 4: Air pollution

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	–1.03	–5.27	–4.25	0.,02
Alternative 2	1.03	0.00	–4.28	–3.12	0.03
Alternative 3	5.27	4.28	0.00	1.03	0.41
Alternative 4	4.25	3.12	–1.03	0.00	0.30

Criterion 5: Local biodiversity impacts

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	–3.88	–1.74	–3.91	0.03
Alternative 2	3.88	0.00	0.72	–2.24	0.24
Alternative 3	1.74	–0.72	0.00	–1.35	0.15
Alternative 4	3.91	2.24	1.35	0.00	0.58

Criterion 6: Built aesthetic and identity

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	0.40	0.28	1.17	0.33
Alternative 2	–0.40	0.00	–0.32	0.02	0.21
Alternative 3	–0.28	0.32	0.00	0.95	0.29
Alternative 4	–1.17	–0.02	–0.95	0.00	0.17

Criterion 7: Traffic demand future proofing

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	2.69	0.50	2.26	0.52
Alternative 2	–2.69	0.00	–0.45	1.07	0.14
Alternative 3	–0.50	0.45	0.00	0.85	0.23
Alternative 4	–2.26	–1.07	–0.85	0.00	0.10

Criterion 8: Coherence within municipality

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Normalized score
Alternative 1	0.00	1.27	0.65	1.46	0.41
Alternative 2	–1.27	0.00	–0.69	0.66	0.18
Alternative 3	–0.65	0.69	0.00	1.18	0.28
Alternative 4	–1.46	–0.66	–1.18	0.00	0.13