Original Article

Assessing the sustainability of buildings using a framework of triad approaches

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ABSTRACT Five triads are presented that can be used as a framework to rank sustainable measures for the built environment in terms of space, transport, energy, water and materials. These new triads are all based on the same known principle of the Trias Energetica, which constitutes a three-step strategy to come to sustainable energy use. Most favourable measures which prevent energy use are defined as the top step and least favourable measures which only benefit the energy efficiency form the last step. In between, the renewable energy sources have found their position. Analogous to this Trias Energetica, the terms 'Trias Toponoma' for space-use, 'Trias Poreutica' for transport, 'Trias Hydrica' for water consumption and 'Trias Hylica' for materials are introduced and explained. The framework of triads can be utilized by city planners, architects, facility managers, house owners, real estate agents and other parties in the building sector to communicate and make decisions on adopting sustainable measures, which will help to decrease the environmental impact of the building sector and to stimulate the development of sustainable buildings.
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INTRODUCTION

The concepts of Sustainable Building and Green Building, the former being the implementation of Sustainable Development defined by the World Commission on Environment and Development (WCED, 1987) in the building sector, both form the basis of continuous incentives stimulating the successful introduction of new products and measures in this sector. With help of these innovations the opportunities are increasing rapidly to reduce the environmental impact of buildings. It is not an easy task to consider all possibilities to reduce the environmental impact of constructions. Different quantitative methods and accompanying tools have therefore been presented to classify the sustainability of buildings or more specific of these products and measures.

The measures, involving the energy use of buildings, won the most attention in residential and commercial real estate. Research of Zimmermann *et al* (2005, p. 1153) for instance shows that buildings consume the most energy during their use. For civil projects (with the exception of pumping facilities) the energy use during the lifetime is of lower importance. In this case the material use has a significant environmental impact; therefore the attention is often projected on the reuse of materials.

Although the field of environmental assessment tools in the building sector is vast (Forsberg and Von Malmborg, 2004, p. 223; Haapio and Viitaniemi, 2008, p. 469) and the existing methods already contribute in achieving the goal of sustainable development in the building sector (Ding, 2008, p. 452), there seems not one common qualitative method that brings five aspects of the environmental impact of buildings together. The most relevant aspects to consider are in this regards space use, energy use, material use, water use and need for transport.

A qualitative method can broaden the attention within a building project to these five aspects of sustainable or green building without making time consuming calculations or experiencing the restrains of a confined framework that reflects on a limited number of measures. Therefore, five three-step schemes are presented in this article based on the proven principle of the Trias Energetica.

Many scholars and practitioners have been using the Trias Energetica for multiple years (for example, Hestnes, 2001; Lysen, 2002; Buvik, 2003; Klunder, 2004, p. 117; Thomsen *et al*, 2005, p. 119; Sunikka, 2006, p. 522; Antvorskov, 2008, p. 1350; Op't Veld, 2008, p. 1344), but the full potential of this three-step methodology has not been a main subject of research yet. The Trias Energetica offers three steps to achieve sustainable energy use. Sustainable measurements related to the built environment can within these five different aspects (land use, energy, materials, water and transport) be ranked with respect to three levels of sustainability.

First, a short historical overview will be given of the origin of step-based schemes in the Netherlands, a land scarce and densely populated country, where the methodology originally was introduced. Subsequently to present a complete qualitative method, the Trias Energetica is transformed to four other aspects which strongly influence the environmental impact of buildings. Furthermore, there are three applications for the Triad framework specified. For each aspect the Triad is fully described in Developing a framework section, after which the discussion focuses on two design concepts. The last section presents conclusions.

BACKGROUND

The first sustainable step or ranking-based model in the Netherlands was proposed as a motion by Member of Parliament Lansink in the late 1970s (Raven and Verbong, 2004, p. 522; Parto *et al*, 2007, p. 238). Incorporated into Netherlands law on environmental conservation, his scheme – the so-called 'Lansink's Ladder' – contains seven steps to cope with waste disposal (Wet milieubeheer, 1979):

1. Prevention: try to create as little waste as possible.
2. Consideration of the raw materials: use raw materials which not harm the environment after product usage.

3. Product reuse: try to reuse a product in its original state as often as possible.
4. Material recycling: when the product cannot be used in its original form, then try to recycle its materials.
5. Combustion as a source of energy: when the product is assigned to be waste, then it can be incinerated in order to generate heat and electric power.
6. Combustion: less favourable is to burn the waste without the generation of heat and electric energy.
7. Landfill: the least preferable option for disposing of products and materials.

Later, Duijvestein (1993) introduced a three-step scheme, which ranked sustainable measures for the building industry with each step in order of sustainability preference. Most favourable measures were part of the first step and the least favourable ones formed the last step. The broad range of resources for a building project were seen as both incoming and outgoing flows. Three steps were specified for the incoming and outgoing flows and showed some similarity with the steps in the 'Ladder of Lansink'. Three steps for the incoming flow are

1. prevent unnecessary use;
2. use endless sources, for example, wind energy, solar energy, loam and wood;
3. use the sources which are not endless, as efficient as possible.

The outgoing flow can be made sustainable by the following:

1. Preventing waste
2. Reuse of waste
3. Disposing waste wisely

Duijvestein not only mentioned the flow of materials, but also other building-related flows such as water and energy.

In many building projects sustainability only focuses on a low energy use, which is required by the Netherlands Building Code. Lysen (1996) introduced his three-way strategy for sustainable energy under the so-called 'Trias Energica'. He named it after Charles de Montesquieu's 'Trias Politica' of 1752. The following scheme for a sustainable energy supply was suggested by Lysen:

1. A continuing improvement in energy efficiency
2. A bigger use of sustainable energy sources
3. A cleaner use of remaining fossil fuels

The combination of the Greek-like terminology of Lysen and the three-step strategy of Duijvestein led to the commonly used name of 'Trias Energetica' in the Netherlands. In identifying strategies for sustainable housing construction Klunder (2004, p. 117) refers to Duijvestein, being her source for the Trias Energetica. However, her citation is referring to a document originating from 1998 and not 1993. The final form of the Trias Energetica to which Hestnes (2001), Lysen (2002), Buvik (2003), Klunder (2004, p. 117), Thomsen *et al* (2005, p. 119), Sunikka (2006, p. 522), Op't Veld (2008, p. 1344) and Antvorskov (2008, p. 1350) refer, provides a more clear and hierarchical approach of sustainability than Lysen's three steps of 1996, namely:

1. prevent the use of energy by reconsidering the energy use (prevention);
2. use sustainable energy sources as widely as possible (renewable);
3. when there still remains an energy demand, then use fossil fuels as efficiently as possible (efficiency).

According to the authors the Trias Energetica became internationally adopted, starting in 2001 by the former president of the 'International Solar Energy Society' Anne Grete Hestnes. She mentions *It is now more or less universally accepted that the European Commission's* trias energetica *(first aim for energy efficiency, then use renewable energy, then supply the rest of the need with what the Commission calls* clean fossil fuels*) should be applied* (Hestnes, 2001). However, the energy use is not the only aspect that influences the environmental impact. Based on the same strategy of avoiding, sustaining and rendering efficient, here a total comprehensive theory is presented, besides energy, for four other building-related aspects: land-use, transport, water and materials. These aspects can be regarded as source flows, which are each for a certain time period allocated within the built environment.

DEVELOPING A FRAMEWORK

The three steps, put forward in the Trias Energetica, are in this article translated to four other aspects of sustainable building. Unlike Duijvestein's strategy, there will be no outgoing flows specified. By not specifying these outgoing flows the methodology is simplified without losing functionality. On first sight it may seem that now it is not possible anymore to include cascading processes. Nevertheless, in general the cascading use of an inflow will be part of the third step of the specific triad; to be as efficient as possible with non-renewable resources. In the situation that all resources for the whole cascade process (this includes, for example, the additional energy for recycling processes) are considered to be renewable and sustainable, then the cascade process will be part of the second step of a triad.

Following Lysen's vision the four aspects are designated as

1. 'Trias Toponoma' for the aspect land-use;
2. 'Trias Poreutica' for the aspect transport;
3. 'Trias Hydrica' for the aspect water;
4. 'Trias Hylica' for the aspect materials.

Three aspects, transport excluded, have already been explored by Chwieduk (2003), who classified three types of buildings; energy-efficient buildings, environmentally friendly buildings and sustainable buildings. By using the three-step strategy these classifications can be distinguished at a more detailed level. Now it will be possible to make more specific choices per aspect and per level in the design process. By emphasizing a certain triad, a designer (for example, architect) could focus on or point out, for example, the low water usage of the design or the optimal material use in a building. The simplicity of distinguishing five aspects, that each has three levels of sustainability, makes it possible to use the framework for at least three purposes:

- *Communication.* In the field of communication it is, because of the systematic approach of the framework, easier to communicate with parties involved, such as the architects or designers, constructors, facility management, wardens and home owners. These actors within the building process often do not (need to) know every detail from the environmental impact of a new sustainable measure, but for them it can be sufficient to express the level of sustainability using the three-step methodology.

- *Evaluation tool.* Implemented measures can be qualitatively classified on the base of their first, second or third rank in the specific triad. By aiming on one or two aspects out of five, it is possible to emphasize certain sustainable characteristics of a building or construction. The triads can be used to compose and assess designs, to select the most favourable sustainable measures which will also fit the customer's demands. They can be used additionally to existing tools as Greencalc+ (Sureac, 2005), the programme Leadership in Energy and Environment Design from the US Green Building Council (Lee and Burnett, 2007) and other assessment tools (like described by Forsberg and Von Malmborg, 2004; Ding, 2008; Haapio and Viitaniemi, 2008). The 'index of building sustainability' and 'index of efficiency in sustainability' specified by Olgyay and Herdt (2004, p. 391) also quantify the ecological impact of a project.
- *Making inventories*. For existing buildings there is also a possible use of the triads in clarifying the sustainability of a house or office, so that the market value of the building can vary with the sustainability degree on each aspect. One can think of a kind of environmental classification of buildings like the proposed energy certificate in the European Directive for Energy Performance of Buildings (EU, 2002).

In the following sections all five aspects of the Triad framework for sustainable building are addressed in more detail.

Trias Toponoma

The Trias Toponoma is a three-step scheme for sustainable space-use. Ideally, the space occupied by constructions used by the present generation should not jeopardize the needs of future generations. Locations which are used for buildings will only rarely be turned back into their original natural state. It is therefore necessary to reflect carefully on whether a certain location should be used for construction activities.

The natural potential of a defined area, such as a city, region or province, has to be at least maintained to ensure sustainable space use. So when an urban area extends, its natural potential decreases. This calls for intervention in another part of the defined area, which increases its natural potential. The size of the enclosed area can be delineated by means of various political or geographical borders. The natural potential of a defined area can, for instance, be classified by the seven so-called 'Hemeroby-steps' described by Beetstra (1998, pp. 108–109). According to Steinhardt *et al* (1999, p. 239), the term 'Hemeroby' comes from the Greek 'hemeros', which means cultivated, tamed and refined. The seven Hemeroby steps are described in Table 1. An application of these steps for the municipality of Haaksbergen is shown in Figure 1.

Mörtberg *et al* (2007) offer with their Landscape Ecological Assessment a sophisticated tool to simulate the consequences of infrastructural projects and other land use changes. The methodology from Beetstra (1998) specifies Hemerobie classes which quantify the natural potential of a region based on its solidification. This method has been developed from the point of view of city planners. The space use of a building is, nevertheless, a different aspect than the common consumables energy, materials or water, for which there are renewable sources. However, an attempt has been made to apply the

Table 1: Names and examples of Hemeroby classification

Class	*Hemeroby*	*Name*	*Examples*
0	Ahemeroob	Natural environment	Rainforests
I	Oligohemeroob	Close to natural environment	Nature reserves
II	Mesohemeroob	Extensive cultivated	Forests, natural wide
III	β-euhemoroob	Cultivated	Meadows, monotonous forests
IV	α-euhemoroob	Intensive cultivated	Agriculture, open horticulture
V	Polyhemoroob	Residential area	Suburban areas, excavation areas
VI	Metahemoroob	Solid surface	Parking lots, city centres

Source: Beetstra (1998).

Kaart natuurpotentiaal centrumgebied

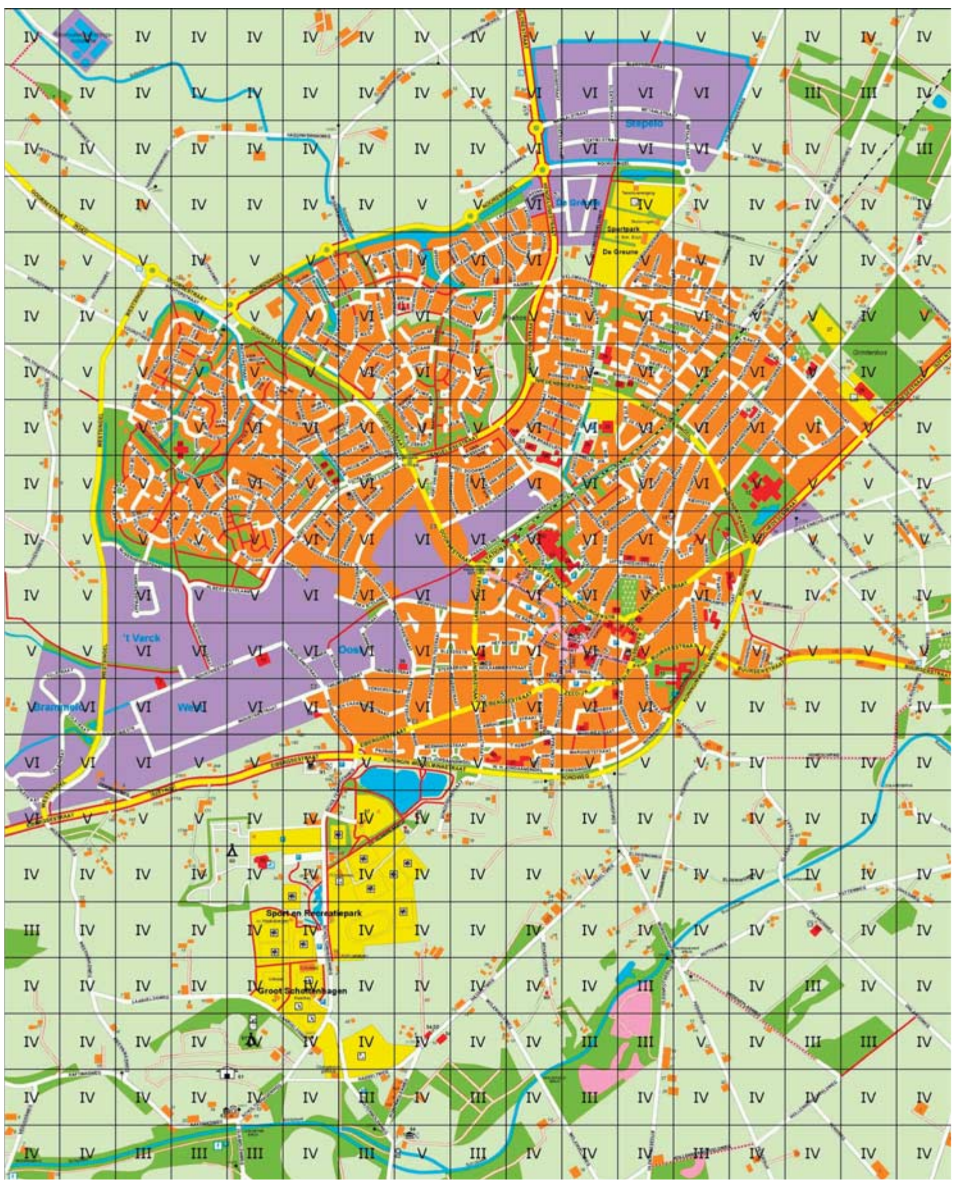

Figure 1: The natural potential of the municipality of Oldenzaal classified by Hemeroby steps for approximately every 0.09 km^2.

Trias approach to space use (Entrop *et al*, 2004). This so-called 'Trias Toponoma' contains the following three steps:

1. In case of step 1 new building development takes place within the existing built-up area (using the methodology of Beetstra (1998) one can speak of a 'metahemoroob' or class VI environment). Use as little 'fresh' natural space as possible by using the third dimension of buildings. In the city centre it is necessary to build higher or deeper structures. Within this first step it is also possible to use the dimension of time by appointing more than one function to a building. This concept will be explained more extensively within the principle of multiple space use.
2. When it is not possible to achieve the necessary building volume in the already developed and built area, then the built up area can be enlarged to the country side of low natural importance (the methodology of Beetstra (1998) uses class III–V). Enlarge the city with a so-called 'green vision', which for recreational functions makes the relatively natural environment part of these new neighbourhoods. This represents a kind of cascading of this non-renewable source.
3. The least sustainable option is to extend the built up area in a rather natural environment (with Hemerobie classes 0–II). In this case, the construction of buildings could take place extensively or in other words spread buildings over a large surface in such a way that it has little effect on the main natural structures of the area.

Some practical examples to realize sustainable solutions based on the framework of this Trias are described in Table 2. In the next section, the three-step method to come to sustainable transport will be introduced, which is strongly related to the Trias Toponoma

Table 2: Concepts to come to sustainable land-use

Step	*Concept*	*Explanation*
1	Multiple space use	Space can be used for multiple functions in three different ways: (1) Certain spatial functions can be stacked; for example apartments can be constructed over a shopping mall (location sharing). (2) A function can be shared by different user groups with only minor adaptations; a school can function as an adult education centre in the evenings (time sharing). (3) Functions can be mixed; in a residential area specific offices or industries might also be allowed.
1	Build within the city before expanding it	Inventive solutions are necessary to cope with the ever growing demand for floor space. Not only technical solutions are required, but also toleration on the part of urban residents. Intensifying the density of cities will help in keeping space open for natural developments, but could reduce the personal freedom of citizens.
1	Space saving	Saving space in industrial zones has led to interesting examples: (1) The combined use of facilities by multiple offices; for example one central canteen in an industrial zone instead of one canteen for every individual company. (2) The use of flexible workplaces, which can be used by more than one employee.
2 and 3	Compensation principle	By making Greenfield building projects more expensive than projects in the built up area; building projects in the urban area can become more attractive. The loss of the natural potential is compensated to keep a proper quality level and quantity of natural environment.
3	Light town-planning	By placing little groups of buildings (or a few solitary buildings) in a wide open natural landscape, it can be possible (under strict conditions) to maintain the natural function of the area (for example, ecologically connected zones) as much as possible. The natural function can even be improved, which may be the case when country houses with large and highly natural surroundings are created.

and urban planning in general. Less obvious are the relations between urban planning and transport on the one hand and energy use on the other. On this relation Saunders *et al* (2008) reflect by using the concept of transport energy that is related to land use and transport systems. They suggest that transport-energy policies have the ability to positively influence urban design regarding the finiteness of transport energy resources and the polluting submissions.

Trias Poreutica

The Trias Poreutica represents a three-step sustainable scheme for the transport between built objects. The subjects of transport, urban planning and infrastructure are closely related, but the sustainability of the infrastructure itself can be qualified by using two other Triases: the space involved with infrastructure by the Trias Toponoma and the material aspects by the Trias Hylica.

Here, attention is focused on the frequency and means of transport. Transport means all movements – motorized or not motorized – that take place within the available infrastructure. Newman and Kenworthy (1999) relate sustainability to a smaller automobile dependence. This principle forms the first step towards sustainable transport. A solitary building can be assessed regarding adopted measures to stimulate sustainable transport. Three classes of measures regarding the sustainability of transport can be qualified by the Trias Poreutica:

1. The first step reduces the need for transport by placing different types of activities close to each other, so shortening the travel distances. In general, the use of motorized transport has to be reduced. Especially, short distances enable the most sustainable alternatives: walking or cycling.
2. Try to make use of sustainable transport methods. The general idea is that public transport is the most sustainable way of transport, when it is not possible to walk or bike. However, public transport still can be improved in terms of fuel consumption, speed, flexibility and price. Over recent years, the environmental advantages of public transport relative to personal vehicles have been decreasing. There will always remain a need for personal motorized transport. To render this form of transport more sustainable than conventional (fossil fuel-based combustion) engines the use of electric cell, bio fuels or hydrogen cars needs to be stimulated. Even in that case, the required electric energy should preferably be generated in a sustainable way completely fulfilling this second step of the Trias Poreutica analogue to the principle of the Trias Energetica.
3. When a demand for motorized transport still remains, then the third step suggests trying to make the non-sustainable transport as efficient as possible without creating traffic jams or long diversions. Cars are becoming more and more efficient through, for example, the use of hybrid engines or computerized engine control. The driver can influence the fuel efficiency by carrying more passengers, driving less aggressively and at a lower speed. The government could reduce the environmental impact of personal transport by facilitating carpooling, green waves and so on. When car pooling would be common practice, there should be fewer traffic jams and less pollution.

Banister (2008, p. 73) speaks of a 'sustainable mobility paradigm' and also Hull (2008, p. 94) uses the term 'paradigm' to catch the complex and paradoxical setting in which the sustainability of transport and mobility has been embedded. The Trias Poreutica can, however, be of assistance in the key elements in promoting the public acceptability of

Table 3: Concepts to come to sustainable transport

Step	*Concept*	*Explanation*
1	Compact or complete cities	City-planning plays an important role in rendering transport more sustainable. In the Netherlands, a city-planning concept from the 1980s has been improved to fit the first step of the Trias Poreutica. The old concept was focused on 'Compact Cities' in which different functions were combined in a small urban area of high density. By combining working, residing and recreating, short travel distances could be guaranteed. This concept had environmental advantages on a large scale, but some negative features on a smaller scale. This led to an improved version: the Complete City. Complete Cities tried to overcome the noise and unattractiveness of a Compact City by supplying natural public facilities, like parks or lanes, at strategic locations (SEV and Novem, 1999).
2	Traffic calming or closed neighbourhoods	By making neighbourhoods more attractive for non-motorized transport, the use of motorized transport for short distances can be reduced. The layout of roads will strongly influence the amount of traffic. In the Netherlands, the existence of a cycle network, separated from the motorized transport, in newly built neighbourhoods is very common. Usually, a small shopping centre in the middle of these neighbourhoods can be reached by bike and by bus. Some city centres do not allow any motorized traffic at all (except early in the morning or in the evening for deliveries to the commerce) resulting in less polluted air, noise reduction and improved safety for pedestrians.
2	Rapid Transit	Public rail and road transport need to become as attractive as personal road transport. A quick and comfortable way to travel can be obtained by offering up-to-date information, properly timed transfers, and quick connections. Information technology uses the Global Position System to give travellers the name of the next bus stop. That same technology can be used to specify the arrival time of the next bus at the bus stop. Another example of Rapid Transit is the use of separated bus lanes in cities with high traffic densities. The subway can also be an example of rapid transit.
3	Speed regulation	Because of the oil crisis during the 1970s, the speed limit for the Dutch highways was originally set to 100 km/hour. Later, the speed limit rose to 120 km/hour. In 2005, the air pollution in four large cities rose to above the maximum acceptable European level. Along some of the highways around these cities the speed limit was set on 80 km/hour to facilitate unhampered traffic flow and to reduce traffic-related emissions (VROM, 2005).

sustainable mobility, which Banister (2008) addresses. Although it is hard to achieve step three without negative consequences for the popularity of public transport, there are sufficient concepts that fit in the scope of the Trias Poreutica (see Table 3).

Trias Energetica

The energy use involved with the use of buildings is one of the most addressed aspects within sustainable building. The Trias Energetica is also the oldest and most original sustainability triad. Furthermore, the energy use is prescribed and limited already by building codes of many countries (Míguez *et al*, 2006). With the implementation of the Energy Performance Building Directive (EU, 2002) the most important design aspect for buildings – after the aesthetics and safety – will be energy use.

In the Netherlands, the energetic measures must be specified in the design of the building so that it will meet the so-called Energy Performance Coefficient and a building licence can be granted (NNI, 2004a, b). This coefficient expresses the ratio between the estimated energy use of the specific building design and the 'standard' energy use of a building with the same size. For residential buildings, energy measures are needed to take this coefficient down to a value of 0.8 specified in the Dutch Building Code (Bouwbesluit, 2003). In 1995, the indicator was originally introduced with a maximum value of 1.4 for new residential buildings. The computational procedure to determine this coefficient has been standardized in two specific norms for residential and non-residential (for example, office) buildings (NNI, 2004a, b).

The Dutch Building Code also prescribes an energy saving measure, namely a minimum heat resistance for the building shell. The advantage of this regulation on insulation is that it is also applicable when modifications are made to existing buildings. The regulation prescribing the Energy Performance is only required for new buildings.

In the Netherlands, the energy saving policy for the built environment is focused on the heating of living space, heating of tap water, ventilation and lighting. In countries closer to the equator the climate demands a policy which is focused on cooling rather than heating, as is the case in northern countries such as the Netherlands. Nevertheless, the energy required for both heating and cooling has to be minimized and its source has to be as sustainable as possible.

Based on Duijvestein (1993) and Lysen (1996) the Trias Energetica refers to three categories of measures, which can bring a sustainable solution for the energy use of houses and offices (see Figure 2):

1. Take measures which reduce the building's energy need, such as insulation and a natural ventilation system. In the case of utility buildings, the use of large glass surfaces oriented to the sun should be carefully considered, because of the possible heat transmission in summer. Although the heat of the sun is considered to be a sustainable form of energy, it is in this case wise to install external window shades to lower the electric energy need of the air-conditioning system.
2. The second step is to use as many renewable sources ad to keep the energy demand as sustainable as possible. The (active or passive) use of solar energy or use of wind energy are examples in this category.
3. If there are insufficient sustainable sources, then it is necessary to use fossil sources. In this case, use the supplies as effectively as possible. The use of highly efficient combination boilers is one way to use gas to heat both living spaces and water.

The Dutch building energy code is just one example of an instrument to improve energy efficiency. Aforementioned Energy Performance Coefficient takes measures into account

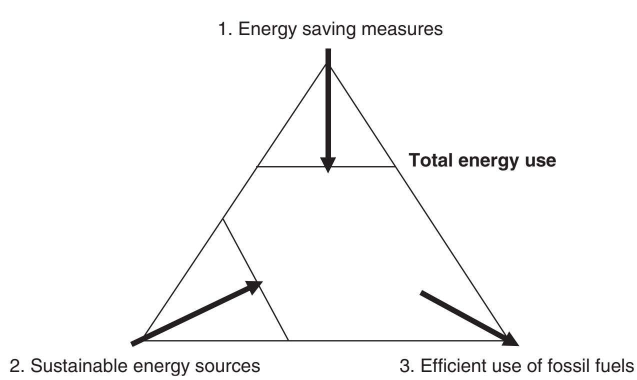

Figure 2: Visual model towards a sustainable implementation of the power consumption according to the Trias Energetica.

from all three steps of the Trias Energetica. Furthermore, three categories of instruments have been proposed by Lee and Yik (2004) from a policy perspective:

1. Building energy codes that are regulatory requirements
2. Incentive-based schemes
3. Eco-labelling schemes

By applying these instruments, it is possible to adjust governmental policy by specifying measures from the first step as mandatory requirements and the measures to the second or third steps as voluntary improvements. General conditions for the regulation and certification of the energy use of buildings are laid down by Casals (2006) to control and limit the energy use in the building sector effectively.

Table 4: Concepts to come to sustainable energy use

Step	*Concept*	*Explanation*
1	Adjustable lighting	During night one can adjust the lighting of infrastructure (for example roads, highways) to the actual presence of users (traffic), using sensors and informatics.
1 and 3	Home information technology	The use of information technology at home can reduce the energy need by controlling ventilation, lighting and heating. The combination of home information technology with low-temperature heating will ensure a higher comfort for the users of the building by providing the demanded temperature at the right time.
1 and 2	Passive solar energy	It focuses on minimizing the need for heating by using a high degree of insulation, reducing air ventilation losses and putting sunshine to good use. This means a southern orientation in the northern hemisphere and a northern orientation in the southern hemisphere. In countries close to the equator with high average temperatures, insulation makes it possible to cut down on energy required for the cooling. There, the orientation of the buildings has to avert incoming sunshine.
1 and 2	Energy balance	Heat and coolness of days and nights can be used to avoid forced heating and cooling, to this end the thermal mass of constructions can be used. Especially concrete constructions are suitable to utilize this principle, because of the high specific mass of concrete. Furthermore, storing heat in underground aquifers can flatten out seasonal fluctuations.
2	Active solar energy	Both passive and active solar energy can make (non-)residential buildings more sustainable. Active solar energy can be achieved by making use of solar collectors (for water heating) or photovoltaic panels (for electricity).
2	Geothermal energy	The earth has provided fossil fuels for centuries, but the more direct supply of energy for the generation electric power or heating of space is only about one century old. The principle of geothermal energy cannot only provide essential heat, but by using a heat pump it is also possible in some parts of the world to cool offices and houses.
3	Cascaded use of energy	To make an energy supply more efficient, a cascade use can be obtained by using heat recovery from sewage water, ventilation and machines. In industrial buildings, heat recovery from machines is clearly possible. In residential buildings, heat recovery from washer-dryer machines can give an implementation of cascade use of energy. The primary function – drying – will, in that case, make it possible to achieve a second function, namely heating. In general, exergy analyses can help to use energy resources as efficiently as possible.
3	Energy saving lights	In infrastructure (roads, waterways, railways) the use of LED's (instead of conventional bulbs) for traffic lighting results in energy saving. The service life time of these LED's is also much longer, so also substantial savings on maintenance can be achieved.

To construct a sustainable building, the concepts in Table 4 can currently be seen as voluntary improvements. Several of these eight concepts can be combined within a particular building project and many other examples of energy saving measures for buildings exist. The realization of a good summer or winter comfort and a healthy climate within a house or office needs complementary measures: such as hybrid ventilation and a specific material choice. A specific – customer orientated – building design consists of a unique combination of concepts and specific measures, which together result in certain level of energy use.

New techniques are being used to come from conventional methods of energy supply to more sustainable methods. However, gas production by the method of Coal Bed Methane is a source of energy of which the sustainability and hence the step in the Trias Energetica is negotiable. Gas production in combination with CO_2 injection into coal seems to result in no net CO_2 emissions (Treffers *et al*, 2005), which is also the case in using biomass energy. However, extracting gas will eventually result in depletion, which certainly does not make it the most favourable energy source.

Trias Hydrica

Water consumption within a building is an aspect that can also be viewed on a three-step basis. Wong and Mui (2008) stated that freshwater consumption has been identified as one of the key issues in sustainable building designs. Their figures showed consumption patterns reaching from 65 to 175 litres per day per person in Europe up to 150 to 365 per day per person in some Asian cities. In the Netherlands, the average water use of one person is around 134 litres per day, of which only 2 litres are used for the consumption (drinking, preparation of food, see Table 5). This offers quite some opportunities to reduce water consumption. Furthermore, the quality of the provided water does not always match the quality that is needed. In many cases residents are supplied with fresh drinking water only, although some goals (for example, flushing the toilet) can still be met with water of a lower quality (for example, stormwater).

Former research from Cheng (2002, p. 264) relates water consumption to energy use. It shows that reducing the water consumption will also affect the energy use, because the treatment and pumping need approximately 0.95 kWh/m^3 drinking water. Based on 134 litres per person per day, and 2 persons per household, this would imply an indirect energy use of about 92 kWh. Benedetti *et al* (2007, p. 1268) speak of an energy use for wastewater treatment of 0.32 kWh/m^3(σ = 0.10 kWh/m^3) among 29 sewer catchments in the Nete river basin in Belgium.

Table 5: Water use for domestic activities in liters per day

Activities	*Water use*
Flushing the lavatory	39 litres/day
Showering	38 litres/day
Doing the laundry	28 litres/day
Bathing	9 litres/day
Washing the dishes	6 litres/day
Food preparation	2 litres/day
Other activities	12 litres/day
Total water use	134 litres/day

Source: SenterNovem (2006).

Table 6: Concepts to come to sustainable water use

Step	*Concept*	*Explanation*
1	Housing without sewerage	In most western countries, houses are connected to the sewerage system. Traditional toilets use vast amounts of water, which demands large sewer pipes and a complex sewer system. Toilets without flush and the use of reed for household water treatment make it possible to construct housing without sewerage connection.
2	Storm water collection	It is possible to use the entire roof for collecting storm water. This storm water can be stored in a tank underground or on the attic to be used for sanitation, gardening and washing clothes for example. The concept of reusing storm water goes a lot further than installing a simple water butt.
3	Grey water network	To avoid using high quality drink water for purposes that can be met with water of a lower quality, so-called grey water networks are developed. This network can supply offices and houses with water that can be used for washing and toilets, but has not the same quality as drinking water. The treatment of this grey water or household water is less intensive and less harmful for the environment than the treatment to obtain high quality drinking water. On a small scale, the cascade use of water can already be accomplished by using a wastewater system for the toilet, for example. This system filters and uses the shower and bathing water only for flushing the toilet, without the high costs and large space use of a central water tank.

In the Netherlands, the sustainability of building-related water consumption is expressed in the Water Performance Coefficient of a building. This coefficient expresses the primary water usage for consumption, washing and sanitation (NNI, 2001). The Water Performance Coefficient, unlike the Energy Performance Coefficient, is not yet formalized in the Dutch Building Code, but offers a quantitative approach for addressing the building-related water consumption. The water-version of the Trias Energetica offers a qualitative approach under the name of Trias Hydrica. It contains the following three steps:

1. The first category consists of measures in the building design which avoid water usage.
2. On the next level renewable sources are used as much as possible, such as stormwater use for gardening, toilets and washing machines.
3. In the third place, it is recommended that precious clean drinking water will be used as efficient as possible, for example, by installing water-saving toilets and showers. Water can, for example, be used in stages of quality, as a form of cascade: Firstly, it can be used for bathing and secondly, the same water can be used for the garden. During these stages of the cascade the application of constructed wetlands can provide a natural environment to improve the quality of the waste water.

In Table 6 are some practical examples of design solutions aligned for a sustainable water use.

Trias Hylica

The same translation of the triads for land use, transport, energy and water can be made for building materials. The building industry accounts for about 30 per cent of the raw materials used in the world (UNEP, 2006). Not only the quantity of these materials has an environmental impact, but equally important is the quality of the materials used in a building's construction. For the production of aluminium, for example, much more energy is required than for the preparation of wood for architectural or constructive purposes. However, aluminium window-frames can last longer without considerable maintenance than their wooden equivalents. They can also be recycled almost endlessly with each time a relatively little energy use.

There is not a specific coefficient for the choice of materials yet, but there are Life Cycle Assessment (LCA) programmes to determine the environmental impact involved with the production, use and dispose of materials ('cradle to grave'). According to Miettinen and Hämäläinen (1997, p. 279): *LCA describes the environmental effects associated with a product, process or activity over its whole life cycle by calculating the material and energy requirements as well as emissions to air, water and soil and by assessing the environmental impacts of those.* Producers of building materials can, for example, determine specific environmental profiles of their products. Although these quantitative procedures for analyzing buildings in small detail are not fully standardized, the International Organization for Standardization (ISO) has in a period of 5 years specified some norms about LCA procedures starting with ISO 14040 (ISO, 1997).

Three steps in 'Trias Hylica' can be distinguished to come to qualitative analyses of buildings:

1. A first category of measures will prevent the unnecessary use of materials, such as smart and efficient designs of components (box girders, hollow floors, H-profiles) and of buildings, and combinations of functions.
2. The second step is to use local renewable materials for the use in buildings and/or production of building materials. Examples of this category include loam, shells, shell lime, flax, wood and cork.

Table 7: Concepts to come to sustainable material use

Step	*Concept*	*Explanation*
1	Optimizing the design	In other industries, like the aerospace industry, product optimization is already common, but in the building industry it is still possible to optimize designs. Optimizing should imply that the materials required and the produced wastes are both minimized. A reduction in quantity and the improvement of the environmental quality of materials has never an end, as the development of new and stronger materials with better specifications will continue.
2	Use of renewable materials	A solution that fits the second category is the use of renewable materials. When properly produced, these materials are inexhaustible and have a natural origin, which under certain conditions also results in favourable effects on the inside climate.
3	Easily dismountable housing	With the use of finite materials, it is important that they can be used as many times as possible. The recycling process can be facilitated by building that can be easily dismantled. Parts of the construction can then be reused on component level. The least preferable solution is to demolish a building so that only the raw materials remain. In this latter case, the separation of waste streams (glass, steel, stone, plastic and so on) is recommended (obliged in the Netherlands) to facilitate recycling.
1 and 3	Prefabrication of construction parts	In contrast to the onsite production of construction parts, offsite production can have certain environmental advantages. The prefabrication of concrete floor parts, for example, ensures higher strength and therefore a smaller weight as compared to traditional solutions. Also recycling of waste streams and optimum use of materials on the own promises is facilitated. It is also possible to deliver such parts just-in-time, so reducing the risk of damage while awaiting the deployment on the construction site.

3. The last possible step is to use non-sustainable sources in the most effective way, for example the use of cement, high strength concrete and steel, better use of remainders of materials and the cascade use of materials.

The same procedure can be used here as with the Trias Energetica and Hydrica. Four concepts are shown in Table 7 for designing a sustainable building regarding material use.

DISCUSSIONS

The first part of the discussion reflects on the difficulty of assessing cascading processes. In Developing the framework section, it has already been addressed that cascading processes are part of the third step. Within the Trias Hylica the ranking of the material wood in all its forms within the three steps is negotiable. In the re-use and recycling of wood, up to six stages (floor beam, floorboard, laminated window frame, hardboard, fibreboard, and fuel for generating heat or electricity), attention needs to be paid to the origin of the wood and the auxiliary energy used in the process of cascading. Only when wood is properly cultivated, processed and transported in a sustainable way and the material therefore really can be considered as renewable, then the second step of the Trias Hylica is applicable.

However, when after its first use the material is going to be reused (for example, as chipboard) by processing it in an unsustainable way (by using harmful glues or non-sustainable forms of energy) the whole process degrades to the third step of the Trias Hylica. Finally, upon the last stage of the cascading process of wood, incineration, it is used to generate heat and electric energy. This final stage can only be characterized as sustainable, when the whole process affront was carefully executed in a sustainable way. The incineration of household waste can therefore not be considered as a sustainable source for generating heat and electric energy, because it is necessary to prevent the creation of waste in the first place.

The second point of discussion involves the paradoxical decisions during the development of buildings and constructions. In the design processes of the built environment architects, designers, and city planners will try to cope with the customers' demand on the real estate market. It is during these design processes that important choices and decisions have to be made to achieve a sustainable object. The five three-step ranking models enable the involved stakeholders to design sustainable buildings in a more methodological way.

Sometimes paradoxical decisions between two different triads or within one triad must be made to come to a sustainable building design. Two design philosophies can help in making a design as sustainable as possible by exploiting its durability and by ensuring its attractiveness, viz:

- *Adaptable housing concept*. This concept focuses on measures to make it possible for habitants to live their entire life in one and the same house. The house can, for example, be refitted to accommodate the common disabilities that elderly people experience.
- *Customer orientated building*. This second concept focuses on the wishes of the customer. The building and the selling process of buildings are often separated. By bringing the customer into contact with the constructor, a house or office can better meet the customer's requirements. However, certain wishes from the customer must be questioned, because the knowledge of the customer will not suffice to be familiar with all technical and environmental implications of their wishes.

CONCLUSIONS

In this article, an assessment framework based on the Trias Energetica was introduced. The five triads form an open framework for many techniques and measures that lower the environmental impact of buildings and infrastructure. Many examples of techniques and measures per aspect have been given to explain the specific triad and its possibilities. By this means measures and buildings can be assessed in a qualitative way.

Literature shows that around the world more methods and systems exist which offer frameworks or can assess the environmental impact of buildings. However, the framework of triads can be used in combination with all of them and can offer scholars and practitioners a compact and easy understandable overview of applied techniques and measures. Vice versa, it is also possible to use the framework to characterize and rank techniques or measures that have not been applied yet, but could be advisable to apply. Combining best qualities of existing tools, methods, framework and systems to qualify and ultimately lower the environmental impact of buildings is one of the major challenges for the future of the built environment. The presented Triad framework may assist to achieve this goal.

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