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Energy, environmental and economic optimization of thermal insulation solutions by means of an integrated decision support system

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ABSTRACT

A new decision support system for the integrated assessment of thermal insulation solutions with emphasis on recycling potential is presented in this paper. The suggested system comprises three main assessment factors: primary energy consumption, the environmental impact and the financial cost; each and every factor is analytically assessed during the four distinct stages of a thermal insulation solution's life cycle. The calculation of the aforementioned factors takes place using analytical algorithms, formulated in such a way that have led to the development of the integrated, holistic decision-making support tool, namely ib3at. Using ib3at it becomes feasible to optimize the end-of-life management of thermal insulation solutions, but also to select, during the design phase of a new building, the optimal thermal insulation solution for each building element. The ib3at is applied for common thermal insulation practices, used widely in new constructions as well as in the renovation of existing buildings.

1. Introduction

Buildings in Europe account for one third of the total energy related CO_2 emissions and even higher in some countries depending on the fuel mix of energy consumption [1–3]. Another major environmental impact of buildings is the production of construction and demolition waste (CDW) that have a major impact on landfills. According to the European agency, CDW account for 10–33% of the total waste stream. For this particular waste stream, demolition phase accounts for 40–50%, renovation procedures for 30–50% and construction procedure only for 10–20%, of the total waste [4]. The building stock presents a low turnover rate due to the high number of existing buildings and their lifetime of 50 and frequently more than 100 years. It is characteristic that 70% of the residential buildings are over 30 years old of which about 35% are more than 50 years [1,5]. In addition demographics in Western and Central Europe are a factor that contributes to the saturation of the demand in the residential building sector, leading to the current trend of emphasising in renovation and refurbishment of the existing housing stock [6]. It is therefore clear that the largest potential for improving energy performance of the building stock lies in the existing buildings and it is essential to focus on sustainable construction practices towards the minimisation of energy consumption and environmental impact also in these constructive activities [7–9].

To assist and promote sustainability in construction, an integrated decision support system (DSS), namely ib3at, is presented for the assessment of thermal insulation solutions (TIS) during their life cycle, placing special emphasis on their recycling potential.

2. Methodology adopted for the ib3at

The basis of the ib3at lies in the analytical calculation of the desirable assessment factors during the life cycle of a TIS. The life cycle consists of four distinct stages namely the construction, the operation, the demolition and the end of life management. Primary energy consumption, environmental impact and financial cost are the three main assessment factors that were chosen to be studied [10]. The methodology adopted for ib3at is schematically presented in the flowchart of Fig. 1.

2.1. Calculation of the assessment factors

The calculation of each assessment factor in every life cycle stage has been carried out with the formulation of proper analytical algorithms. Primary energy consumption can be calculated from Eq. (1),

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Nomenclature

A	external surface (m^2)
CA	disposal cost (€/kg)
$CA(D;R)$	total cost for processing waste produced from demolition (D); deconstruction (R) in a waste management facility (€)
$(C;EC;EIA)C$	cost (C); primary energy consumption (EC); environmental impact assessment factor during construction phase (€;MJ;unit of factor)
CCS	maximum capacity of transport vehicle (kg)
$C(D;R)$	total cost for demolition (D); deconstruction (R) (€)
$(C;EC;EIA)DR$	cost (C); primary energy consumption (EC); environmental impact assessment factor during demolition phase (€;MJ;unit of factor)
$CO(C;H)$	cost during operation phase (C: cooling period; H: heating period) (€)
$(C;EC;EIA)OHC$	cost (C); primary energy consumption (EC); environmental impact assessment factor during operation phase (€;MJ;unit of factor)
$CT(D;R)$	total cost for the transportation of waste produced from demolition (D); deconstruction (R) to a waste management facility (€)
$(C;EC;EIA)TIS$	total cost (C); primary energy consumption (EC); environmental impact assessment (life cycle) (€;MJ;unit of factor)
$(C;EC;EIA)TS$	transportation cost (C); primary energy consumption (EC); environmental impact assessment factor per kilometer (€/km;MJ/km;unit of factor/km)
$(C;EC;EIA)WM$	cost (C); primary energy consumption (EC); environmental impact assessment factor during end-of-life management phase (€;MJ;unit of factor)
d	density (kg/m^3)
ECA	primary energy consumption for transportation of waste to a waste management facility (MJ/kg)
$ECA(D;R)$	total primary energy consumption for processing waste produced from demolition (D); deconstruction (R) in a waste management facility (MJ)
$EC(D;R)$	total primary energy consumption for demolition (D); deconstruction (R) (MJ)
$ECO(C;H)$	primary energy consumption during operation phase (C: cooling period; H: heating period) (MJ)
$ECT(D;R)$	total primary energy consumption for the transportation of waste produced from demolition (D); deconstruction (R) to a waste management facility (MJ)
$ECTS(A;B;I)$	primary energy consumption for transportation of not able to be recovered mixed insulation waste (A); demolition waste, excluding insulation (B); recovered clean insulation waste (I) from the implementation of deconstruction (MJ/km)
$EIAA(D;R)$	environmental impact assessment factor for processing demolition (D) or deconstruction (R) waste in a waste management facility (unit of factor)
$EIA(D;R)$	environmental impact assessment factor for demolition (D); deconstruction (R) (unit of factor)
$EIAFeqC$	environmental impact assessment factor during construction phase (unit of factor)
$EIAO(C;H)$	environmental impact assessment factor during operation phase (C: cooling period; H: heating period) (unit of factor)
$EIAT(D;R)$	environmental impact assessment factor for the transportation of demolition (D); deconstruction (R) waste to a waste management facility (unit of factor)
NR	normalized value of assessment factor (–)
PC	value of assessment factor per citizen of the country where the methodology is applied (unit of factor)
PR	coefficient of recovery of clean insulation waste (–)
QBB	quantity of building materials (excluding insulation) (kg)
QBI	quantity of insulation materials (kg)
QDM	quantity of materials derived from the implementation of demolition (kg)
$QRM(A;B;I)$	quantity of not able to be recovered mixed insulation waste (A); demolition waste, excluding insulation (B); recovered clean insulation waste (I) produced from the implementation of deconstruction (kg)
R	value of assessment factor (unit of factor)
$Rating$	total rating (–)
SD	number of routes necessary for the transportation of waste to a waste management facility (–)
SED	bulking factor (–)
$SR(A;B;I)$	number of necessary containers for transportation of not able to be recovered mixed insulation waste (A); demolition waste, excluding insulation (B); recovered clean insulation waste (I) from the implementation of deconstruction (–)
t	thickness (m)
TD	distance from the waste management facility (km)
y	on/off variable (–)
years	operating time (number of years)
z	on/off variable (–)

Subscripts

i	thermal insulation solution
j	insulation material
l	waste management facility
g	assessment factor

financial cost from Eq. (2) and environmental impact from Eq. (3).

$$ECTIS_i = ECC_i + ECOHC_i + ECDR_i + ECWM_i = \sum_{j=1}^{n} t_{ij} \cdot d_{ij} \cdot ECC_{ij} + [(ECOH_i + ECOC_i) \cdot \text{years}] + \sum_{j=1}^{n} t_{ij} \cdot d_{ij} \cdot ECDR_{ij} + \sum_{j=1}^{n} t_{ij} \cdot d_{ij} \cdot ECWM_{ij} \quad (1)$$

$$CTIS_i = CC_i + COHC_i + CDR_i + CWM_i = \sum_{j=1}^{n} t_{ij} \cdot d_{ij} \cdot CC_{ij} + [(COH_i + COC_i) \cdot \text{years}] + \sum_{j=1}^{n} t_{ij} \cdot d_{ij} \cdot CDR_{ij} + \sum_{j=1}^{n} t_{ij} \cdot d_{ij} \cdot CWM_{ij} \quad (2)$$

$$EIATIS_i = EIAC_i + EIAOHC_i + EIADR_i + EIAWM_i$$