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THE RELATION BETWEEN BUILDING COSTS AND EMBODIED ENERGY: NEW INSIGHTS

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ABSTRACT

Since the Yom Kippur War, and the subsequent Oil Crisis, the energy issue invaded the political, economic and academic debate. Several manufacturing sectors, the building industry as well, have since been committed to achieving a higher level of efficiency in energy use. Under this framework, starting from the end of the seventies, a specific research branch has been devoted to deepening the issue of the energy embodied in various commodities and goods, and, among others, in the construction materials. Nonetheless, during the following decades, this promising research branch has been partly neglected, due to a prominent interest in the building energy consumption in operation. On the contrary, during the last few years, the embodied energy topic has gone back to be a major research item, according to the growing awareness that the energy used to produce the buildings represents a remarkable share of the life-cycle energy. Such a circumstance is not at all peculiar if we consider high-performance buildings, as is the case of the passive house, and it has been validated by several recent studies.

In a recently published study, we show that the energy embodied in building products, except for raw materials, is a positive logarithmic function of their production cost. The embodied energy is inferred by the inventory edited by Hammond and Jones at the University of Bath. Besides, the costs are gathered from a price list of building products, which is commonly used to arrange the bill of quantities of any construction project. In this paper, starting from the aforementioned empirical finding, we aim at providing further insights into the relation tying together the embodied energy and the cost of building materials.

Rather than assuming one-shot estimates of the costs, for each of the considered building materials, we investigate their variation range. Subsequently, relying on a random distribution of all the costs within the identified ranges, we perform a Monte Carlo simulation. By running several trials of one hundred thousand iterations each, we are able to outline the probability distributions of the interpolation functions. The main empirical findings are as follows: there is a well-established relation between the construction cost and the embodied energy,

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so the former represents a reliable predictor of the latter, and this relation is stronger for some homogeneous subsets of building products.

Keywords: Building industry, Building cost, Construction materials, Embodied energy

Introduction

The research field devoted to addressing the energy efficiency issue has widely developed during the last four decades. The initial interest to support the reduction of energy consumptions, in the wake of the oil shocks of the seventies, has been accompanied, at least starting from the nineties, with a strong commitment to providing solutions useful for the reduction of greenhouse-gas emissions. Under this framework, we have seen the development of several research branches. The building energy efficiency represents a prominent topic, due to the role played by the real estates in determining the global amount of consumptions and emissions. Indeed, according to Eurostat [1], residential and commercial construction absorbs about 36% of the former and produces some 40% of the latter.

Part of the issues addressed in both the theoretical and applied research relates to the economic implications of building energy efficiency. Several pertinent instances are as follows. Many studies analyze the additional up-front cost, if any, to be incurred when investing in green buildings [2]. Other authors focus on the price and rent premiums that efficient buildings allow achieving, both in the case of the properties intended to be sold under free market condition [3], as well as in the case of affordable social housing [4]. Two further relevant topics consist in the economic viability of retrofit solutions aimed at improving the energy performance of the building stock [5], on the one hand, and in the economic viability of the constructions built according to cutting-edge technologies and most advanced standards, such as passive houses and self-sufficient buildings [6], on the other hand.

A specific field, which grounds its roots in the research developed starting from the late seventies, concerns the assessment of the energy used during the whole production process [7]. The embodied energy (henceforth referred to as EE) may be defined as the amount of energy that is, directly and indirectly, required to produce goods and services. The term "directly" means during the manufacturing process while the term "indirectly" refers to the energy load used to mining, transforming and transporting the production factors [8].

According to several literature reviews on this subject [9-11], the determinants of the EE have been widely analyzed. They vary from the geographic location to the manufacturing technology [12-13], both of which may affect the quality of the materials [14] and the organization of the production processes [15]. Focusing on the building industry, three recent studies suggest that a non-linear relation with the construction cost (CC from now on) may characterize the EE [16-18]. Specifically, Langston and Langston [16] find evidence of the correlation between EE and CC by analyzing thirty projects developed in the Melbourne area from 1997 to 2003, although the relation is stronger at the building scale rather than at the level of the individual materials. In addition, the analysis performed by Jiao et al. [17] confirms the occurrence of a certain relation between EE and CC, although their sample is rather limited in size, so as to hinder the ability to generalize the results.

In the wake of the outcomes achieved so far, in a recently published study, we address the issue of the energy embodied in the building materials from an economic perspective, finding evidence for their logarithmic relation with the production cost [19]. Furthermore, the relation turns out to be positive for several clusters of semi-finished materials and ready-to-use goods – including glass products, plastics and sealants, steel products and timber – with the notable exception of the raw materials – such as limestone, sandstone and the like. The results above strictly depend on the estimation process of both EE and CC. As far as the former is concerned, the data source is represented by the well-known inventory of energy and carbon embodied in construction materials, which data have been collected by Hammond and Jones [20-21] at the University of Bath. The data about the latter are gathered from a building materials price list [22], which is commonly used to draft the bill of quantities relative to construction projects. Both the sources are affected by some degree of uncertainty. In this study, we aim at investigating the effect of this uncertainty on the strength and sign of the relation we expect to find between EE and CC.

The remainder of this paper is structured as follows. Section 2 presents the data gathered and the method used to treat the uncertainty issue. Subsequently, Section 3 discusses the results and their implications. Finally, Section 4 strives to draft some concluding remarks and further research developments.

Data Sources and Method

Embodied Energy Inventory and Building Materials Price List

The inventory of energy and carbon embodied in construction materials [20] collects data from an extensive analysis of the peer-reviewed literature, of technical reports, and of other papers. It mainly adopts the two perspectives referred to as cradle-to-site [21, 23] and cradle-to-gate [24], instead that the cradle-to-grave setting [25]. The inventory provides data on nearly two hundred materials, divided into thirty categories. The building materials price list [22] reports the market prices for hundreds of products commonly used within the construction industry. These prices are representative of the technical cost of construction, as the sum of the costs of materials, the manpower costs, and the expenses related to the construction site support services. We consider here only the costs of materials.

For each item included in the inventory, the corresponding entry is searched in the price list. Since the EE values are expressed in MJ/kg, all the CC values are converted into Euros/kg, according to the dimension and mass of the materials. The matching process leads to a dataset of 56 elements (Table 1) suitable to be processed using statistical regression techniques, in order to identify the best-fitting relation between

EE and CC. A high explanatory power can be achieved by adopting a linear-log curve, according to the following equation:

$$EE = \alpha + \beta \cdot \ln CC + \varepsilon \quad (1)$$

where a is the intercept of the function, b is the regression coefficient, and e is an error term.

The results are far more satisfactory if the building materials are divided into the following homogeneous clusters: A) semi-finished or ready-to-use materials; B) raw materials and thermally processed minerals; C) glass; D) plastics and sealants; E) steel; F) timber. Using a single independent variable, the R^2 index of the model approximates the strength of the logarithmic relation between EE and CC. It reaches up to 0.819 for the cluster A, 0.961 for the cluster E, and 0.993 for the cluster C [19].

Table 1. Cost estimates of the building materials (first part).

Building material	**Cluster**	**Items ***	**Unit cost (Euros/kg) ****		**Descriptive statistics (Euros/kg)**	
			Min	Max	Mean	St Dev
Asphalt	A	5	0,	0,	0,49	0,37
Bitumen	A	16	0,66	3,33	2,11	0,88
Calcium Silicate Sheet	B	12	0,97	1,44	1,31	0,11
Calendered Sheet PVC	D	5	3,23	5,14	3,87	0,67
Carpet tiles	A	5	9,21	12,32	10,82	1,27
Cellular Glass	C	1	3,83	3,83	3,83	-
Cement	A	12	0,10	0,23	0,14	0,04
Ceramics	A	12	0,27	1,15	0,45	0,27
Concrete 25/30 Mpa	A	2	0,05	0,05	0,05	0,00
Concrete 28/35 Mpa	A	6	0,05	0,05	0,05	0,00
Concrete 32/40 Mpa	A	10	0,05	0,05	0,05	0,00
Copper Tube & Sheet	A	3	2,78	10,20	7,71	3,48
Cork	B	2	1,12	2,25	1,69	0,56
Expanded Polystyrene	D	10	3,10	4,13	3,53	0,45
Felt (Hair and Jute)	A	1	0,19	0,19	0,19	-
Felt General	A	6	5,25	8,25	6,31	1,16
Fibreglass (Glasswool)	C	11	2,70	4,85	4,06	0,63
Flax	A	7	2,54	2,93	2,71	0,19
General bricks	A	16	0,04	0,98	0,22	0,27
General timber	F	18	2,42	2,42	2,42	0,00
Glass	C	8	0,62	0,99	0,79	0,15
Granite	B	27	1,02	2,19	1,53	0,36
High Impact Polystyrene	D	2	3,90	3,91	3,91	0,01
Iron	B	14	0,53	1,25	0,73	0,23
Laminated Veneer Lumber	F	2	1,53	1,64	1,58	0,06
Lead	B	2	1,01	1,04	1,03	0,02
Lime	A	4	0,06	0,06	0,06	0,00
Limestone	B	7	0,39	1,22	0,78	0,25

* Number of items in the price list; ** Data gathered from the price list.

Although the outcomes are statistically significant, we should bear in mind that the data used are affected by some degree of uncertainty, and so are the results. Indeed, the price list contains several products related to each material, with differences in shape, size and other basic features. For instance, it provides the CC for eight kinds of wood varnishes, which values fall in the range from 4 to 19 Euros/kg. The average value is representative because all products are commonly commercialized and used within the building industry. Nevertheless, it is worth asking whether the relation between EE and CC remains unchanged by letting the latter vary over the intervals reported in Tables 1 and 2.

Table 2. Cost estimates of the building materials (second part).

Building material	**Cluster**	**Items** *	**Unit cost (Euros/kg)** **		**Descriptive statistics**	
			Min	Max	Mean	St Dev
Linoleum	A	5	5,55	6,87	6,02	0,49
Low Density Polyethylene	D	1	5,43	5,43	5,43	-
Marble	B	16	1,04	2,79	1,48	0,43
Mastic Sealant	D	1	8,47	8,47	8,47	-
Perlite - Expanded	B	5	0,71	1,16	0,94	0,15
Plasterboard	A	2	0,25	0,25	0,25	0,00
Plywood	F	11	1,62	5,12	3,55	1,18
Polycarbonate	D	8	6,04	7,25	6,19	0,40
Polyurethane Flexible Foam	D	2	10,15	10,15	10,15	0,00
Polyurethane Rigid Foam	D	7	4,50	7,80	5,78	1,13
PVC Pipe	D	6	1,25	2,72	2,01	0,56
Rockwool	B	5	0,89	1,13	0,96	0,09
Rubber	B	1	0,25	0,25	0,25	-
Sandstone	B	10	0,50	1,21	0,68	0,21
Sawn Hardwood	F	14	0,55	3,62	1,45	0,76
Sawn Softwood	F	6	1,12	1,56	1,30	0,17
Slate	B	17	0,43	5,35	2,60	1,05
Stainless steel	E	2	7,62	7,67	7,65	0,02
Steel bar & rod	E	8	1,28	1,38	1,31	0,03
Steel coil (Sheet)	E	8	0,89	1,76	1,35	0,26
Steel pipe (virgin)	E	8	2,43	3,27	2,87	0,30
Steel section	E	7	1,62	3,56	2,16	0,60
Thermoformed Expanded	D	6	5,09	12,36	7,64	2,41
Toughened Glass	C	4	1,91	2,58	2,23	0,30
Vermiculite - Expanded	B	5	1,54	2,92	1,96	0,51
Waterborne Paint	A	6	5,94	10,44	7,40	1,61
Wax	A	1	0,93	0,93	0,93	-
Wood stain/Varnish	A	8	4,01	18,84	8,84	4,21

* Number of items in the price list; ** Data gathered from the price list.

Monte Carlo Simulation Method

The Monte Carlo (MS) simulation provides the most suitable methodological framework to address the posed question. The origins of this family of techniques date back to the studies developed during the mid-forties of the twentieth century by the physicist Enrico Fermi and the mathematicians Stanisław Marcin Ulam and John von Neumann [26]. According to its most general definition, under the umbrella of the MS method falls any technique that makes use of random numbers to solve a problem [27]. More to the point, MS aims to provide, as the solution to a problem, a parameter belonging to "a hypothetical population ... using a random sequence" that allows "to construct a sample of the population, from which statistical estimates of the parameter can be obtained" [28] (p. 2). In other words, the major strength of the MS approach lies in the ability to transform a mere one-shot result into a confidence interval, and to associate it to a probability distribution.

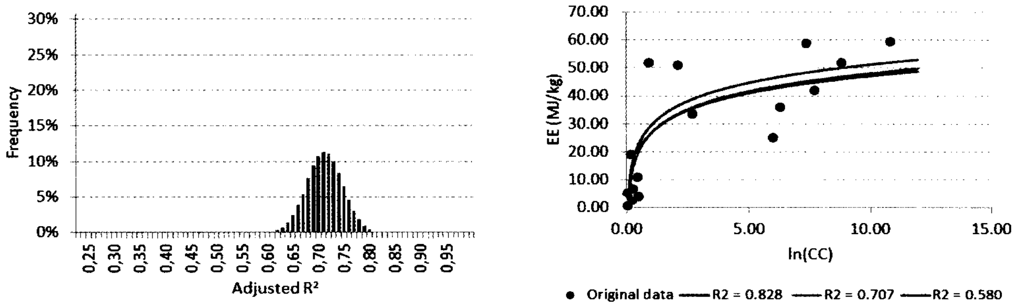
The MS techniques have been adopted to tackle various problems in a broad range of applications. In the building industry and the real estate sector, MS simulations have been widely used to deal with the uncertainty issue by performing sensitivity analysis, namely by assessing the robustness of the results in front of more or less predictable variations of the inputs [29-31]. As regards the energy use in buildings, MS analysis has long since proven to be the preferable sensitivity tool, since it is nearly-optimal to deal with the high number of uncertain parameters that the building thermal simulation programs need to handle [32].

Results and Discussion

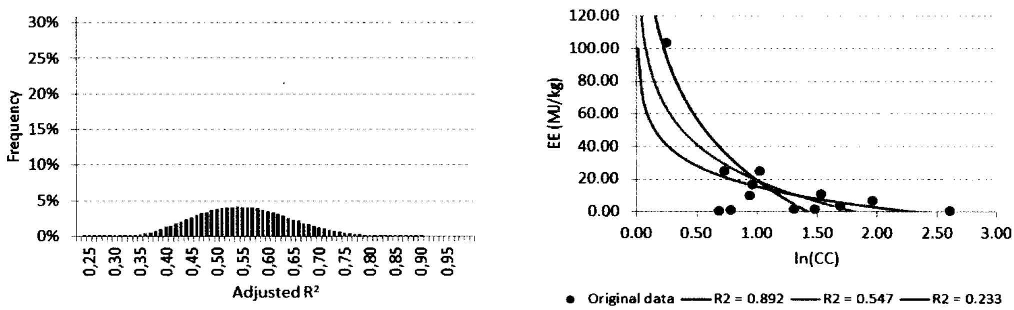
The simulation processes are developed performing several trials of one hundred thousand iterations each. During the iterations, the CC is free to vary over the ranges reported in Table 1, according to a random distribution function. The fitting curve parameters - see Eq. (1) - are re-estimated at each step, and so is the R^2 index. The probability distributions of the Adjusted R^2 indexes are shown in Figs. 1 and 2, along with a selection of interpolating curves.

The results are particularly interesting for the clusters A (various semi-finished products and ready-to-use goods) and D (plastics and sealants). The distribution of the R^2 indexes approximates a Gaussian curve with mean values of 0.71 and 0.63, respectively. On the whole, for the cluster A, the probability of achieving an Adjusted R^2 falling within the range from 0.68 to 0.75 accounts for some 75%. Furthermore, the interpolating functions are close each other. This means that the values of the regression parameters are fairly robust and rather insensitive to the potential swings of the independent variable CC.

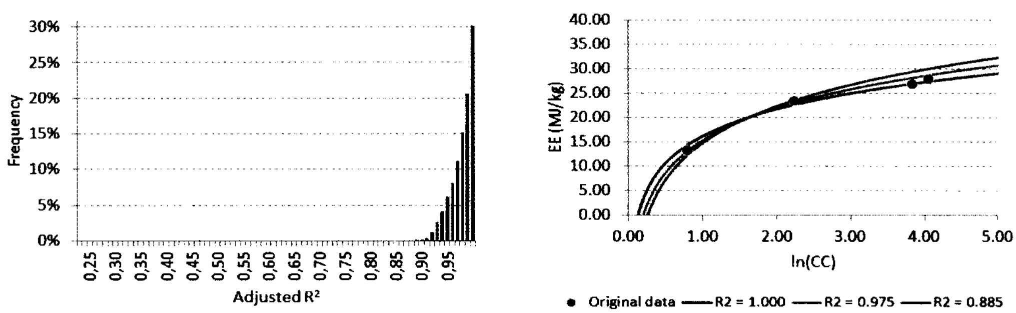
The robustness of the results is clearly represented by the clusters E (steel products) and, above all, C (glass products). The R^2 indexes of the former assume a normal asymmetric distribution, with a major probability density on the right side, around a value equal to 0.99. The R^2 indexes of the latter cluster follow an exponential distribution curve, with the highest probability to achieve an Adjusted R^2 value equal to the unit. Therefore, we may feel confident that the outcomes are stable to any fluctuation in the independent variable CC, and that the linear-log specification of the interpolating function maintains a high explanatory power.



Cluster A



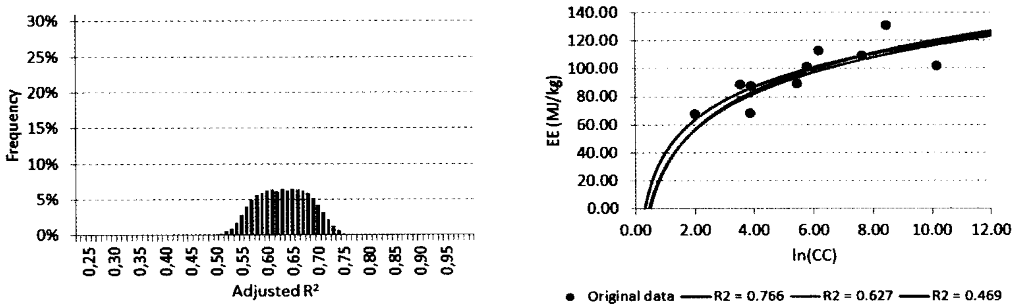
Cluster B



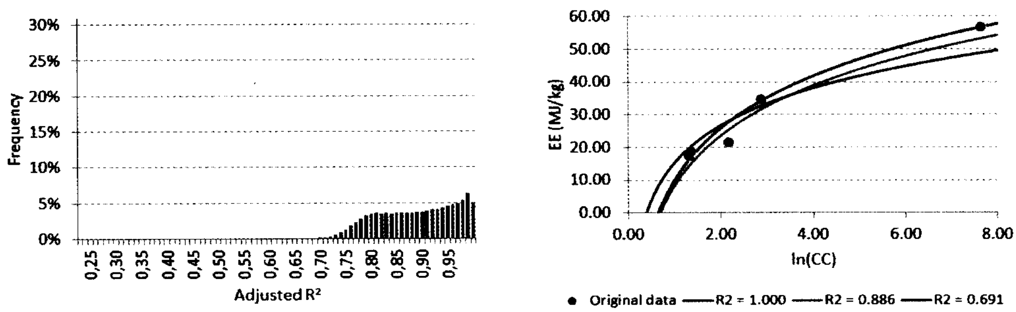
Cluster C

Fig. 1. Results of the Monte Carlo simulation on the interpolation functions (left: distribution of Adjusted R^2 indexes; right: plot of data and fitting curves).

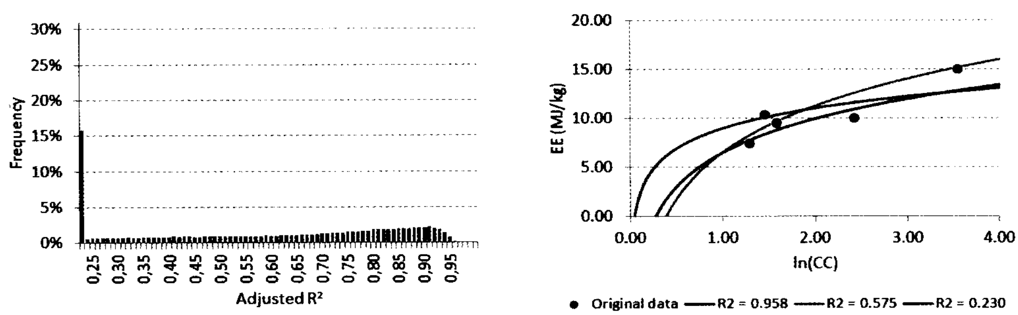
Contrary to the preceding cases, the clusters B (raw materials) and F (timber) are characterized by weak results. In both clusters, the probability distribution of the R^2 indexes extends over a wide range of values, and the interpolating curves diverge. The cluster B is extremely interesting because it is the only one showing an inverse relation between EE and CC. In the cluster F, moreover, the distribution of the R^2 indexes is considerably skewed, and its tail leans toward the left side. All this points out that the uncertainty characterizing the cost of the materials needs to be further investigated, as it may significantly affect the results.



Cluster D



Cluster E



Cluster F

Fig. 2. Results of the Monte Carlo simulation on the interpolation functions (left: distribution of Adjusted R^2 indexes; right: plot of data and fitting curves).

Conclusions

According to the empirical findings achieved in this study, we can argue that there is a well-established relation between the energy embodied in the construction materials and their production cost. The relation is likely to be non-linear, and a linear-log function fits the data with a satisfactory explanatory power. Furthermore, the relation is positive for all the semi-finished products and ready-to-use goods, negative instead for the raw materials. The cost represents a reliable predictor of the amount of energy embodied during the manufacturing process. Nonetheless, given the stronger correlation for some homogeneous subsets of building products, further investigations appear to be required.

As an essential advancement of this research branch, we see the opportunity to tackle a two-fold issue. Firstly, we expect to gain knowledge about the reasons why the non-linear relation, represented by the natural logarithm of the independent variable, fits very well a part of the data. This entails the need to deepen the capital and labor intensity of the building materials, according to the cluster they belong to. Secondly, we expect to single out the underlying causes of the distinctive trait characterizing the raw materials, namely why their EE drops when CC increases.

References

[1] Eurostat, *Energy, transport and environment indicators*, 2011. Available: http://ec.europa.eu/eurostat/documents/3930297/5966062/KS-DK-11-001-EN.PDF/a1caaacc-1f22-42fc-8bab-93d0f808ea75?version=1.0 (accessed April 21, 2016).

[2] L. N. Dwaikat and K. N. Ali, "Green buildings cost premium: A review of empirical evidence," *Energy Build.*, vol. 110, pp. 396–403, 2016.

[3] Bio Intelligence Service *et al.*, *Energy performance certificates in buildings and their impact on transaction prices and rents in selected EU countries*, Final report prepared for European Commission, DG Energy, 2013.

[4] S. Copiello, "Achieving affordable housing through energy efficiency strategy," *Energy Policy*, vol. 85, pp. 288–298, 2015

[5] S. Copiello and P. Bonifaci, "Green housing: Toward a new energy efficiency paradox?," *Cities*, vol. 49, pp. 76–87, 2015.

[6] R. Galvin, "Are passive houses economically viable? A reality-based, subjectivist approach to cost-benefit analyses," *Energy Build.*, vol. 80, pp. 149–157, 2014.

[7] R. Costanza, "Embodied energy and economic valuation," *Science*, vol. 210, no. 4475, pp. 1219–1224, 1980.

[8] I. Boustead and G. F. Hancock, *Handbook of Industrial Energy Analysis*. Chichester: Ellis Horwood, 1979.

[9] M. K. Dixit *et al.*, "Identification of parameters for embodied energy measurement: A literature review," *Energy Build.*, vol. 42, no. 8, pp. 1238–1247, 2010.

[10] M. K. Dixit *et al.*, "Need for an embodied energy measurement protocol for buildings: A review paper," *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 3730–3743, 2012.

[11] L. F. Cabeza *et al.*, "Affordable construction towards sustainable buildings: review on embodied energy in building materials," *Curr. Opin. Environ. Sustain.*, vol. 5, no. 2, pp. 229–236, 2013.

[12] A. H. Buchanan and B. G. Honey, "Energy and carbon dioxide implications of building construction," *Energy Build.*, vol. 20, no. 3, pp. 205–217, 1994.

[13] B. C. Lippiatt, "Selecting cost-effective green building products: BEES approach," *J. Constr. Eng. Manag.*, vol. 125, no. 6, pp. 448–455, 1999.

[14] G. J. Treloar *et al.*, "An analysis of the embodied energy of office buildings by height," *Facilities*, vol. 19, no. 5/6, pp. 204–214, 2001.

[15] S. Pullen, "Estimating the embodied energy of timber building products," *J. Inst. Wood Sci.*, vol. 15, no. 3, pp. 147–151, 2000.

[16] Y. L. Langston and C. A. Langston, "Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies," *Constr. Manag. Econ.*, vol. 26, no. 2, pp. 147–160, 2008.

[17] Y. Jiao *et al.*, "The relationship between total embodied energy and cost of commercial buildings," *Energy Build.*, vol. 52, pp. 20–27, 2012.

[18] D. Bansal *et al.*, "Effect of construction materials on embodied energy and cost of buildings—A case study of residential houses in India up to 60m2 of plinth area," *Energy Build.*, vol. 69, pp. 260–266, 2014.

[19] S. Copiello, "Economic implications of the energy issue: Evidence for a positive non-linear relation between embodied energy and construction cost," *Energy Build.*, vol. 123, pp. 59–70, 2016.

[20] G. P. Hammond and C. I. Jones, "Embodied energy and carbon in construction materials," *Proc. ICE - Energy*, vol. 161, no. 2, pp. 87–98, 2008.

[21] G. P. Hammond and C.I. Jones, *Inventory of Carbon & Energy (ICE)*, Version 2.0, University of Bath, 2011. Available: http://web.mit.edu/2.813/www/readings/ICEv2.pdf.old (accessed December 23, 2015).

[22] Aa.Vv., *Prezzi informativi dell'edilizia – Nuove costruzioni*. Rome, Dei Tipografia del Genio Civile, 2008.

[23] M. K. Dixit *et al.*, "System boundary for embodied energy in buildings: A conceptual model for definition," *Renew. Sustain. Energy Rev.*, vol. 21, pp. 153–164, 2013.

[24] G. P. Hammond and Á. O'Grady, "The implications of upstream emissions from the power sector," *Proc. Inst. Civ. Eng. - Energy*, vol. 167, no. 1, pp. 9–19, 2014.

[25] A. M. Moncaster and K. E. Symons, "A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards," *Energy Build.*, vol. 66, pp. 514–523, 2013.

[26] C. Jacoboni and P. Lugli, *The Monte Carlo Method for Semiconductor Device Simulation*. Wien-New York: Springer Verlag, 1989.

[27] F. James, "Monte Carlo theory and practice," *Reports Prog. Phys.*, vol. 43, no. 9, pp. 1145–1189, 1980.

[28] J. H. Halton, "A retrospective and prospective survey of the Monte Carlo method," *SIAM Rev.*, vol. 12, no. 1, pp. 1–63, 1970.

[29] N. French and L. Gabrielli, "Discounted cash flow: accounting for uncertainty," *J. Prop. Invest. Financ.*, vol. 23, no. 1, pp. 75–89, 2005.

[30] M. Hoesli *et al.*, "Monte Carlo simulations for real estate valuation," *J. Prop. Invest. Financ.*, vol. 24, no. 2, pp. 102–122, 2006.

[31] R. M. S. F. Almeida *et al.*, "Towards a methodology to include building energy simulation uncertainty in the Life Cycle Cost analysis of rehabilitation alternatives," *J. Build. Eng.*, vol. 2, pp. 44–51, 2015.

[32] K. J. Lomas and H. Eppel, "Sensitivity analysis techniques for building thermal simulation programs," *Energy Build.*, vol. 19, no. 1, pp. 21–44, 1992.