Paper 152

Proceedings of the Fourteenth International Conference on
Civil, Structural and Environmental Engineering Computing,
B.H.V. Topping and P. Iványi, (Editors),
Civil-Comp Press, Stirlingshire, Scotland

Life Cycle Assessment of a Steel-Framed Residential Building

I. Zygomalas[1], D.N. Kaziolas[2], G.E. Stavroulakis[3] and C.C. Baniotopoulos[4]
[1]Institute of Metal Structures, Department of Civil Engineering
Aristotle University of Thessaloniki, Thessaloniki, Greece
[2]Technological Educational Institute of Kavala, Kavala, Greece
[3]Institute of Computational Mechanics and Optimization
Department of Production Engineering and Management, Technical University of Crete, Chania, Greece
[4]Institute of Metal Structures, Department of Civil Engineering, Aristotle University of Thessaloniki,
Thessaloniki, Greece, and Chair of Sustainable Energy Systems, School of Civil Engineering
The University of Birmingham, United Kingdom

Abstract

One of the most widely acknowledged policies, which is also strongly promoted by legislation and government officials globally, is sustainable development. Since the introduction of the term and the development of its content, the movement for sustainable development has been accepted by all business sectors as a set of principles that have to be incorporated into standard practice. Particularly in the case of business sectors such as construction that have been identified as the largest consumers of raw materials and energy there has been considerable pressure to optimize processes in terms of sustainability, with particular emphasis on the environmental impact caused. Steel structures constitute a construction technology which holds significant potential in terms of sustainability. The purpose of the current research is to quantify this potential by calculating the environmental impact caused throughout the life cycle of a steel-framed residential building. A life cycle assessment is conducted, taking into account issues such as raw material acquisition, construction and waste management. The results obtained are used to draw conclusions regarding the application of the life cycle assessment methodology to steel buildings and the environmental data required. Furthermore, observations regarding the quantification of the environmental impact caused by the steel-framed residential building and the identification of the most environmentally damaging processes in regard to the life cycle of the building are also made.

Keywords: sustainable development, sustainability, environmental impact, life cycle assessment (LCA), steel structures, steel building.

1 Introduction

The movement for sustainable development has gained a lot of ground since the content of the term was introduced. After a number of seminal events such as United Nations conferences and reports that depicted the impact of human activity on the environment, sustainable development has become one of the priorities of world leaders. The main object of this global challenge is to minimize the negative effects of man’s activities on the environment, while also taking into account social and economic issues. The environmental dimension of sustainable development is characterized by the urgency for solutions that will enable future generations to continue to pursue their needs without the need for compromise. As a result, it has attracted the interest and work of researchers aiming to develop methodologies to reduce the environmental impact caused by all business sectors.

A number of studies were therefore conducted in order to determine the aspects of human activity that are mainly responsible for the negative impacts on the environment. Among the business sectors that were identified as the largest consumers of energy and natural resources was construction. Construction projects require vast amounts of materials and energy for their delivery, which is particularly the case for large-scale projects such as public buildings, bridges etc. This observation has been made numerous times and as a result, it is currently widely acknowledged that the construction sector has to undergo significant changes in order to promote sustainability.

The sector has responded to this requirement and has already carried out research in an attempt to approach the issue of sustainability concerning its activities [1, 2]. The methodologies that have been developed are mostly aimed at the optimization of the design process of construction projects at their very early stages, where the influence of decision-making is maximized [3, 4]. One of the most widely used methodologies to quantify the environmental impact of construction projects is Life Cycle Assessment (LCA) [5, 6]. Although LCA was developed for other types of products, its efficiency has led to its utilization in several cases, among which construction projects [7].

The use of LCA within construction has highlighted the sustainability potential of several technologies and solutions such as steel construction [8, 9]. As a material, steel can be recycled indefinitely and thus be used for the production of new steel products without compromising quality or properties. This provides a significant advantage for steel construction as it enables the minimization of waste and reduces the amount of raw materials that have to be extracted for the manufacturing of steel construction products [10, 11].

The aim of the current research is to examine this potential of steel construction and quantify the environmental impact caused by its application. An existing steel-framed residential building is used as the basis for the calculations and a life cycle assessment is conducted [12, 13], taking into account issues such as raw material acquisition, construction and waste management.

2 Steel-framed residential building

The steel-framed residential building that is selected as the basis of the calculations of the environmental impact is a ground-floor single-storey residence with a steel deck constructed in Thessaloniki, Greece, as displayed in Figures 1 and 2. The load-bearing frame of the building is constructed of structural steel hollow sections, while the floor slab and foundation are constructed of reinforced concrete.

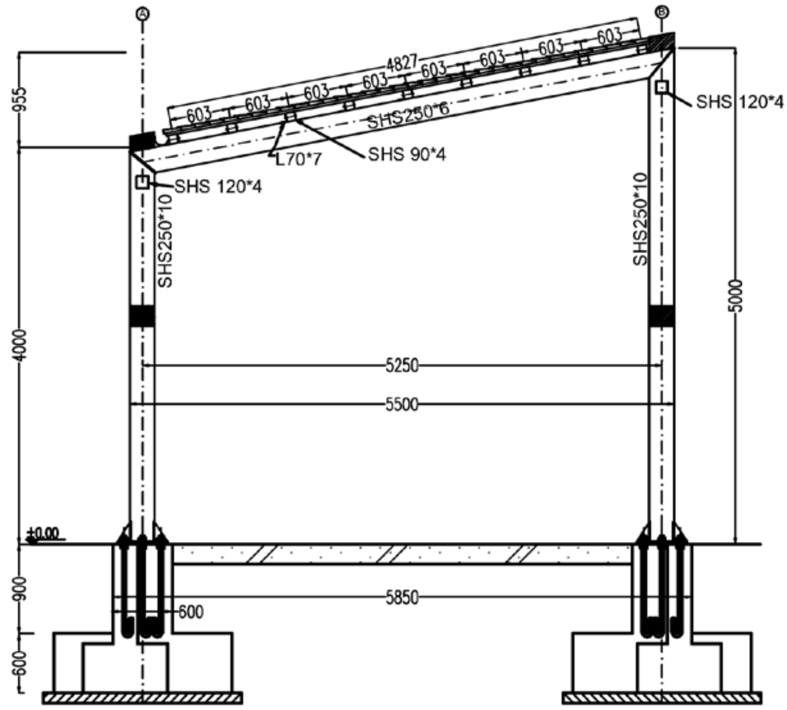

Figure 1: Side view of the examined steel-framed residential building

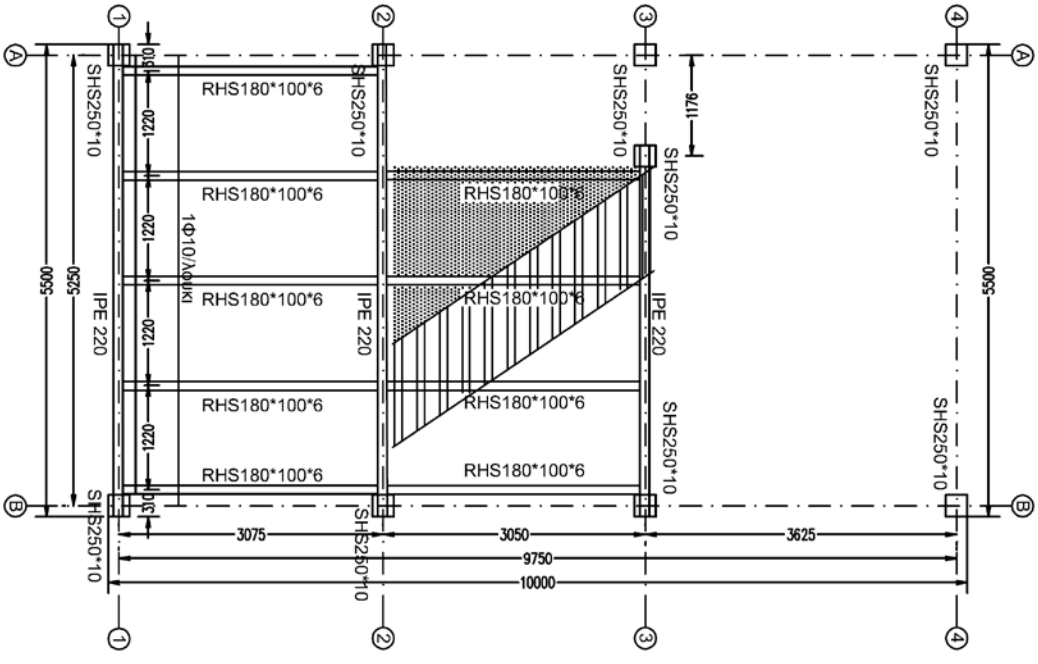

Figure 2: Plan view of steel deck of examined steel- framed residential building

3 Life Cycle Assessment (LCA) of steel building

3.1 Goal and scope of LCA

The goal of the LCA analysis is the calculation of the environmental impact of the life cycle of the examined steel building. The life cycle stages that are taken into account include the acquisition of the necessary raw materials for the manufacturing of the necessary construction materials, their transport to the site, the construction of the building and the handling of the retrieved materials at the end of the service life of the building. For the latter, an end scenario was developed; it addresses certain issues regarding the handling of the materials and waste, which have a significant effect on the environmental impact of the life cycle of the building. According to the end scenario, specific percentages of materials are retrieved, recycled or disposed of in landfills. These particular waste treatments, along with the percentages with which they are taken into account are presented in Table 1.

Material	Waste treatment
Structural steel and steel sheet	90% recycled 10% considered irretrievable and disposed in landfill
Concrete	80% recycled (crushed to be used as gravel) 20% considered irretrievable and disposed in landfill
Reinforcing steel	90% recycled. 10% considered irretrievable and disposed in landfill

Table 1: Waste treatments for each type of material used for the construction of the steel building

It is also noted that for the transport of the materials to the various end-of-life facilities (sorting plants, recycling plants, landfills etc.) a 30 km transport distance is taken into account, while the distance assumed for the transport of the materials to the site for the construction of the building is 10 km.

The functional unit for the current LCA analysis is the construction of the above mentioned steel-framed building, while the geographic coverage refers to the Greek region and could be generalized for Europe as well.

3.2 Life Cycle Inventory (LCI)

The materials required for the construction of the steel-framed building that were taken into account for the LCA analysis are presented in Table 2. As can be observed, the materials used in the largest quantities are the structural steel sections for the load-bearing frame, the concrete for the ground-floor slab and the foundation and the steel reinforcement bars used for the concrete. It can therefore be expected that these materials will be responsible for the largest environmental impacts as well.

Main materials and processes	Unit	Quantity
Structural steel sections	kg	6862.6
Connection and joints of steel elements	kg (bolts)	311.3
	m (welding)	91.4
	kg (steel plates)	968.6
	kg (steel connectors)	66.4
	kg (steel bars)	17.8
Concrete	m^3	51.1
Steel reinforcement for concrete	kg	3760.3
Excavation	m^3	161.6
Steel sheet profile for deck	kg	217

Table 2: Main materials and processes for the construction of the steel building

	Substance	Category	Unit	Life Cycle of steel building
Inputs:	Coal (brown, in ground)	Raw material	kg	13056,57
	Dolomite ($CaCO_3$, in ground)	Raw material	kg	2,622847
	Iron (46% in ore, 25% in crude ore, in ground)	Raw material	kg	-9784,39
	Manganese (Mn, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground)	Raw material	kg	0,310217
	Oil (crude, in ground)	Raw material	kg	1836,03
	Steel scrap	Raw material	kg	15863,43
	Water (unspecified natural origin)	Raw material	m^3	73,27323
	Zinc (Zn, in ground)	Raw material	kg	3,06E-05
Outputs:	Carbon dioxide (CO_2)	Air emission	kg	3227,882
	Carbon dioxide, fossil (CO_2)	Air emission	kg	21721,62
	Carbon monoxide (CO)	Air emission	kg	44,12758
	Carbon monoxide, fossil (CO)	Air emission	kg	-198,523
	Dinitrogen monoxide (N_2O)	Air emission	kg	0,319522
	Hydrogen Chloride (HCl)	Air emission	kg	2,804202
	Hydrogen Sulphide (H_2S)	Air emission	kg	-0,18464
	Lead (Pb)	Air emission	kg	-0,01632
	Mercury (Hg)	Air emission	kg	0,000749
	Methane (CH_4, fossil)	Air emission	kg	4,941774
	Nitrogen oxides (NO_x)	Air emission	kg	37,84439
	Non-methane volatile organic compounds (NMVOC)	Air emission	kg	10,88984
	Particulates, < 2.5 um ($PM_{2,5}$)	Air emission	kg	1,481376
	Particulates, < 10 um, stationery (PM_{10})	Air emission	kg	0,043914
	Sulfur dioxide (SO_2)	Air emission	kg	43,52497
	Sulfur oxides (SO_x)	Air emission	kg	1,185597
	Zinc (Zn)	Air emission	kg	0,045081
	Ammonia, as N (N)	Water emission	kg	0,001716
	Cadmium, ion	Water emission	kg	0,023829
	Chemical Oxygen Demand (COD)	Water emission	kg	10,31319
	Chromium, ion	Water emission	kg	0,010071
	Iron	Water emission	kg	0,056764
	Lead (Pb)	Water emission	kg	0,059168
	Nickel, ion	Water emission	kg	2,796057
	Suspended solids	Water emission	kg	2,203338
	Zinc, ion	Water emission	kg	2,445924
	Calcium	Soil emission	kg	0,26721
	Heat, waste	Soil emission	MJ	197,6113
	Iron	Soil emission	kg	-0,04002
	Oils, unspecified	Soil emission	kg	4,845755

Table 3: Life Cycle Inventory (LCI) of the life cycle of the steel-framed building

The first set of results from the LCA analysis is a detailed list of environmental inputs and outputs. Inputs refer to the raw materials and energy consumed, while outputs refer to the substances that are emitted to the air, water, soil or the waste generated throughout the life cycle of the steel building. This list contains more than 800 entries in total and a selection of the most important substances to be monitored [14] is presented in Table 3. It is noted that the few negative values refer to the beneficial influence of the recycling taking place according to the end scenario. In this aspect, these values constitute environmental benefit rather than burden.

3.3 Life Cycle Impact Assessment (LCIA)

The substance emissions listed in the LCI stage of the analysis are grouped and weighted according to a set of predefined coefficients as outlined in the impact assessment methodologies that are available. For the current analysis the Eco-Indicator 99 (Eco-indicator 99 (E) V2.08 / Europe EI 99 E/E) methodology is used to provide a detailed perspective of not only the extent but the type of environmental impact caused by the life cycle of the steel building as well [15]. In Figure 3 the environmental impact results concerning the main construction materials and processes are presented.

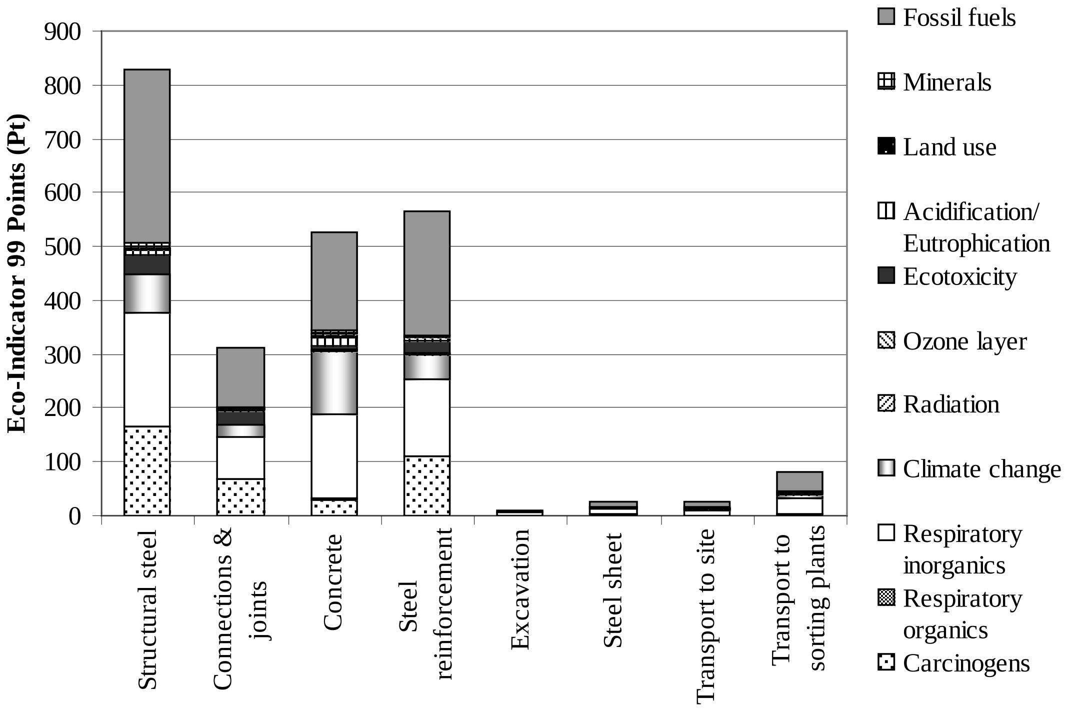

Figure 3: Eco-Indicator 99 environmental impact results of the main construction materials and processes

As expected, the structural steel and reinforced concrete are responsible for the largest percentage of environmental impact caused. The impact caused by the reinforced concrete as a total -impact for concrete and steel reinforcement- is similar to the impact caused by the structural steel used, when considering it in combination with the impact caused by the connections and joints of the structural steel members. In specific, the reinforced concrete causes 1093 Pt of environmental impact (1 Pt is representative of one thousandth of the yearly environmental load of one average European inhabitant), while the structural steel, along with the connections and joints used to connect the structural members, are responsible for 1141 Pt. Although the two materials seem to cause similar impacts it should not be neglected that the main structural material used for the construction of the building is steel, while the concrete is only used partially for the foundation and ground-floor slab.

The remaining materials and processes cause relatively smaller environmental impacts, with the exception of the transport of the materials to the various sorting plants (recycling, landfills, etc.) at the end of the service life of the building. This process, due to the 30 km transport distance assumed, causes a noticeable impact of 80 Pt.

In regard to the type of environmental impact, it is mainly the 'fossil fuels' indicator, which refers the quality of natural resources, that is mainly burdened. As can be observed in Figure 4, the 'respiratory inorganics' indicator, which is associated with negative effects on human health, is also considerably burdened, followed by 'carcinogens' –also associated with human health- and 'climate change'.

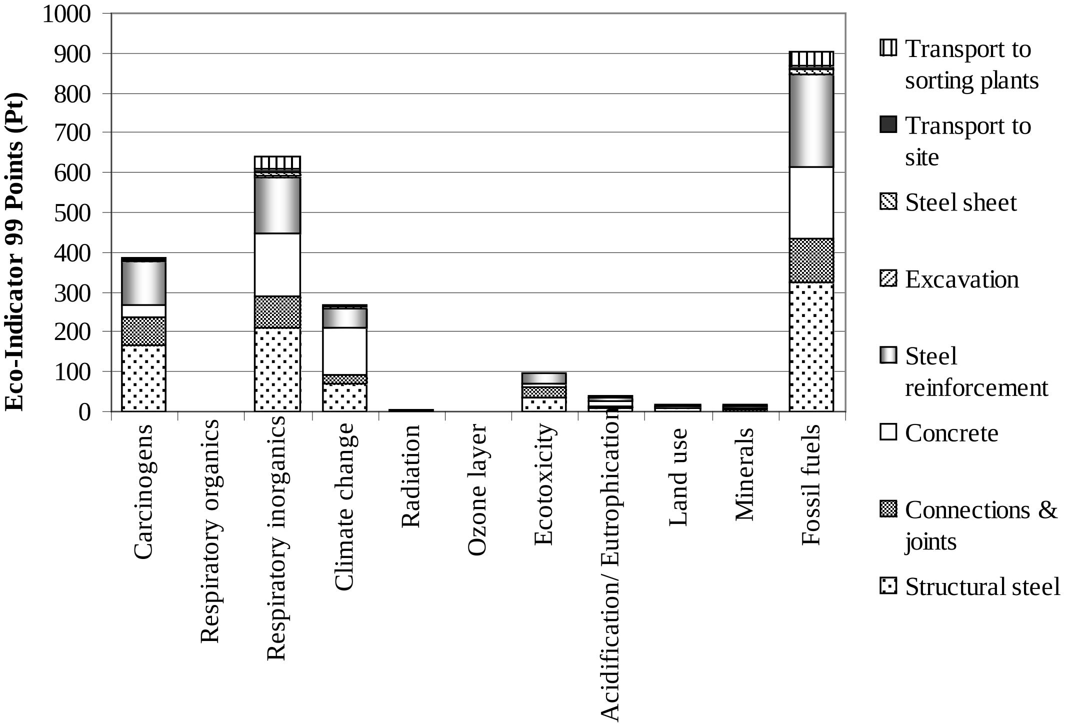

Figure 4: Eco-Indicator 99 environmental impact indicators burdened by the main construction materials and processes

For the quantification of the environmental impact of the complete life cycle of the steel-framed residential building, the end scenario that was developed was incorporated into the calculations. The results are presented in Figure 5.

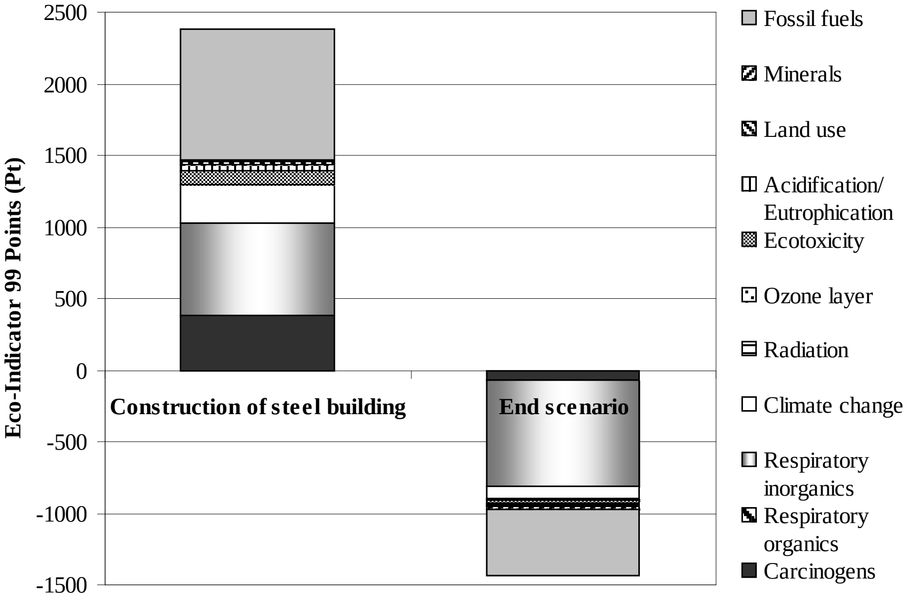

Figure 5: Environmental impact of the life cycle of the steel-framed building

The results are grouped into two main categories, the ‘construction’ group which includes the acquisition of raw materials and energy required for the manufacturing of the construction materials necessary for the construction of the steel-framed building, the construction processes taken into account and the transport of the materials to the site and the various sorting plants at the end of the building’s service life. The second category refers to the environmental impact of the handling of the materials once the building is demolished. The purpose of this grouping is to assess the actual impact of the end scenario in direct comparison to the rest of the materials and processes of the steel building’s life cycle.

The results that were obtained show that the handling of the materials at the end of the building’s service life can provide significant environmental benefits that reduce the impact of the building’s construction by more than half. In specific, the construction of the steel building was found to cause 2377 Pt of environmental impact, while the positive effect of the recycling of the materials can reduce this impact by 1431 Pt. These benefits are derived from the end scenario as assumed at the outset of the LCA analysis.

The positive impact of the end scenario is also displayed in Figure 6, where the impact of the steel building’s life cycle on the environmental indicators of the Eco-Indicator 99 impact assessment methodology is displayed. As can be observed, the two mainly burdened indicators -namely the ‘fossil fuels’ and the ‘respiratory inorganics’ indicators- are positively influenced by the end scenario to a significant degree. The ‘fossil fuels’ environmental impact is reduced by about 50%, while the ‘respiratory inorganics’ impact is completely balanced.

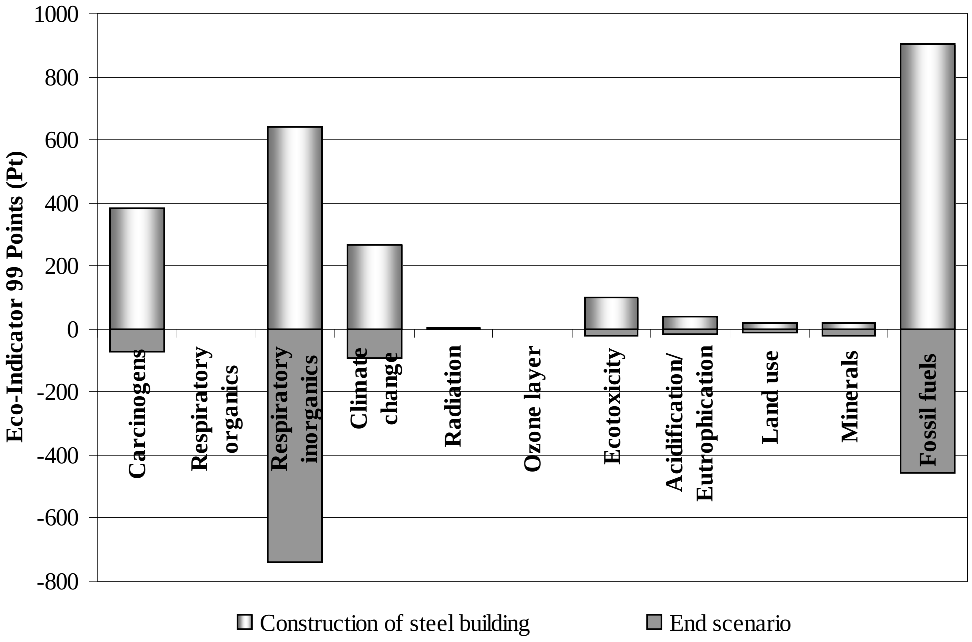

Figure 6: Eco-Indicator 99 environmental indicators burdened by the life cycle of the steel building

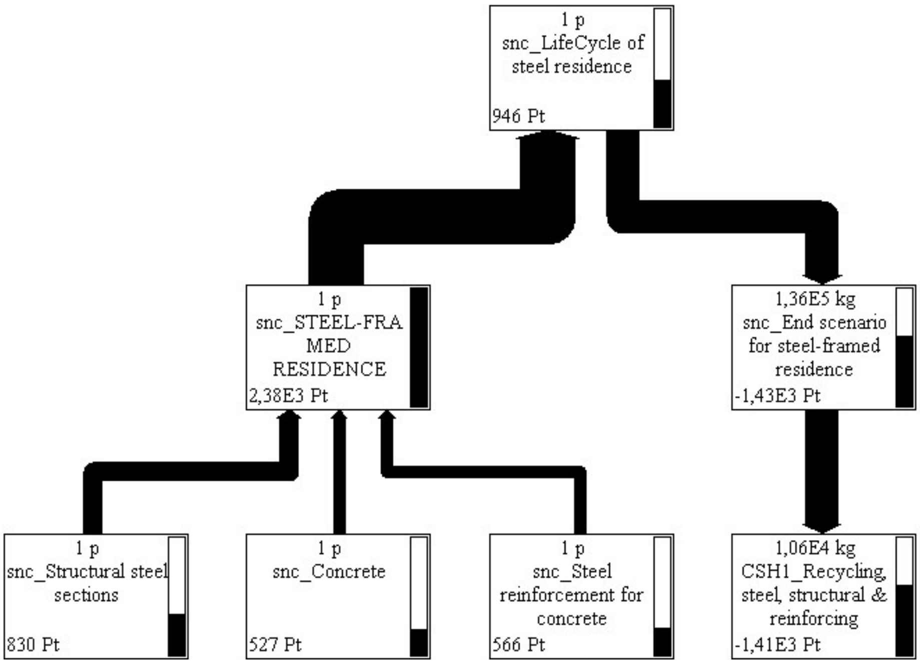

Figure 7: Illustration of environmental impact flow for the life cycle of the steel building

In order to determine the exact processes that are responsible for the environmental benefits derived form the end scenario, the flow of the environmental impact is displayed in Figure 7. For presentation purposes only the most influential processes are included in this illustration. It is shown that it is the recycling of the steel which is used for the construction of the steel building which provides the environmental benefits that significantly reduce the total environmental impact of the building’s life cycle.

4 Conclusions

The purpose of the current research was to examine the potential of steel construction in terms of sustainability. Life cycle assessment was used to quantify the environmental benefits of an existing steel-framed residential building, taking into account issues such as raw material acquisition, construction and waste management. The results obtained include a detailed list of environmental inputs and outputs, which includes the quantity of important air emissions such as carbon dioxide or carbon monoxide.

The environmental impact assessment that was conducted showed that the structural steel and reinforced concrete are responsible for the largest percentage of environmental impact caused by the materials required for the construction of the steel building. Although the two materials cause similar impacts as individual totals, it should not be neglected that the main structural material used for the construction of the building is steel, while the concrete is only used partially for the foundation and ground-floor slab. It can therefore be argued that the construction of the examined building with structural steel causes a lower environmental impact than if it was constructed solely of reinforced concrete. Of the remaining materials and processes, only the transport of the materials to the various sorting plants at the end of the building’s service life causes a noticeable impact. In regard to the type of environmental impact caused, it was found to mainly affect the quality of natural resources and human health.

It was also shown that the handling of the materials at the end of the building’s life cycle can provide significant environmental benefits that can reduce the impact its construction by more than half. These benefits were shown to be a result of the recycling of the steel used for the construction of the steel building.

Acknowledgments

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: **ARCHIMEDES III**. Investing in knowledge society through the European Social Fund.

References

[1] H. Trumpf, H. Schuster, K. Sedlbauer, and W. Sobek, “An approach for an Integrated Design Process focussed on Sustainable Buildings”. In: Bragança L, Koukkari H, Blok R, Gervásio H, Veljkovic M, Plewako Z, Landolfo R, Ungureanu V, Silva LS, (eds), Proceedings of the First Workshop of COST Action C25 – Sustainability of Constructions: Integrated Approach to Life-time Structural Engineering, Lisbon Multicomp, Lda, Portugal, 2007.

[2] R. Landolfo, L. Cascini, and F. Portioli, “Sustainability of steel structures: Towards an integrated approach to life-time engineering design”. Frontiers of Architecture and Civil Engineering in China, 5 (3), pp. 304-314, 2011.

[3] D.N. Kaziolas**,** I. Zygomalas, G. E. Stavroulakis and C. C. Baniotopoulos, “Environmental sustainability assessment methodologies for steel and timber structures”. In: Proceedings of the 9th WSEAS International Conference on Energy, Environment, Ecosystems and Sustainable Development (EEESD’13), pp. 37-42, Lemesos – Cyprus, 2013.

[4] L. Bragança, R. Mateus, and H. Koukkari, “Assessment of Building Sustainability”. In: Bragança L., Koukkari H., Blok R., Gervásio H., Veljkovic M., Plewako Z., Landolfo R., Ungureanu V., Silva L.S. (eds.), Proceedings of the First Workshop of COST Action C25 – Sustainability of Constructions: Integrated Approach to Life-time Structural Engineering, Lisbon Multicomp, Lda, Portugal, 2007.

[5] I. Zygomalas, E. Efthymiou, C.C. Baniotopoulos, and R. Blok, “A newly developed Life Cycle Inventory (LCI) database for commonly used structural steel components”. Structure and Infrastructure Engineering, Taylor & Francis Group, Vol. 8, Iss. 12, 2012, pp. 1173-1181, 2012.

[6] M.A. Curran, and P. Notten, “Summary of Global Life Cycle Inventory Data Resources”. US Environmental Protection Agency, 2006.

[7] O. Ortiz, F. Castells, and G. Sonnemann, “Sustainability in the construction industry: A review of recent developments based on LCA”. Construction and Building Materials, 23, 28–39, 2009.

[8] B.A. Burgan, and M.R. Sansom, “Sustainable steel construction”. Journal of Constructional Steel Research, 62, 1178–1183, 2006.

[9] G. Hillier, “Steel and sustainability Construction products for a sustainable society”. Ironmaking and Steelmaking, 31 (6), pp. 440-443, 2011.

[10] M. Yellishetty, G.M. Mudd, P.G. Ranjith, and A. Tharumarajah, “Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects”. Environmental Science and Policy, 14 (6), pp. 650-663, 2011.

[11] A.H. Oti, and W. Tizani, “A sustainability appraisal framework for the design of steel-framed buildings”. Proceedings of the 13th International Conference on Civil, Structural and Environmental Engineering Computing. Chania, Crete, 6-9 September 2011.

[12] International Organization for Standardization (ISO), “International Standard ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework”, 2006.

[13] International Organization for Standardization (ISO), “International Standard ISO 14044:2006 Environmental management - Life cycle assessment – Requirements and guidelines”, 2006.
[14] European Environment Agency, “Europe’s environment – The fourth assessment”, Office for Official Publications of the European Communities, Luxembourg, 2007.
[15] The Netherlands Ministry of Housing, Spatial Planning and the Environment, “Eco-Indicator 99, Manual for designers: A damage oriented method for Life Cycle Impact Assessment”, 2000.