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Integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) for sustainable constructions

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The construction industry and the scientific community continue to seek for innovative approaches that can estimate the level of sustainability to be achieved at the end of the project from the early design stages. One of the tools developed for this purpose is Building Information Modelling (BIM), which represents the state- of- the- art tool for bringing together different expertise and achieving optimal designs at an early design stage for the maximization of their impact. The key objective of this work is to expand the level of the prospect of this tool, which is believed not to have been fully exploited. Within this context, this paper integrates BIM with an established methodology for assessing a product's or a system's environmental performance – Life Cycle Assessment (LCA) – in an attempt to maximize the benefits from this synergy and achieve the most sustainable constructions. The impact from the integration of these two valuable tools is presented for a water supply system using case studies for a range of different materials. Comparison of a modern Vernetztes Polyethylen (VPE) water supply system against two systems made from traditional materials (steel and copper) was made. The results of this study show that a VPE water supply system performs at least 75% better than the steel system, and at least 88% better than a copper water supply system across all LCA impact categories, while the carbon dioxide emissions released during the production of a VPE system are almost the one tenth of traditional materials water supply systems.

KEYWORDS: Building Information Modelling (BIM), Life Cycle Assessment (LCA), Material, Sustainability, Water supply system, Facility, Building.

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Introduction

The building sector constitutes the largest energy consumer in Europe, establishing the construction industry as one of the most significant contributors to the burdening of the natural environment. Accordingly, during the past decade the industry has taken huge steps towards the greening of the buildings sector, and constantly searches for novel and effective approaches to achieve the most sustainable constructions, as specified by the European Union Directive on the energy performance of buildings (Directive 2010/31/EC). Building Information Modeling (BIM) is defined as a digital representation of the physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (National Institute of Building Sciences, 2014). The employment of such information systems has penetrated the construction industry, due to their ability in enhancing the effectiveness of construction projects not only throughout their life cycle, but also across different construction business functions (Jung and Joo, 2011). Accordingly, a range of stakeholders involved in a construction project can retrieve and generate information from the same model, thus allowing them to work cohesively (Ding et al., 2014). Nonetheless, the potential of BIM is envisioned to grow larger if further exploited through its integration with another life cycle approach.

BIM has been reported to support various tasks within the construction industry, among of which building energy performance analysis studies. BIM provides a platform based on which building energy saving design can be structured (Yuan and Yuan, 2011). Shoubi et al. (2015) utilized BIM for the assessment of various combinations of materials for the reduction of the operational energy use of the building. Ladenhauf et al. (2014) presented an algorithm for the preparation of input data for energy analysis based on building information models. Similarly, Ham and Golparvar-Fard (2015) presented a system, together with new methods for automated association and updating of actual thermal property measurements with BIM elements in Green Building Extensible Markup Language (gbXML) schema for improving the reliability of building energy modelling.

LCA is a standardized methodology for the systematic analysis of the environmental performance of processes or products throughout their whole lifecycle (EN ISO 14040: 2006). LCA has been employed in the building sector since the 90s, and currently represents an established objective method for evaluating the environmental impact of construction practices (Cabeza et al., 2014a). Rønning and Brekke (2014) have confirmed the effectiveness of the methodology in informing decision makers on the environmental performance of buildings. In fact, it has been reported that LCA has been used to assess the environmental performance of a range of different building materials including concrete and mortar (Marinković, 2013; Brás and Gomes, 2015), building thermal insulation materials (Dylewski and Adamczyk, 2014; Pargana et al., 2014), wood constructions (Guardiglia et al., 2011; Sathre and González-García, 2014), Phase Changing Materials (PCM) (Cabeza et al., 2014b), and windows (Salazar, 2014).

However, only a limited number of studies have integrated BIM with the LCA methodology to either investigate the environmental performance of a building element or of a whole building at an early design stage. On the one hand, BIM supports integrated design and improves information management and cooperation between the different stakeholders, and on the other hand, LCA is a suitable method for assessing environmental performance (Anton and Diaz, 2014). In fact, Kulahcioglu et al. (2012) presented a prototype software, which allows the interactive analysis of a 3D building model with its environmental impacts. In the case of Wang et al. (2011), BIM was employed to conduct whole building LCA based on a 50- year life- time. The results of their study indicated that the most effective design in terms of energy savings was replacing the curtain walls with brick walls for the top three floors. Ajayi et al. (2015) also carried out a BIM-enhanced LCA for a whole two- floor building. In this case, a 30- year life- cycle period was assumed for the conductance of a variability analysis on the design and materials. Regarding the design analysis, the work were revealed that timber house are the most environmental ones. These results come in agreement with the findings of Iddon et al. (2013), where the timber framed design of a typical detached house had the lowest total CO_2 equiv. emissions (213t CO_2) over the 60 year lifespan among the other investigated designs. Also, the European Plastic Pipes and Fittings Association (Teppfa) conducted LCAs for different plastic pipe systems, in each case the LCAs were compared against a traditional material. The report released by Georg Fischer piping system included four plastic pipe systems, which were compared against ductile iron and copper pipe systems. The report highlighted that the superiority of the plastic system, evident by the GWP and Ozone Depletion Potential (ODP) findings. The plastic pipes performed at least 60% better than the traditional materials in both impact categories.

The key objective of this paper is the integration of BIM with LCA for the realization of the most sustainable building design. Within this context, two case studies for the production of water supply systems comprised of different materials are implemented. BIM is employed for the modelling of the water supply systems, while LCA is implemented for the comparison of a modern Vernetztes Polyethylen (VPE) water supply system against two systems made from traditional materials, namely steel and copper. The results of this work lead to some significant conclusions regarding the benefits of BIM and LCA integration for the increase of the level of sustainability of the built environment.

Methods

The building information model design of the water supply system under investigation is presented in Fig.1, while Table 1 presents the design characteristics, employed for the implementation of the LCA, for each of the designs; VPE water supply system (D1), steel water supply system (D2), copper water supply system (D3). To this end, DDS-CAD was employed to model the design of the water supply system, while GaBi software (Version 6) adopted the model to implement a 'cradle-to-gate' LCA based on the principles described in the ISO 14040 Standard (ISO, 2006) for the investigation of its environmental performance and the definition of its level of sustainability throughout its life cycle. It is also worth mentioning that the environmental impacts during the installation, operational, and end- of- life phases for the water supply systems under examination were not considered in this LCA. Accordingly, any potential impacts during these life- cycle phases were found outside the defined system boundaries. The system boundaries of this work are illustrated in Fig.2, while the functional unit of the system has been defined as one unit of water supply system, approximately 120 kg of piping. For the purposes of this study, the International Reference Life Cycle Data System (ILCD) recommendations methodology was employed. The specific methodology generates a set of 13 impact categories, of which the following were chosen to be investigated in this paper:

- Global Warming Potential (GWP 100 years),
- Acidification Potential (AP),
- Ozone layer Depletion Potential (ODP, steady state),
- Photochemical Ozone Creation Potential (POCP)
- Resource Depletion, Mineral, Fossil, and Renewable (ADP elements & fossil).

The sustainability of the VPE water supply system was assessed against two traditional materials' systems, steel and copper. Table 1 presents the design characteristics of the water supply systems that are constant across all three designs, as well as the ones that were altered for each of the designs.

Table 1

Design characteristics of water supply systems

Designs	Product number	Product description	Quantity	Unit
D1, D2, D3	TH353/2504	Hot water tank water heater 250 litre	1	pcs
	ZP150/915	Pipe insulation 9x15 mm gray insulation thickness 9 mm	72,12	m
	ZP150/918	Pipe insulation 9x18 mm gray insulation thickness 9 mm	13,029	m
	ZP150/922	Pipe insulation 9x22 mm gray insulation thickness 9 mm	31,713	m
	ZP150/928	Pipe insulation 9x28 mm gray insulation thickness 9 mm	2,565	m
	TA340/04	Shut off valve DN 15 without discharge valve	1	pcs
	TA340/05	Shut off valve DN 20 without discharge valve	2	pcs
	ZPuM25	Circulating pump DN 25 sleeve	1	pcs
	BA-20120605-076	Shower tub round 800x120 mm	5	pcs
	BIN649	Standing position bidet	1	pcs
	BSN40/50	Hand basin 500x375 mm	2	pcs
	SW-20120605-032	Shower with single lever mixer	5	pcs
	SW-20120605-049	Bidet mixer single lever	1	pcs
	WC059	Wall WC wash down with on top cistern	2	pcs
	WC330	Urinal flush backwards	1	pcs
D1	SS2001/707	VPE system pipe length 6 m DVGW 15x1 mm	72,12	m
	SS2001/710	VPE system pipe length 6 m DVGW 18x1 mm	13,029	m
	SS2001/712	VPE system pipe length 6 m DVGW 22x1,2 mm	31,713	m
	SS2001/714	VPE system pipe length 6 m DVGW 28x1,2 mm	2,565	m
D2	SS091209020	Steel pipe welded DN 15 (1/2”)DIN EN 10220 raw (black)	73,203	m
	SS091209021	Steel pipe welded DN 20 (3/4”)DIN EN 10220 raw (black)	45,971	m
	SS091209022	Steel pipe welded DN 25 (1”)DIN EN 10220 raw (black)	0,61	m
D3	SS091209003	Copper pipes length 5 m 15x1 mm	61,541	m
	SS091209004	Copper pipes length 5 m 18x1 mm	24,827	m
	SS091209005	Copper pipes length 5 m 22x1 mm	31,991	m
	SS091209006	Copper pipes length 5 m 28x1,5 mm	2,636	m

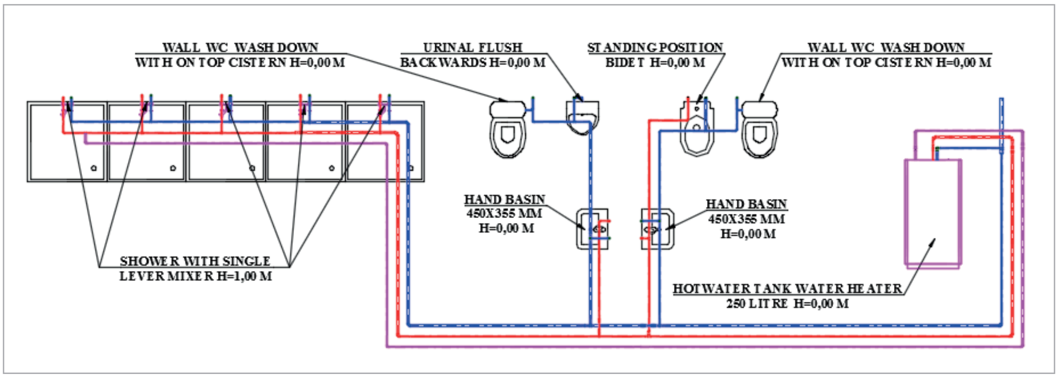


Fig. 1
Building Information Modelling (BIM) of water supply system under investigation

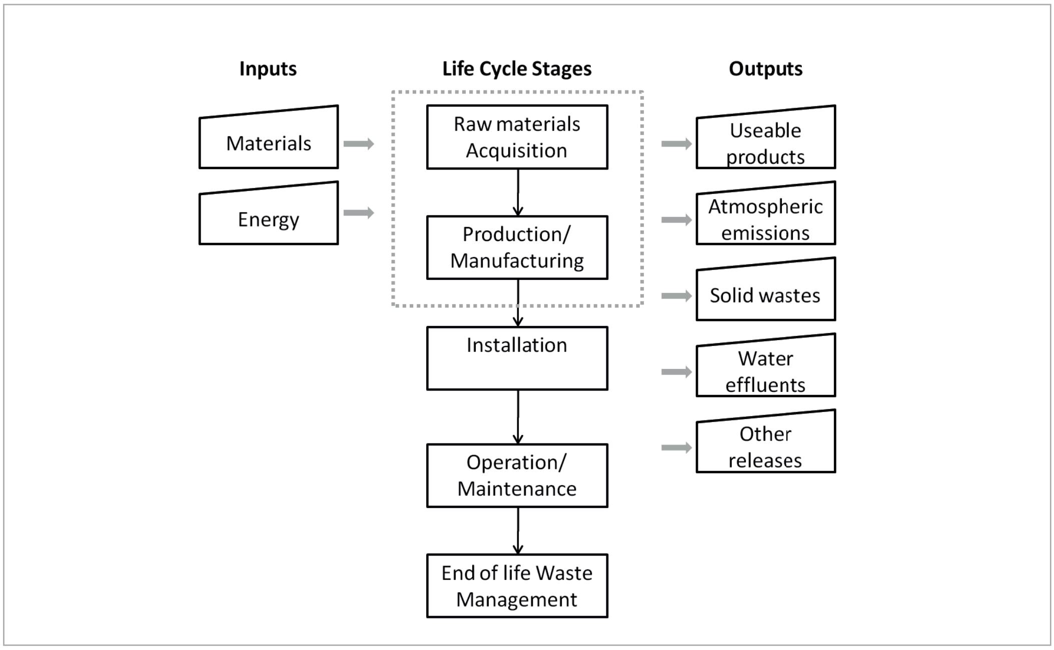


Fig. 2
System boundaries of the Life Cycle Assessment (LCA) conducted in this work

Life Cycle Inventory (LCI)

The LCI involves with the data recording of the 'cradle-to-gate' input resources and energy requirements, as well as the output impacts, in terms of environmental degradation, associated with the raw materials and the water supply system production. In particular, the dataset for the polyethylene water supply system includes all relevant process steps and technologies over the supply chain, mainly based on industry data, complemented by secondary data. The LCI of the VPE water supply system under investigation is given in Table 4. The LCI of the steel water supply system covers the raw materials extraction and processing for its manufacturing; the inputs of Table 5 relate to all raw material inputs, including steel scrap, energy, water, and transport, while the outputs include steel and other co-products, emissions to air, water and land. It is worth noting that the LCI does not include a credit for recycling of steel at end of life or a burden for steel scrap input during manufacturing. The dataset for the copper water supply system covers all relevant process steps and technologies over its supply chain, encompassing mining and processing (concentrate production), hydrometallurgy (leaching, solvent extraction, electro winning) and pyrometallurgy (smelting, converting, fire refining, electrolytic refining). Similarly to the rest of the investigated systems, the LCA does not provide credit for the copper scrap after the use of the product (Gabi database). The LCI of the copper water supply system under investigation is given in Table 6.

Results and Discussion

The results of the LCIA, illustrated in Fig. 5, indicate the VPE water supply system production is superior in terms of sustainability compared to the investigated traditional materials. This can be mainly attributed to the fact that the pipes used to produce the VPE system utilize recovered materials and energy (Table 2). Given that climate change has evolved into an influential factor in the decision- making of both the public and the private sector, it probably provides the strongest indication for the environmental performance and sustainability level of a product or a system to the non- scientific communities. The GWP of the VPE water supply system is 17.7 kg CO_2- equivalent, against the steel and copper's, 128.and 151.3 kg CO_2- equivalent, respectively. Thus regarding the GWP impact category, the VPE water supply system performs 86.3% better than the steel system, and 88.3% than the copper water supply system. However, in the case of Ozone Depletion, an environmental impact strongly associated with policy regulations and influences political action, the picture is very different. The VPE water supply system is indicated to have no contribution to the ozone depletion, while copper has negligible impact compared to the steel water supply system. In particular, the impact of the copper's system is 0.3 kg of R-11 equivalent, while the steel's reached the 9.3 kg of R-11 equivalent. The impact categories associated with tropospheric processes and pollution, namely photochemical ozone formation and acidification, have also been chosen for analysis in this paper in view of the fact that they directly affect the human health. POCP and AP illustrate comparable results in the LCIA. The performance of the VPE water supply system for the photochemical ozone formation impact category is 0.04 kg NMVOC equiv. and 0.08 mole of H+ equiv. for the acidification category. Accordingly, the specific system's performance compared to the steel system is 79.0% better for the POCP and 75.0% for the AP categories. Furthermore, in comparison to the copper water supply system, the plastic system performs approximately 89.0% in both tropospheric pollution- related impact categories. Regarding the ADP category, closely related to the carbon emissions and the depletion of non- renewable energy resources, the VPE system is also evidently superior to the competing systems employing traditional materials. More specifically, the impact of the plastic system in this impact category is minimal- at 0.005 kg of Sb- equivalent, performing 98.4% and 99.9% better than the steel and copper systems, 0.32 and 6.36 kg of Sb- equivalent respectively, which utilize both primary and waste materials for their production. Furthermore, the comparison of the VPE water supply system against the traditional materials' systems in terms of life- cycle non- renewable energy consumption and carbon dioxide emissions is also indicative of their environmental performance. The non- renewable energy consumption of the plastic system is 600 MJ, whereas for the steel and copper the specific value rises to 1360 MJ and 1890 MJ, respectively. As a result, the conventional water supply systems are observed to be 55.9% for the steel system and 68.3% for the copper system more fossil- fuelled energy intensive than the VPE system. Additionally, the results of the analysis also indicated that the production of the VPE system emits 14.1 kg of CO_2, approximately the one tenth in comparison to the production of a water supply system utilizing a traditional material- 121 kg of CO_2 and 141 kg of CO_2 for the steel and copper systems, respectively. The findings of this work are comparable with findings of the report released by Georg Fischer piping system. In the specific report, the GWP resulting from the production of the PE piping system was found to be around 7 kg CO_2-equiv, whereas the ODP around 1×10^{-7} kg CFC11-equiv. The deviation in the results can partly be attributed in the variation of the functional units of the two studies. The functional unit of the Georg Fischer report was defined as the underground transportation of drinking water, over a distance of 100m, from the exit of the water plant to the water meter of the building, by a typical public European PE pipe water distribution system over its complete life cycle of 100 years, calculated per year. However, this work has set its functional unit to one unit of water supply system, which totals approximately to 120m of piping.

It is also noteworthy that the European Union Public Procurement Directive (EUPPD), 2013 recommends the employment of BIM for construction and projection contracts. Accordingly, an in-

Table 2

Life Cycle Inventory (LCI) of water supply systems under investigation (Gabi database)

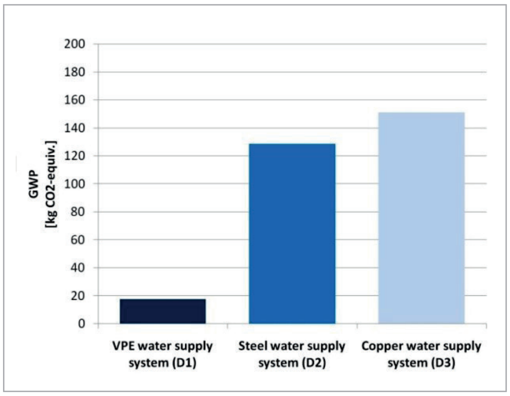
		D1: VPE water supply system		D2: Steel water supply system		D3: Copper water supply system	
Process	Unit	Inputs	Amount	Inputs	Amount	Inputs	Amount
Production	kg	*Materials*		*Materials*		*Materials*	
		Municipal waste	0.118	Steel scrap (St)	6.28	Reverts 21-40 % Cu	0.0559
						Copper slag concentrate	0.0796
						Steel scrap (St)	0.0849
						Scrap (71-95 % Cu)	0.256
						Scrap (20-40 % Cu)	0.328
						Cu scrap (purchased)	16.3
						Copper scrap (>95% Cu content)	30.9
	MJ	*Energy*					
		Thermal energy (recovered)	-10				
		Industrial waste (incineration)	0.627				
		Outputs		Outputs		Outputs	
Production	kg	*Materials*		*Materials*		*Materials*	
		Wooden pallet (EURO)	1.25E-9	Wooden pallet (EURO)	7.47E-13	Waste rock	580
		Wood	0.00633	Wood	3.18E-6	Used emulsion	0.357
		Waste paper	0.00662	Waste paper	1.07E-11	Tailings (deposited)	9.04
		Waste	0.0103	Waste for recovery	5.11	Slag	1.9
		Toxic chemicals	0.018	Waste	0.00943	Radioactive tailings	0.0738
		Tailings	0.000507	Steel welded pipe	50.5	Overburden (deposited)	727
		Slag	0.144	Sludge (from processing)	0.000631	Medium radioactive wastes	0.000725
		Production residues	0.0321	Sludge	0.00432	Low radioactive wastes	0.00148
		Polyethylene tube (PE)	7.12	Slag (Mn 6,5%)	0.456	High radioactive wastes	0.0000103
		Plastic	0.0347	Slag (Iron plate production)	0.0216	Gypsum)	0.21
		Packaging waste (plastic)	3.7E-11	Slag (containing precious metals)	5.02E-5	Furnace dust	1.88
		Packaging waste (metal)	0.000857	Slag (Waste for recovery)	0.00728	Furnace ashes	22.7
		Overburden (deposited)	0.224	Slag (Hazardous waste)	0.00172	Filter dust	0.00423

Process	Unit	Outputs	Amount	Outputs		Outputs	Amount
Production	kg	*Materials*		*Materials*		*Materials*	
		Organic waste	3.56E-6	Sinter/ Pellet Dust	3.58E-6	Dross	0.0561
		Municipal waste	-0.111	Rolling tinder	1.47E-18	Copper tube	68.6
		Mineral waste	0.00943	Rolling gravel	0.0405	Converter slag	4.56
		Inert chemical waste	0.00516	Red mud (dry)	0.208	Converter dust	0.3
		Industrial waste for municipal disposal	-0.0164	Production residues	1.03E-10	Black acid	0.0247
		Incineration good	0.00632	Plastic	2.81E-5	Anode sludge	0.0767
		Demolition waste (deposited)	8.6E-8	Pickled hot rolled coil sludge	0.000488	Anode scrap	0.512
		Chemicals	0.0236	Overburden (deposited)	239	Acid slime	0.0584
				Non Hazardous non organic waste for disposal	1.72		
				Neutralized residues	0.00105		
				Natrium oxide	0.0024		
				Mineral waste (Hazardous waste for disposal)	0.603		
				Mineral waste (Consumer waste)	0.00993		
				Hot Rolling Sludge	1.17		
				Hazardous waste	0.00566		
				Hazardous organic waste for disposal	0.000113		
				Hazardous non organic waste for disposal	0.199		
				Gypsum (FGD)	0.00555		
				Gypsum	0.0114		
				Dross (Fines)	0.000511		
				Cryolite	0.000472		
				Cooling water	-0.00747		
				Cold rolling emulsion treatment sludge	4.91E-5		
				Chemicals	0.0000102		
				BOF Slag	0.127		
				BOF gas dust	0.0494		
				Aluminium scrap	5.25E-5		

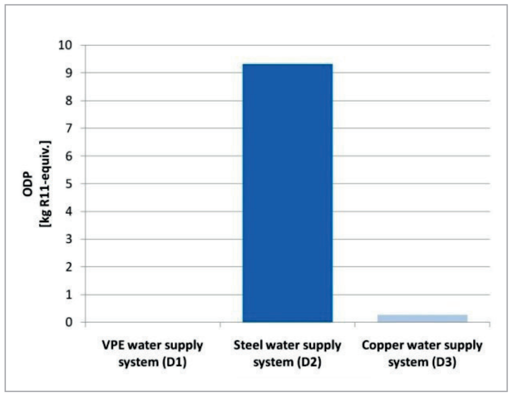
creasing number of construction companies are implementing BIM to increase the quality, as well as the productivity of their work. The significance of supplementing BIM with LCA is found in the attainment of the objective of achieving the most sustainable building projects in practice. For that reason, scientific findings and recommendations are valuable in this field.

Fig. 5

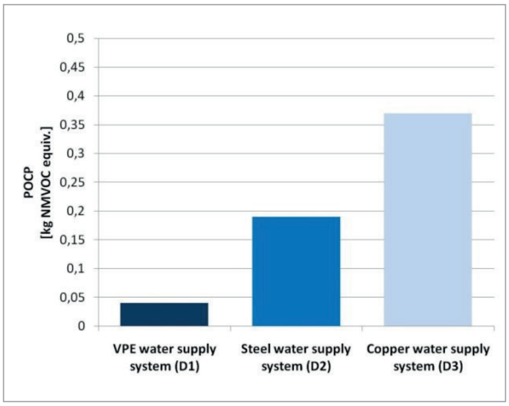
Life Cycle Impact Assessment (LCIA) of investigated water supply systems



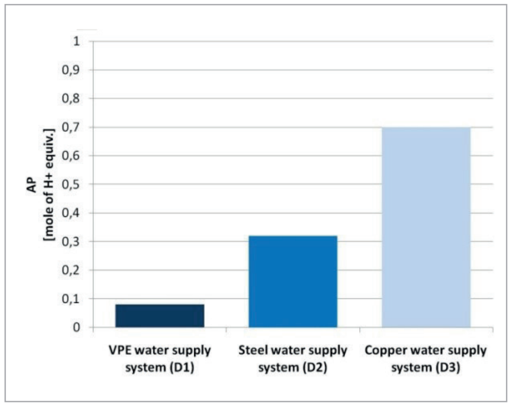
Global Warming Potential (GWP)
[kg CO_2-equiv.]



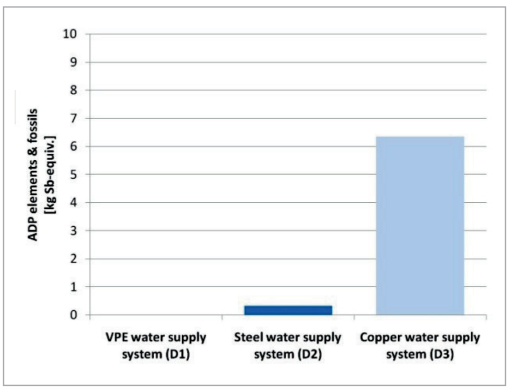
Ozone Depletion Potential (ODP)
[kg R11-equiv.]



Photochemical Ozone Creation Potential (POCP)
[kg NMVOC equiv.]



Acidification Potential (AP)
[mole of H+ equiv.]



Resource Depletion, Mineral, Fossil, and Renewable (ADP elements & fossils)
[kg Sb-equiv.]

Conclusions

This work demonstrated the benefits that arise from the synergy of two well- established methodologies, BIM and LCA. The LCA that for the definition of the level of sustainability and environmental performance of the modern VPE system against the traditional steel and copper water supply systems was conducted according to the design of the specific systems using sophisticated BIM tool. The results of the LCA revealed the superiority of the production of the modern VPE water supply system in terms of sustainability compared to the investigated traditional materials. The VPE water supply system performed 86.3% better than the steel system, and 88.3% than the copper water supply system in the GWP impact category, and also indicated that its production does not contribute ozone depletion. Additionally, it was illustrated that it achieves a reduction in the tropospheric pollution- related potential, photochemical ozone formation and acidification, by least 74.4% in comparison to the production of conventional water supply systems. The impact of a VPE system's production is also negligible on the natural element and fossil resources, in contrary to the production of a copper system, which was observed to be the less sustainable one across the majority of the investigated impact categories. The advantages from integrating of BIM and LCA have been demonstrated through the implementation of this case study. Evidently, this synergy cannot only point towards the most sustainable designs from an early stage in the construction project, but also provides the opportunity to several different expertise and stakeholders to collaborate for the maximization of the desirable impacts.

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