ORIGINAL PAPER

Sustainability in bridge construction processes

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Abstract Sustainability must be seen as a global issue. In order to achieve that goal, it is necessary to apply its principles to all industrial activities, including those that are not traditionally engaged with such guidelines, which is the case of Bridge Construction. This paper evaluates the consumption of steel and energy and the emissions of carbon dioxide due to the use of movable scaffolding systems (MSS) in the Bridge Construction industry. The values obtained considering the use of conventional MSS are compared with the ones obtained using a new sustainable technology which is herein synthetically described—the organic prestressing system (OPS). In order to compare the sustainability of the two systems, a prediction of the material and energy consumptions, and CO_2 emissions for traditional MSS and for MSS equipped with OPS is performed until 2025.

Introduction

Plethora of bridge construction methods are currently used all over the world. The bridge construction method used in a specific bridge depends, among other issues, on the bridge characteristics (span length, type of deck, number of spans, etc.), the location of the bridge and the experience of both the contracting entity and the constructor.

One of the most used bridge construction methods is the cast in situ span by span construction with movable scaffolding systems (MSS). These equipments are large traveling steel structures that support the formwork that gives shape to the bridge. Depending on its characteristics, a traditional MSS can weigh up to more than 1,000 tons (mostly steel).

The use of MSS in bridge construction involves three main processes, which consume steel and energy and are responsible for the emission of carbon dioxide: manufacturing, transportation and operation.

Considering the significant dimensions of these equipments, their manufacture implies the use of considerable amounts of steel and energy, also producing important emissions of carbon dioxide.

The use of organic prestressing system (OPS) on MSS allows a significant reduction of steel needs—implying reductions of both energy consumptions and carbon dioxide emissions. On the other hand, this new technology implies additional energy consumption during its operation, due to the fact that OPS makes use of energy (instead of mass) to achieve stiffness.

After a brief presentation of the OPS concept and of its first full scale application, comparisons between the consumptions of steel and energy, and the emissions of carbon dioxide due to the use of MSS with or without OPS are presented.

OPS technology—structural efficiency

OPS is an innovative structural solution that resulted from a research and development process initiated in 1994, at the

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Faculty of Engineering of the University of Porto. Typical scientific main stages were followed: fundamental research (Pacheco and Adão Da Fonseca 1996; Pacheco 1999, 2002), numerical analysis (Pacheco and Adão Da Fonseca 1997, 2002; Pacheco et al. 2004; Guerra et al. 2004), experimental tests (André et al. 2006) and, more recently, a full scale application was implemented (Pacheco et al. 2007).

OPS is a concept inspired in the behavior of an organic structure found in nature: the muscle (Pacheco and Adão Da Fonseca 1996; Pacheco 1999, 2002). It is nothing else than an actively controlled prestressing system, in which the tension applied is automatically adjusted to the actuating loads, through a control system, in order to reduce structural deformations and minimize tensions.

Numerical studies of different OPS applications to civil engineering structures reveal that OPS can be very advantageous for structures with high "live-load/dead-load" ratios (Pacheco and Adão Da Fonseca 1997). Scaffolding systems are a good example of such structures, as the dead load (self weight of the MSS) is around 20% of the weight of the live load (weight of fresh concrete).

The main structural advantages of OPS when applied to MSS are simple to identify. Regarding Fig. 1, the prestressing forces imposed by the cables are simultaneously applied with the pouring of the fresh concrete (live load), so that the beam with a main span L assumes a structural behavior similar to a continuous beam with three times L/3 long span. Deflections and bending moments are substantially reduced. If a conventional prestressing was applied (previously) to the "empty structure" (Fig. 2), an undesirable behavior would occur—the prestressing effect would be, by itself, nearly as much adverse as the live-load (deck weight) effect.

The main elements of the OPS system are: (1) an actuator in the organic anchorage, (2) unbonded cables, (3) sensors and (4) an electronic controller in the girder control unit (Fig. 3).

The control strategy of the OPS system adopts the mid-span vertical deflection as the primordial control variable. The mid-span deflection is measured by means of sensors (pressure transducers) strategically spread along the structure. To implement this technique, a reservoir is fitted in a fixed location (near a pier) and pressure sensors, spread along the structure and connected by a fluid circuit (Fig. 4), measure variations in the hydrostatic pressure (Pacheco et al. 2004; André et al. 2006).

The sensors transmit the information to an automaton, which processes it according to a control algorithm, and then "decides" between maintaining or changing the prestressing force (Pacheco and Adão Da Fonseca 1997; Pacheco et al. 2004). Typically, in a concrete pouring situation, the concrete pouring mode is turned on and, if the mid-span deflection exceeds a pre-defined limit, the automaton "decides" to increase the hydraulic jacks (actuator) stroke, moving the organic anchorage beam and simultaneously tensioning the prestressing cables.

In addition, OPS performs continuous monitoring of the main girder steel structure, evaluating the main structural parameters and emitting warnings or alarms in case of anomalous situations.

Rio Sousa Bridge—brief description of pilot application

In 2005, the first full scale prototype of a MSS with OPS was implemented for the construction of the Rio Sousa

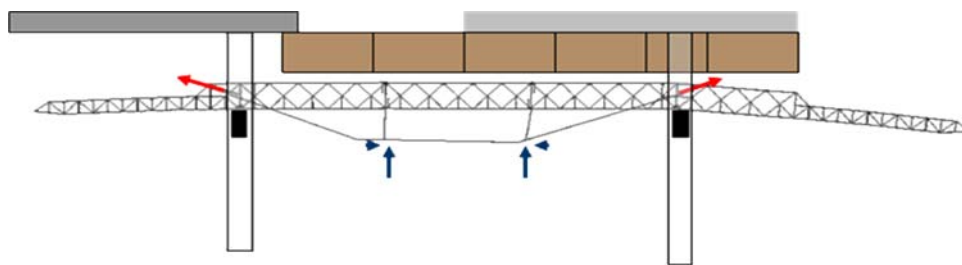**Fig. 1** Structural effects of OPS on a scaffolding structure

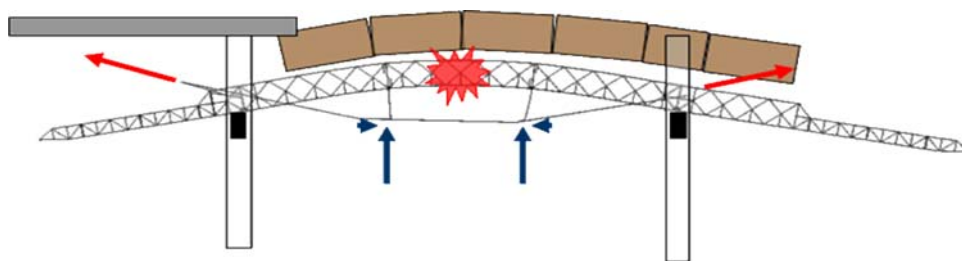**Fig. 2** Structural effects of conventional prestressing on a scaffolding structure

Fig. 3 3D scheme of a movable scaffolding system equipped with OPS (Pacheco et al. 2004)
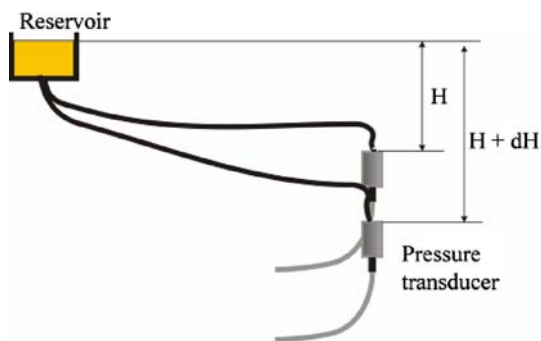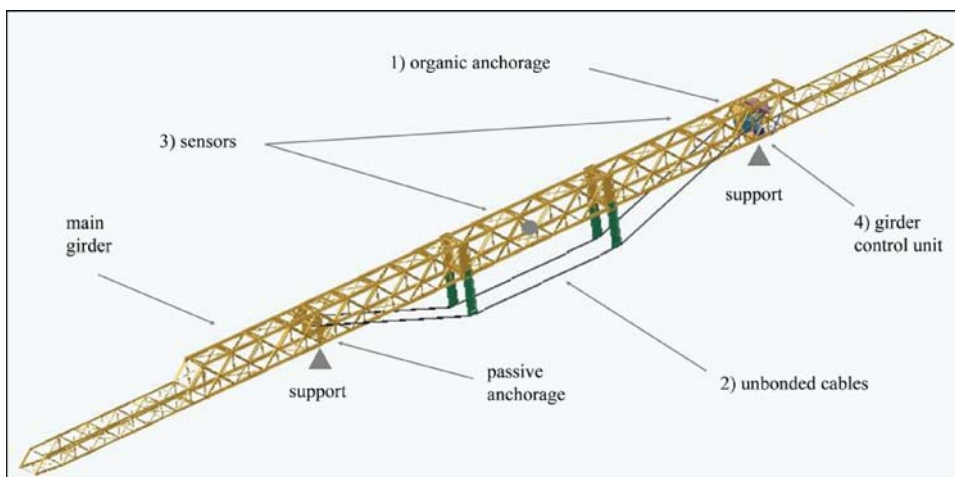

Fig. 4 Static column fluid pressure measurement (Pacheco et al. 2004)

highway bridge in northern Portugal. The bridge includes two common prestressed concrete decks, both comprising 15 × 30 m long spans (Fig. 5) (Lisconcebe 2004).

An underslung MSS was developed comprising four independent steel main girders strengthened with an OPS system, brackets, friction collars and bogies sets (Fig. 5).

The main girders are modular trusses. Their transversal section (1.25 m × 2.00 m) was designed for easy transportation and on site assemblage. The steel weight of the 4 main girders is approximately 108 metric tons (BERD and AFAssociados 2005). According to numerical studies, additional 30% of structural steel would be required in a conventional system for the same purposes (Guerra et al. 2004; Pacheco et al. 2007). Moreover, any conventional solution is unlikely to achieve such a high performance concerning deflection limitation.

Why is OPS a clean technology?

The use of the OPS technology in MSS allows a significant reduction of steel needs, implying reductions of both energy consumption and carbon dioxide emissions. However, OPS uses additional energy during its operation, due to the fact that it makes use of energy (instead of mass) to achieve stiffness.

Fig. 5 View of Rio Sousa Bridge

In order to evaluate the effect of the OPS technology in this industrial application, a systematic comparison is performed considering common life cycles of MSS. For simplicity, only the main processes are considered: manufacturing, transportation and operation on site.

Steel consumption

This analysis is made considering a representative MSS with 500 ton, which corresponds to the average weight of a traditional MSS (Moura 2005).

According to previous publications, the OPS system allows an average reduction of 30% in steel consumption (Guerra et al. 2004). Thus, the representative MSS with OPS technology weighs approximately 350 ton, resulting in nearly 150 ton saving per representative MSS unit.

Energy consumption

During their life cycle, MSS are responsible for a considerable amount of energy consumption, mainly during manufacturing and transportation processes.

In order to secure uniformity in the analysis, the Ton of Petroleum Equivalent (TPE) is adopted as the measure of energy consumption. The conversion between energy consumption and TPE is done according to the Portuguese Standard for the Regulation of Energy Consumption—RGCE.

Manufacturing

Manufacturing includes the production of the raw material and assemblage of the MSS modules. According to RGCE, it is established that the energy consumption per metric ton of constructed steel is 0.51 TPE/metric ton (RGCE). Therefore, the energy consumption for the fabrication of one MSS without OPS is 255 TPE, which is to be compared with 181 TPE for an equipment with OPS (179 TPE are due to the MSS structural steel structure manufacturing).

Manufacturing of the hydraulic equipment of the OPS corresponds to a reduced amount of energy consumption. Indeed, even considering that cold rolling steel manufacturing processes (used for hydraulic components manufacturing) represent an energy consumption per ton 2 to 3 times larger than the remaining steel components (Stubbles 2000), the weight of hydraulic equipment represents less than 0.5% of the MSS global weight (BERD and AFAssociados 2005). The same applies to the electronic equipment, which represents less than 0.05% of the MSS global weight (BERD and AFAssociados 2005).

Transportation

In a normal life cycle, main transportation operations occur "to site" and "from site". For simplicity partial transportations "to" and "from factory" are not herein considered.

For the evaluation of energy consumption during transportation, it is considered that, in average, a MSS has to travel an average distance of 300 km to be brought to site (Moura 2005), and it is assumed that only ground transportation with road trucks is used for the transportation of the equipment.

According to international transportation agents, a 26-ton truck consumes 35 diesel liters per 100 km, i.e., 0.0135 l of diesel/km/ton. The density of diesel is 835 kg/m^3 and the conversion factor between the diesel consumption and TPE is 1.045 TPE/metric ton of diesel (RGCE), leading to 1.175×10^{-5} TPE/km/metric ton of steel.

Therefore, the energy consumption required for the transportation "to site" and "from site" of the representative MSS without OPS is 1.8 TPE, comparing to 1.2 TPE for the representative equipment with OPS.

Operation

The operation of a MSS involves multiple tasks that are very similar for equipments with or without OPS. Thus, only the energy consumption due to the OPS operation is considered in this analysis (differential quantification).

According to the first full scale application technical data, where a 170 ton equipment was used (BERD and AFAssociados 2005), OPS consumed approximately 3 kW h per hour of operation. Therefore, for the representative MSS with OPS technology, weighing 350 tons, the energy consumption by the OPS is predicted to be 6 kW h per hour of operation. Considering approximately 350 h of operations during the construction of a typical bridge deck, a consumption of about 2,100 kW h would be expected. Taking a conversion factor between kW h and TPE of 290×10^{-6} (RGCE), a consumption of 0.6 TPE is expected for the operation of a MSS with OPS.

Energy consumption balance

Considering the manufacturing, transportation and operation, the aggregated reduction of energy consumption achieved with OPS technology for the representative MSS is nearly 74 TPE (Table 1).

Carbon dioxide emissions

The carbon dioxide emissions analysis is performed only for manufacturing and for the transport operation. The

Table 1 Steel and energy consumptions and CO_2 emissions for the representative MSS units with and without OPS

	MSS without OPS	MSS with OPS
Steel consumption (tons)	500	300
Energy consumption (TEP)		
Manufacturing	255.0	181.2
Transportation	1.8	1.2
Operation	0.0	0.6
Total	256.8	183.0
Carbon dioxide emissions (tons)		
Manufacturing	270.3	192.0
Transportation	4.9	3.4
Total	275.2	195.5

operation stage is not relevant concerning carbon dioxide emissions.

Manufacturing

Although no specific information of MSS manufacturers is available, it is possible to estimate carbon dioxide (CO_2) emissions of steel manufacturing, considering average indicative values of this industrial sector. According to average values included in an OCDE/IEA report (OECD/IEA 2007), a gross relation between CO_2 emissions and energy consumption is 1.06 CO_2 ton/TPE. These values lead to an estimation of CO_2 emissions of 270 ton for traditional MSS and of 192 ton for MSS equipments with OPS.

Transportation

The calculation of carbon dioxide (CO_2) emissions is performed adopting a density of 835×10^{-6} metric ton/diesel liter (RGCE). It is also considered that 1 metric ton of diesel produces 43.33 GJ (Global Reporting Initiative 2006) with an efficiency of 90%, and finally, it is established that 1 GJ of diesel emits 74.1 kg of CO_2 (Portuguese National Inventory Report on Greenhouse Gases 1990).

Therefore, the CO_2 emission during transportation is 2.41 CO_2 kg per liter of diesel. Multiplying this value by 0.0135 liters of diesel/km/ton, a value of 0.0402 kg of CO_2/km/ton is obtained, that can be used to estimate the CO_2 emissions due to the transportation of MSS "to site" and "from site". This results in 4.9 tons of CO_2 emissions for a traditional system, compared with 3.4 tons of CO_2 emissions for a system equipped with OPS technology.

Rebuilt equipments

Usually, MSS are used several times due to economic reasons, and normally each rebuilding process implies a partial addition of steel.

The average additional amount of steel used to rebuild a MSS is nearly 15% of the steel weight of the original MSS (Moura 2005). Thus, a representative rebuilt MSS is considered, admitting that it implies 15% additional consumption of steel and energy during the manufacturing process, and that it represents 115% additional consumptions and CO_2 emissions, during the transportation process.

The OPS effect—scenarios

This study is based on scenarios taken from the available data of a marketing study for the MSS world market until 2025, developed by a MSS supplier (Moura 2005), that considers three different scenarios (low, medium and high) for the evolution of the number of new and rebuilt MSS in the world (Fig. 6) and for the implementation of OPS technology in MSS (Fig. 7).

For the evaluation of "the OPS effect" due to the introduction of the OPS technology in MSS, only the medium scenarios are considered. Therefore, scenario A considers only traditional MSS units without OPS (Fig. 6) and Scenario B is a predicted combination of both kinds of MSS, with and without OPS (Fig. 8).
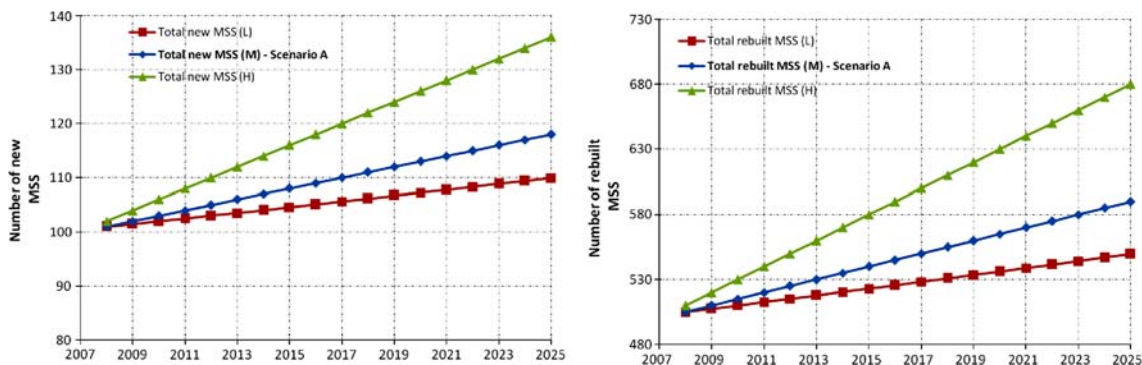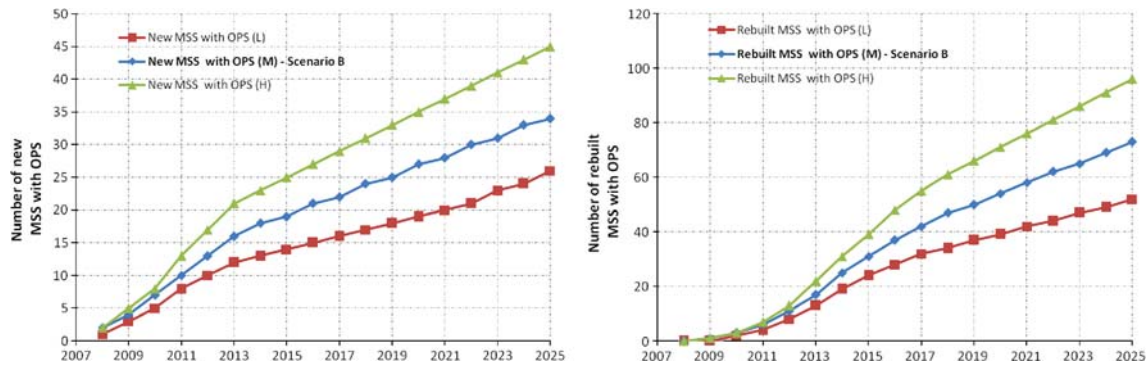
Fig. 6 Number of new and rebuilt MSS

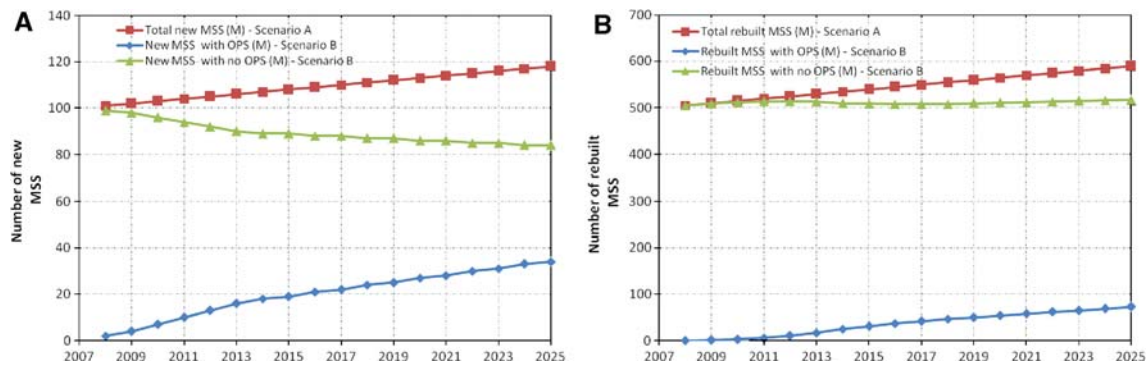**Fig. 7** Number of new and rebuilt MSS with OPS

Fig. 8 Scenarios A and B for new and rebuilt MSS

According to the marketing document mentioned above, for Scenario A, 118 new MSS units and 590 rebuilt MSS units will be produced per year by 2025. According to the same document, 34 new MSS units with OPS will be produced and 73 rebuilt ones will be used in 2025. Also according to Scenario B, 84 new MSS units and 517 rebuilt MSS units, both without OPS, will be used in 2025.

The OPS effect—results

Considering the above scenarios A and B, the "OPS effect" is evaluated performing linear combinations of the global number of new MSS units and rebuilt ones, based on the above presented values of steel and energy consumptions, and CO_2 emissions (Table 1), obtained for the representative MSS equipments with and without OPS.

If Scenario B occurs, in 2025, nearly 6.750 tons/year of steel consumption reduction would be achieved (Table 2). The reduction in steel consumption has an important economic impact on the fabrication of MSS, but it also implies reduction of energy consumption and emissions of CO_2. Indeed, Scenario B implies a reduction of energy consumption of about 3,300 TPE/year (Table 3) and nearly 3,575 metric tons/year of CO_2 emissions (Table 4).

Table 2 Steel consumption for scenarios A and B (metric ton)

	2010	2015	2025
Scenario A (All MSS without OPS)	90,125	94,500	103,250
Scenario B	89,008	90,953	96,508
Saving	1,117	3,547	6,742

Table 3 Energy consumption for scenarios A and B (TPE)

	2010	2015	2025
Scenario A (All MSS without OPS)	47,189	49,479	54,061
Scenario B	46,640	47,739	50,755
Saving	549	1,740	3,306

Table 4 Emissions of CO_2 (metric tons)

	2010	2015	2025
Scenario A (All MSS without OPS)	52,109	54,639	59,698
Scenario B	51,514	52,740	56,083
Saving	595	1,898	3,614

If cumulative curves are considered, much more expressive values are obtained. By 2025, total savings of about 70,000 ton of steel and 34,000 TPE of energy are achieved
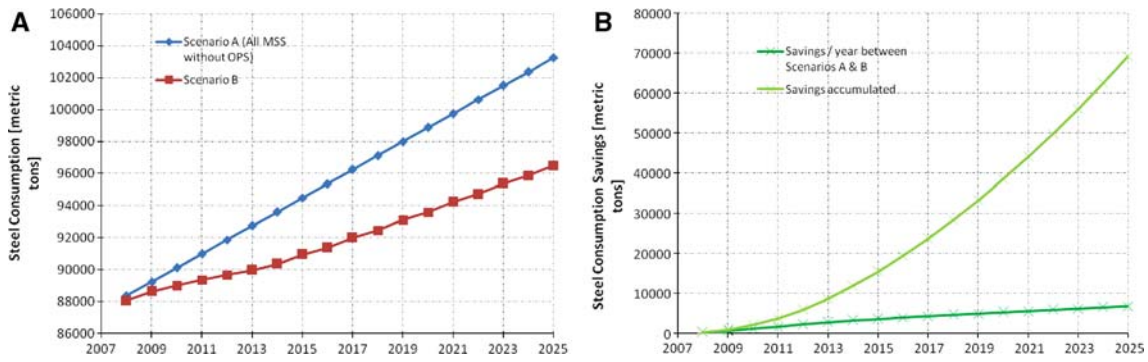
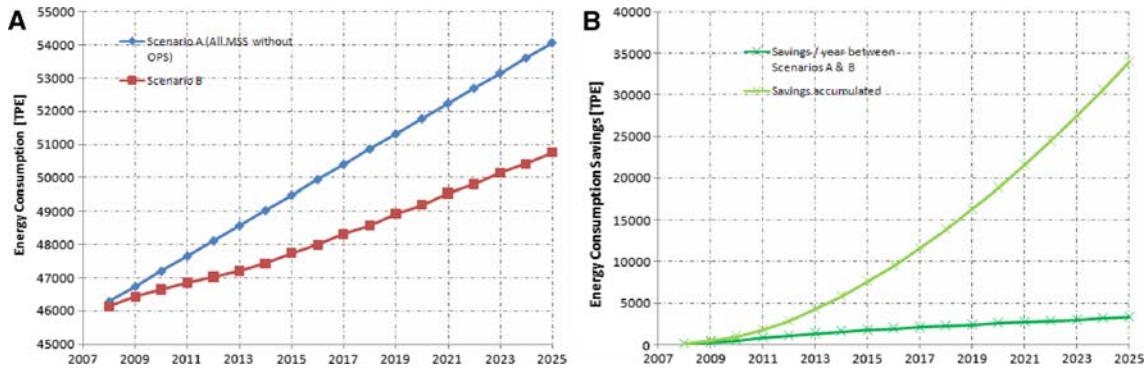**Fig. 9** Steel consumptions and savings for Scenarios A and B

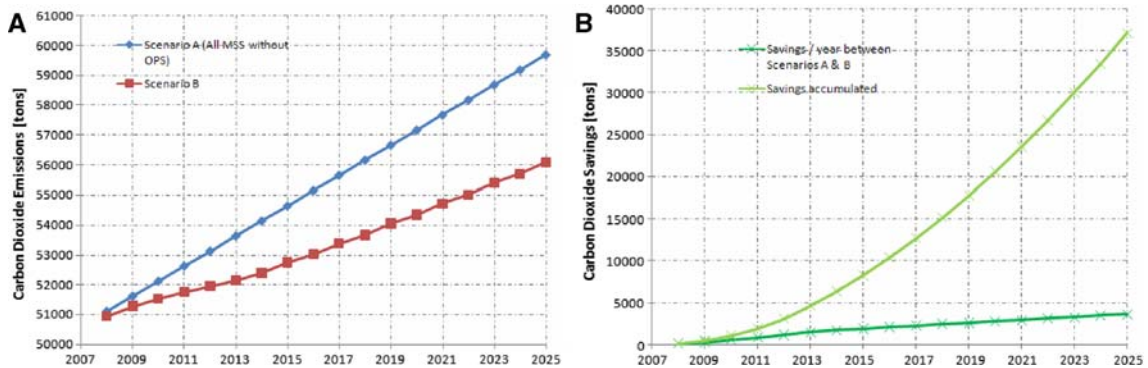**Fig. 10** Energy consumptions and savings for Scenarios A and B

Fig. 11 CO_2 emissions and reduction for Scenarios A and B

(Figs. 9, 10), and a reduction of nearly 37,000 metric tons in the emission of CO_2 is also achieved (Fig. 11).

Conclusions

Considering average scenarios, the introduction of OPS technology in the Bridge Construction industry shall represent significant savings in terms of steel needs and energy consumptions. Also, it shall represent an important reduction of carbon dioxide emissions. According to numerical predictions, a reduction of 6.5% in steel consumption per year will be achieved in this specific industrial area in 2025. A reduction of nearly 6% is predicted concerning both energy consumptions and Greenhouse gases emission. By 2025, that would mean a reduction of 6,750

tons/year of steel needs; 3,300 TPE/year of energy consumption and 3,575 metric ton/year of CO_2 emissions.

It is concluded that, besides the technical advantages, the OPS implementation contributes to the sustainability in bridge construction.

Moreover, the global savings could be even more important if contractors are encouraged to save energy and to decrease carbon dioxide emissions: the proportion of MSS with OPS would then become greater and mentioned benefits would increase.

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