A structured approach to the evaluation of the energy requirements of HPGR and SAG mill circuits in hard ore applications

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Synopsis

The application of high pressure grinding rolls (HPGR) has been growing in the mining industry for the last 10 to 15 years. The major benefits supporting this trend are better energy efficiency, improved grinding capacity, and higher metal recovery in downstream processes such as heap leaching and flotation.

In general there is limited quantitative knowledge on the true benefits of HPGRs relative to SAG mills in comminution, and about which situations one deals with better than the other. This paper will present a structure for comparison of the energy requirements for HPGR versus SAG mill considering complete circuits for comminution of precious and base metals hard ores. The work presented is from the design of four complete circuits based on ore data from two sites.

Introduction

Climate change, energy efficiency, greenhouse gas emissions, and carbon footprint have gained high priority status in public interest (Sullivan and Oliva, 2007). Electricity costs have been rapidly increasing in response to record fuel costs for power generation. Moreover, several countries, such as the Southern African countries, are now facing a shortage of electric power. Chile, the world leader in copper production, may face electricity rationing in the near future (Walsh, 2008). The mining industry has realized the high importance of energy efficiency and is currently placing this issue at high priority level (Bearman, 2006).

Comminution processes account for the largest portion of energy consumption in the mining operations, and it has been demonstrated that significant energy savings can be realized by their optimization (Valery and Jankovic, 2002). Fundamental and applied research on fracture phenomena demonstrates that interparticle comminution at high pressure consumes substantially less energy than conventional grinding processes, and served as the origin for the development of the high pressure roll crusher (HPRC) known as, high pressure grinding rolls (HPGR) (Schonert, 1988 and 1991).

Additional benefits have been linked to the application of the HPGR, such as differential comminution in diamond-bearing kimberlite, grinding media elimination when replacing SAG mills, and improved performance in leaching and flotation resulted from micro-cracked rocks (von Michaelis, 2005) (Morley, 2006).

The application of HPGRs in comminution circuits has improved in the last couple of decades and seems to be very well established for processing cement, diamonds, and iron ore (Broeckmann and Gardula, 2005). In the last few years HPGR-based plants to process precious and base metals from hard ores have been designed and some have already started production. The main examples are:

- SM Cerro Verde, copper, Peru
- PT Freeport Indonesia, copper-gold, Indonesia
- Zapadnoe, gold, Irkutsk, Russia
- Boddington, gold, Australia
- Bendigo, gold, Australia
- Mogalakwena North, platinum, South Africa
- Ruby Creek, molybdenum, Canada.

Although the development of these recent projects indicates a greater acceptance of the application of HPGR, there is still uncertainty as to the extension of its benefits. Among them is the net circuit energy savings when comparing complete SAG circuits to complete HPGR circuits, since extra equipment is required when using the HPGR.

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Objectives

The main objective of this work is to improve the understanding of the energy requirement differences between complete comminution circuits using SAG mill and HPGR technologies.

In addition, this work also aims to indicate the magnitude of saving in steel consumption that is expected with the application of HPGR based circuits and the consequent elimination of SAG mill balls. Reduction in steel ball consumption not only has direct economic impacts, it also saves the energy that would be used in the fabrication and transportation of the balls (Pokrajcic and Morrison, 2008).

Methodology

Design criteria

The hypothetical cases used for this study are two mines each with the option of SABC (SAG mill-ball mill-crusher) or 3-stage crushing with HPGR comminution circuits for the processing of precious or base metals hard ores.

These hypothetical projects are assumed to be located in very distinct regions of the world. One project would be located in a very remote area subjected to harsh winters, with plant heating requirements, and relying on electricity from the power grid. The other project is assumed to be located in a semi-arid region subjected to very mild winters, with no heating requirements, and connected to the power grid. Both cases are typical of new projects for precious and base metals mining operations.

For each mine, the values for daily production and final grinding were estimated based on personal experience and historical information. The physical and grindability parameters of the ore were based on real ore data from two different sites from previous work that will not be disclosed for confidentiality agreement reasons (AMEC, 2006) (AMEC, 2007). HPGR modelling parameters came from pilot test results conducted with the same ores.

The two orebodies that are used for this study contain a low percentage of clays and are formed of non stick rocks, i.e. ores that are amenable for crushing and high pressure grinding. The HPGR lab/pilot tests also indicated that product cakes are moderately competent flakes that can be deagglomerated by the application of wet screening.

The daily production, final grinding values, physical and grindability parameters of the ore, and the HPGR modelling parameters were grouped to generate the core process design criteria for the two mines as shown in Table I.

Other ore parameters that were used in the design process were the complete crusher table parameters from the JK drop-weight tests and HPGR test results including the feed and product size distributions. This information is too extensive to report here but is available upon request (AMEC, 2006) (AMEC, 2007).

Flowsheet development

Currently, after many years of SAG application, it has been recognized and demonstrated that the inclusion of pebble crushing in hard ore SAG circuits results in substantial energy savings (Vanderbeek, 2004). Since for this research the JK A*b parameters and their. Positions in JKTech's database indicate both ores are hard, SABC circuits will be used for the comparisons. For the HPGR plant design there are several possible flowsheet arrangements. However, it has been demonstrated that having the HPGR in closed circuit with fine screens for the tertiary crushing stage provides maximum energy efficiency. For hard ore the secondary crushing product should be screened before feeding the HPGR to avoid oversize material damaging the rolls (Morley, 2006).

Figure 1 shows the simplified flowsheets for the two types of circuits used in this research. The SABC circuit is very typical and the HPGR circuit has great similarities to the one applied at Cerro Verde (Vanderbeek, 2006). The only modification is that the sequence of the material being fed at the fine ore conveyor is reversed to minimize problems in the transport of the moderately wet material.

Modelling and simulation

Complete comminution circuit models were developed using a JKSimMet® simulator. This simulation package is a powerful tool available for analysing the effect of ore characteristics and machine operating parameters on crushing and grinding

Table I

Summarized design criteria

Design criteria (summary)	Case A		Case B	
	SABC	HPGR	SABC	HPGR
Feed rate (t/d)	55 000	55 000	40 000	40 000
Solids SG	2.60	2.60	2.73	2.73
Circuit F80 (mm)	125	125	125	125
Bond abrasion index (g)	0.32	0.32	0.22	0.22
Crusher (impact) work index (kWh/t)	12.5	12.5	14.4	14.4
JK parameter A x b	50.4	50.4	28.7	28.7
JK parameter ta	0.46	0.46	0.38	0.38
Ball mill work index (kWh/t)	14.1	13.2	16.5	16.0
Ball mill work index reduction	n/a	6.3%	n/a	3.0%
HPGR net spec. energy req. (kWh/t)	n/a	1.68	n/a	1.85
HPGR specific throughput rate (ts/hm³)	n/a	261	n/a	237
Final product P80 (μm)	140	140	180	180
Climate—mean temp. winter/sum. (°C)	-25/+14	-25/+14	+17/+22	+17/+22

circuits, and is generally well accepted in the industry after 20 years of successful use. Although this simulator has been used predominantly for SAG mill circuits it has been increasingly applied for HPGR circuits. In addition, JKSimMet® is apparently the only commercially available package that incorporates HPGR modelling capabilities.

The HPGR model embedded in the package was developed at the Julius Kruttschnitt Mineral Research Centre at the University of Queensland, Australia (Morrell *et al.*, 1996). The model has been verified against data collected from industrial units operating at different diamond mines (Daniel and Morrell, 2004), and the results indicated that the model is robust enough for the evaluation of new and optimization of existing comminution circuits.

Figure 2 is a screen snapshot of one SABC model developed with JKSimMet® (A-SABC case) and Figure 3 shows an HPGR case (A-HPGR case). As shown in these pictures, the simulation produces a comprehensive set of information, among them the stream values of solids, the power draw per equipment, and size distribution details.

For this study, the SAG mill simulations utilized breakage constant parameters based on a comparable size mill that had been surveyed in the past (AMEC, 2006) (AMEC, 2007), and the ore characteristics from grindability testwork as per the developed design criteria. Usually, several tests are conducted from samples collected in different parts of the orebody and an analysis of the hardness variability is conducted. Thus, a number of simulations are conducted to refine the sizing of the mill and usually one test result is selected for final design and the nominal material balance is derived from there. The selected test usually represents the medium hardness or a certain percentile of the hardness, such as the 75th percentile of hardness, depending on the variability throughout the orebody, the mining schedule or other particular characteristics of the project. However, for this work just one set of tests per case was utilized and it is assumed that it best represents the nature of the orebody.

Crusher modelling was developed based on Andersen's model (Andersen, 1988) and the necessary constant parameters were determined using JKSimMet® Model-Fit capability, i.e. inputting information from test work or plant survey, (such as feed and product size distributions, lab machine dimensions, and operating parameters), to the model and running a special simulation that back-calculates the constants several times until the best fit is found (JKSimMet®, 2004). For the model-fit of the crushers the input information required consisted of results from the drop-weight tests and feed and product size distributions. Since no crusher pilot test was available for this work, the size distributions were assumed based on simulations performed with Metso Bruno® crushing and screening simulation software (Kaja, 2002). The ore properties are as per the design criteria shown in Table I.

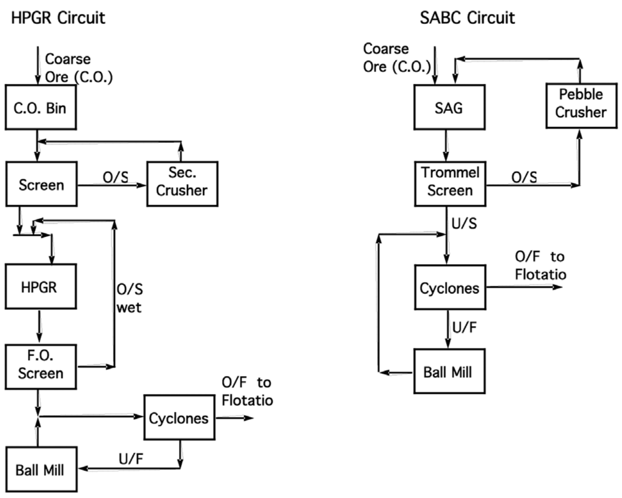

Figure 1—Simplified SABC and HPGR flowsheets

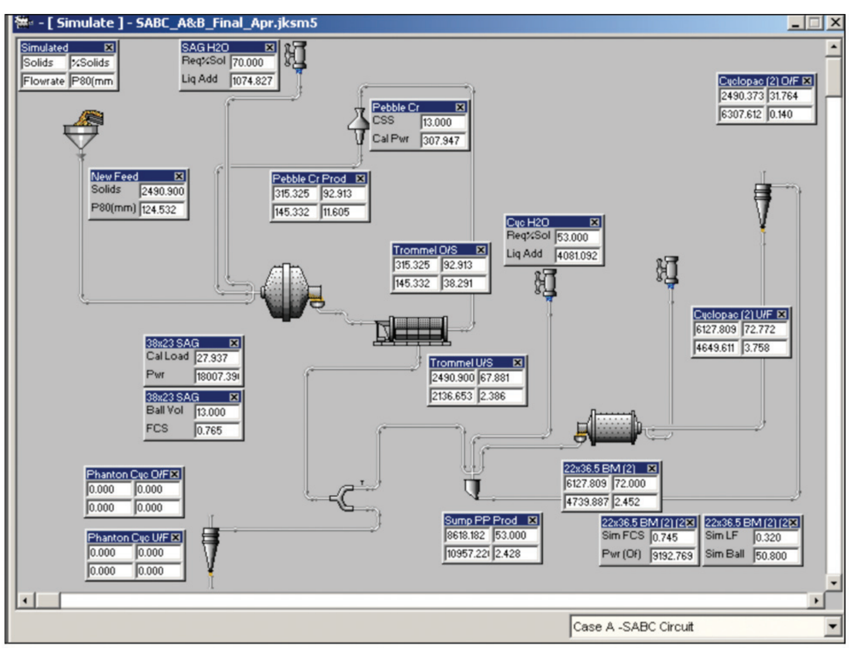

Figure 2—JKSimMet® screen snapshot of case A-SABC

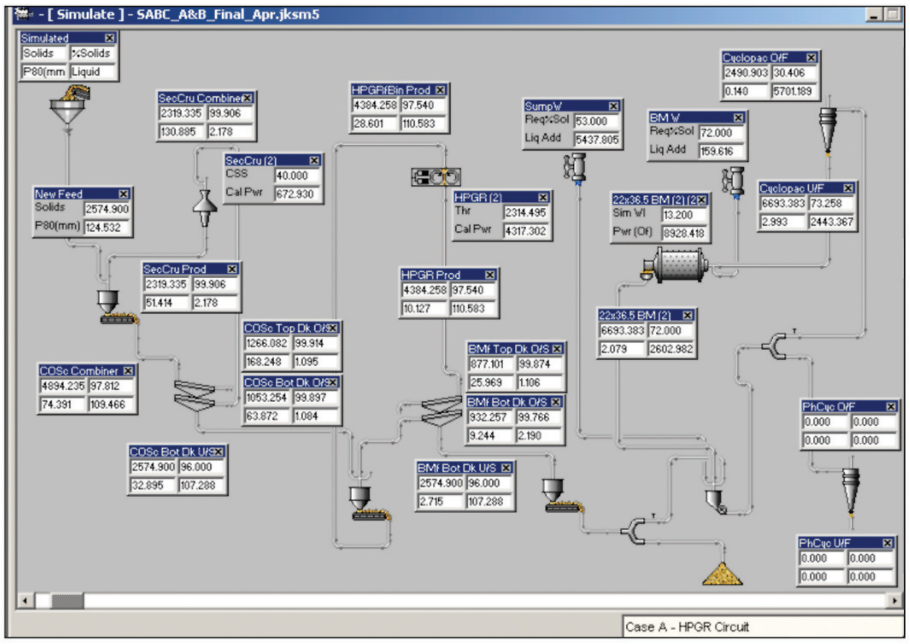

Figure 3—JKSimMet® screen snapshot of case A-HPGR

Ball mill energy requirements were based on Bond's third theory of comminution and the diminution of fine material in the Ball mill-hydrocyclone circuit by the application of the 'phantom' cyclone method with adjustments based on AMEC's experience.

Screens and hydrocyclones were modelled with the JKSimMet® standard efficiency curve model (Kavetsky, 1979). The required parameters for this model were based on manufacturers' recommendation for the cyclones and screens.

Development of the HPGR models was based on the pilot-scale testwork results and the Model-Fit process. Model fitting was considered adequate for both cases by analysing the correlation between the experimentally measured product size distribution from the pilot tests and the simulation predictions based on the model-fitted parameters. This methodology was described by Daniel and Morrell in 2004.

Equipment sizing

Optimization consisted of several simulation interactions and ball mill energy requirement calculations. During this process, different values for SAG mill machine/operational parameters, such as ball load, total grate open area and speed, and HPGR parameters, such as roll dimensions and speed, were tried. In addition, this optimization exercise took into consideration equipment vendor information, and information gathered from past projects.

The four final refined JKSimMet® models were used for the specification of the main pieces of equipment for the comminution plants. With the information from these models, preliminary general arrangement drawings were developed. These layouts, along with resultant material balances, were used for the material handling system design.

The design of the conveyors, surge bins, feeders and dust collection/suppression systems, was performed with the assistance of AMEC's Material Handling department to assure a prefeasibility level of accuracy.

Results and discussions

Pure comminution energy

The simulation work produced an estimation of the instantaneous energy draw of the mills, crushers and HPGRs. These data were corrected based on the circuit availability to estimate the average power draw per hour as reported in Table II. The availability factors were assumed based on historical information from operations and current industrial practice.

As shown in the table, the HPGR circuit provides savings in comminution energy in the order of 25.1% and 30.2% for cases A and B respectively. From these results the potential for energy savings provided by the application of HPGRs in these types of ores becomes apparent. This fact has already been reported by a number of authors (Morrell *et al.*, 1996) (Vanderbeek, 2006) some of them working for HPGR suppliers (Gunter *et al.*, 1996) (Broeckmann and Gardula, 2005) (Klymowsky *et al.*, 2006) and was to some extent expected at the beginning of this study.

Complete circuit comminution energy

Following the same methodology described above, the hourly average power draw values were calculated for all significant systems and pieces of equipment included in the design of the four concentration plants, as shown in Table III.

As presented in the table, the HPGR energy savings for the complete circuit decreased substantially from 25.1% to 7.7% in case A, and from 30.2% to 18.4% in case B. Although the magnitude of the savings decreased, the amounts of reduction are still very significant since it is related to the highest energy consumption portion of any mining operation.

Table II

Pure comminution energy

Description	Qt.	Unit power			Total power kW	Specific energy kWh/t
		Inst. kW	Simu. kW	Available factor		
SABC—Case A						
SAG mill—11.6 m D x 7 m L (38 x 23 ft)	1	19 985	18 007	0.92	16 566	7.23
Pebble crusher MP 800	1	597	307.9	0.92	283	0.12
Ball mill—6.7 m D x 11.1 m L (22 x 36.5 ft)	2	10 000	9 193	0.92	16 915	7.38
Totals					33 765	14.73
HPGR—Case A						
Sec. crusher MP 1000	2	746	672.9	0.89	1 198	0.52
Tert. HPGR—2.2 D x 1.7 W m	2	5 000	4304	0.89	7 661	3.34
Ball mill—6.7 m D x 11.1 m L (22 x 36.5 ft)	2	10 000	8 928	0.92	16 428	7.17
Totals					25 286	11.03
Energy savings HPGR circuit—Case A					25.1%	
SABC—Case B						
SAG mill—11.6 m D x 5.5 m L (38 x 18 ft)	1	15 000	13 766	0.92	12 665	7.60
Pebble crusher MP 1000	1	746	736.2	0.92	677	0.41
Ball mill—7.6 m D x 11.6 m L (25 x 38 ft)	1	14 500	13 323	0.92	12 257	7.35
Totals					25 599	15.36
HPGR—Case B						
Sec. crusher MP 800	2	597	558.6	0.89	994	0.60
Tert. HPGR—1.9 D x 1.55 W m	2	3 700	3056	0.89	5 440	3.26
Ball mill—7.6 m D x 11.0 m L (25 x 36 ft)	1	13 500	12 442	0.92	11 447	6.87
Totals					17 881	10.73
Energy savings HPGR circuit—Case B					30.2%	

Table III

Complete circuit comminution energy

Description	Case A		Case B	
	Total power kW	Spec. energy kWh/t	Total power kW	Spec. energy kWh/t
SABC circuit				
Comminution equipment	33 765	14.73	25 599	15.36
Conveyors and feeders	610	0.27	575	0.34
Pumps	1 649	0.72	1 199	0.72
Dust and heating systems and extras	2 346	1.02	28	0.02
	38 370	16.74	27 402	16.44
HPGR circuit				
Comminution equipment	25 286	11.03	17 881	10.73
Conveyors and feeders	3 660	1.60	2 388	1.43
Screens	300	0.13	195	0.12
Pumps	1 731	0.76	1 259	0.76
Dust and heating systems and extras	4 454	1.94	634	0.38
	35 432	15.46	22 357	13.41
Energy savings HPGR circuit	7.7%		18.4%	

Steel usage

In comminution circuits, steel is used in the form of steel balls as media for the tumbling mills, both for the SAG and the ball mills, as well as in many other components, such as: mill liners, HPGR rolls, crusher liners, chute liners, bin liners, etc. The total consumption of steel is usually a high operational cost. Although the precise estimation of this cost is not a straightforward task, it is common during the design phase of the projects to estimate the wear rate through a combination of ore abrasiveness test work, empirical models and historical data. The empirical model used in this research is based on the work by Bond, with improvements suggested by Norman and Decker, and adjustments made by the author based on historical data (Bond, 1964) (Norman and Decker, 1985).

For this study, it was assumed that the HPGR circuits and the SAG mill circuits would have similar steel consumption for liners (including HPGR roll surfaces and SAG mill liners, grates and pulp lifter bars) and ball mill media. In other words, it is assumed that the main difference in steel consumption lies in the SAG mill balls. Therefore, the HPGR circuit benefit would be the value corresponding to the wear of SAG steel balls at the corresponding SABC circuit.

In order to estimate this potential savings in steel consumption, the SAG mill ball wear rates were calculated based on Bond's ore abrasion indices, Bond's wet ball mill equation, and a correction factor of 65% (based on the author's database with a number of current operations) and the results are shown in Table IV.

Ore variability

It is a fact that ore properties will vary through project life and this work provides only two points in a possibly large spectrum. Therefore the results presented here should not be seen as two precise estimations for two very specific cases but should be interpreted as an indication of the potential energy savings for projects dealing with average ore hardness between these two points.

Additionally, the extension of the ore variability through the orebody needs to be considered when comparing the SABC to the HPGR circuit. Research, testing and modelling has indicated that the application of SABC brings higher risk of production variability than HPGR circuits when dealing with highly variable ores (Humphries *et al*., 2006) (Vanderbeek, 2006).

Heating and ventilation

For case A, the energy required for heating systems in a project located in an area with harsh winters was taken into consideration. The estimated energy requirement had a considerable effect on the total energy consumption. The total energy value for the SABC circuit increased from 36 MW to 38.4 approximately, and for the HPGR circuit from 31.8 to 35.4 when the heating requirements were included in the analyses. The HPGR circuit requires significantly more energy than the SABC circuit because it has a separate building for the secondary crushers and there are numerous conveyor belt galleries that have to be maintained at a minimum of +5°C. Although the extent of the savings decreased from approximately 11.7% to 7.7% with the addition of the heating requirements, the HPGR case still represents a considerable reduction in total energy requirements.

This result indicates that heating energy requirements have an effect in the comparison between HPGR and SAG circuits if the project is located in a cold climate area. However, for this specific case, it was assumed that the power would not be generated at site, which may not be the case for a number of operations at very cold and remote areas. In such cases, the fact that the energy can be easily recovered from fuel power generators may give the HPGR case a greater advantage.

Table IV

SAG mill steel ball consumption

Case A		Case B	
SAG balls kg/t	SAG balls t/h	SAG balls kg/t	SAG balls t/h
0.504	1.16	0.465	0.78

Clay content and ore crushability

In the case of this 'new' application of the HPGR for precious and base metal hard ores, high clay content ores, or ores that easily produce a high portion of extremely fine material during comminution, have previously been considered impossible to treat and the HPGR option has been excluded from studies. It is possible that the extension of the savings proposed by this work will assist in changing this perception.

Truly there is a need for comprehensive test work for these types of ores and the HPGR flowsheet requires modification. Experience with other types of ore, such as diamond ores, indicated that something around 0.7 kWh/t applied through scrubbers ahead of secondary crushers can eliminate the fine material from the circuit, minimizing the problems and reducing the tonnage in the downstream crushing and milling circuits. There is currently a project under development by AMEC that provides the opportunity for future research in this area.

Availability and maintainability

Since only a small number of precious and base metal HPGR plants are being operated at the present moment, the assumptions for circuit availability should be further explored to increase the confidence in the findings of this study. However, the major problem of short life of rolls reported at early trials with HPGR treating hard abrasive ores resulted in the development of superior designs for these components. Substantial improvements in this area are claimed by all three HPGR manufacturers. A good example is the application of tungsten studded roll tyres to provide an autogenous layer on the roll surface minimizing its wear rate.

Ore abrasiveness is an important factor that has not been included in this study. This parameter can not only influence the wear rate of HPGR rolls, but also the consumption of mill liners and steel balls. Future analyses will be conducted in this field.

Additional HPGR benefits

Additional effects in downstream processes are not addressed in this work but it should be recognized that benefits such as improved flotation performance through preferential liberation and reduced levels of ore oxidation through the reduction of steel usage as grinding media have also the potential to decrease overall energy consumption. It can be expected that improved flotation equates to fewer/smaller flotation mechanical cells and therefore less power. These benefits are being assessed by other researchers (Humphries *et al*., 2006) and more information is expected to emerge in the future.

Conclusions

This paper has presented the development and application of a methodology for evaluating the total energy requirements of HPGR and SAG comminution plants. Using this methodology a comparison between the total energy usage for HPGR and SABC circuits for two orebodies has been done. The analysis included the detailed design of four complete comminution circuits.

The work produced an estimation of the energy savings that can be achieved in the treatment of similar precious and base metal hard ores. It has demonstrated that these saving are within the range of 7.7% and 18.4%. In addition, it has shown that a significant reduction in steel consumption could be achieved based on the elimination of the SAG mill steel media. As well, this lower steel usage reduces the energy requirements and the carbon footprint of external suppliers.

The limitations of this work relate to assumptions about clay contents, heating and ventilation requirements and ore hardness variability. These were discussed, concluding that, independent of the magnitude of these factors, the potential benefits of HPGR in energy and carbon footprint became so apparent that such an option should not be discarded at early stages of design studies, especially when climate change issues are highly significant.

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