sustainability

MDPI

Review

A review of energy and environmental management practices in cast iron foundries to increase sustainability

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Supplementary material

Table S1. Management practices for all foundry process steps.

Theme	Type	Practice	References
Process integration	1	Intensify the use of energy and raw materials by optimising their use between more than one process or system.	[22,42,53]
Recycling	1	Consider the possibility of using the largest size container possible.	[26]
	1	Optimise raw material use and minimise their impact by selection.	[92]
	3	Treat solid residues for their external reuse.	[26]
	3	Apply a good segregation of various residue and waste types to allow reuse, recycling or disposal.	[26,61,92]
	3	Provide incentives to staff for maintaining good segregation practices.	[61]
	3	Reuse, recover and recycle products, materials, (solid) residues, (production) wastes, used containers, and all metal from returns, rejects, cutoffs, shakeouts, and slag.	[22,26,41,61,90,92,94, 96,103,104]
Management of flows	1	Optimise the management and control of (internal) material flows, also using simulation models, management and operational procedures.	[26,92]
Storage and handling	1	Clearly identify storage areas through appropriate signs.	[26]
	1	Develop storage systems to avoid double handing and allow direct discharge from trucks and easy unloading of skips, or other containers, by fork lift or overhead crane.	[74,92]
	1	Select, design, and construct storage areas considering site geological and hydrogeological conditions.	[61,96]
	1	Store, handle and transport (potentially) dusty materials and wastes so as to prevent or minimise dust and air emissions, and wind whipping (especially where the storage is open within a building). Store dusty materials in confined storage areas within buildings, appropriate (closed and/or covered) containers/packaging, purpose built silos, sealed bags, or under cover. Fit external above ground conveyors for dusty materials with protection against wind whipping.	[26,89,92,96]
	1	Cover transfer points and chemical storage areas, equip	[89,96]

		them with ventilation and collection systems, and design them to minimise spill risks. Duct transfer points to suitable arrestment equipment.	
	1	Collect waste from dry arrestment plant in a way that dust emissions are minimised.	[89]
	1	Store raw materials for melting under cover in clearly defined areas, or in storage bins.	[74,78]
	1	Store scrap metal on an impermeable surface with a drainage, collection, and treatment system. The application of a roof can reduce the need for such a system.	[26,92,96,105]
	1	Apply separate storage for various metal types or grades, according to composition and type for charging.	[26,92]
	1	Store binder in a roofed and ventilated, locked storage area, where spilled liquid is collected (consider additional precautions for highly flammable liquid storage).	[26]
	1	Store waste liquor from scrubbers in fully enclosed containers.	[89]
	1	Pave process and coal stockpile areas to segregate potentially contaminated stormwater for pretreatment and treatment in the waste water treatment unit.	[96]
	1	Design leachate collection system and location of coal storage facilities.	[96]
	2	Avoid outdoor or uncovered stockpiles. Where outdoor stockpiles are unavoidable, use sprays, binders, dust suppressants, stockpile management techniques, and windbreaks.	[26,92,96]
	2	Implement spill control plans and an adequate provision to contain liquid and solid spillage.	[89,96]
	2	Do not permit dry sweeping of dusty spillages in circumstances where it may result in the generation of airborne dust outside any building.	[89]
	2	Minimise scrap deliveries, and handling and transport activities at night.	[26,92,96]
	3	Use bulk or recyclable containers.	[26,92]
Planning and scheduling	2	Minimise unnecessary delays, problems, irregularities, startup and shutdown. Have adequate procedures in place for startup and (emergency) shutdown.	[26,41,53,89]
	2	Schedule on/off (start/stop) of equipment and adopt a day-to-day scheduling.	[48]
	2	Plan melting according to moulding capacity and adequately coordinate timing between melting and moulding shop, between production control and the melting and moulding departments.	[26,29,74,78,87]
	2	Reschedule plant operations, shave off power demand peaks, minimise peak load and phase shift (especially during melting), also through an automatic controller. Level the electricity demand and take advantage of reduced rates during certain times.	[21,30,41,47,53,55]
	2	Lower idling losses and idling energy demand during weekends and holidays.	[86]
Insulation	1	Adopt better insulation, use adequate surface insulation to limit heat dispersion, and utilise new insulating materials.	[22,28,40,63,96]

Tidiness and housekeeping	2	Carry out and schedule regular and good housekeeping, maintaining the workplace clean and free of clutter, especially during materials handling, also to keep small leaks and spills to a minimum.	[26,40-42,53,61,89,92, 94,96]
	2	Clean wheels and roads, fouled surfaces and pipes, flues and ductwork (to prevent material accumulation), external surfaces, open yards and storage areas (to prevent dusty material accumulation) and return belts in the conveyor belt systems (to remove loose dust).	[26,40,42,53,61,89,92, 96]
Maintenance	2	Establish a structured maintenance programme to perform regular and preventive maintenance and routine programmed inspections on all plants and equipment. Keep maintenance schedule, inspection logs, and up-to-date record of all activities, also using computer packages, preventative maintenance software, and/or simulation tools.	[26,40-42,50,52,53,61, 87,89,92,94,96]
	2	Clearly allocate responsibility for the planning and execution of maintenance, and ensure that regular inspections are performed by responsible and delegated staff. Provide a written maintenance programme to operators.	[26,41,42,61,89,92]
	2	Switch off equipment when not in use or not needed.	[40-42,53]
	2	Ensure that spares and consumables are held on site, or available at short notice from guaranteed local suppliers, so that plant breakdowns can be rectified rapidly.	[89]
	2	Document and analyse abnormal operating conditions to identify the root causes and then address these to ensure that events do not recur.	[42,53]
	2	Identify and report leaks, broken equipment, fractured pipes, worn bearings, and rectify them at the earliest opportunity.	[40,42,53]
Noise mitigation	1	Develop and implement a noise reduction strategy/plan.	[26,92]
	1	Close off holes and openings, use noise reducing flaps on all outside doors.	[26,92]
	1	Blow air actively into the foundry hall to cause a small increase in the indoor pressure.	[26]
	1	Improve sound insulation of buildings and use enclosure systems for high-noise unit operations.	[26,92]
	2	Keep all doors shut (especially during the night).	[26,92]
Waste water management	1	Adequately treat each waste water flow.	[26,92,96]
	1	Separate waste water types on site according to their composition and pollutant load.	[26,90,92]
	1	Bund and drain to sumps areas where spillage is most likely to occur.	[90]
	1	Collect surface water run-off.	[26,92]
	1	Remove suspended solids contained in run-off from open and raw material stocking areas prior to disposal to any off-site storm water system.	[90]
	2	Control possible sources of fugitive emissions to water.	[26,92]
	2	Regularly check and document the integrity of storage tanks and bunds.	[90]
	3	Use waste heat for the evaporation of waste water, when waste heat is available on a continuous basis.	[26]

Equipment layout	1	Improve equipment layout, considering unnecessary movement of materials into and out of the process areas, time-consuming and wasteful processes (e.g. over-fettling), unnecessary space for inventory of consumables and work in progress, shortcomings, redundancy, duplication of effort and waste.	[41,61]
	1	Consider input from knowledgeable operators and staff for defining a well layout of process equipment.	[41]
	1	Minimise distance among each equipment to reduce wiring losses.	[105]
Yield	1	Redesign process examining process flowchart, using process simulation software, and conducting process simulations, visits to other sites, benchmarking, identifying key process problems and brainstorming solutions.	[26,41,55,61,69,92]
	2	Reduce scrap applying process controls and correct operation practices.	[26,41,46,47,63,85,86]
	2	Maintain good inspection processes for removing reject product from the process as soon as possible, record every incident of scrap and analyse it to identify the problem.	[61]
Air emission management	1	Prevent, minimise, capture, collect, and abate fume, flue-gas, exhaust air, and the emissions of VOCs, dust, dioxins, lead, zinc, cadmium before their release. Pay attention to VOC capture during moulding, casting and pouring.	[26,89,90,92,96]
	1	Design hood and duct, apply furnace enclosures, apply roofline collection (to apply as a last resort) for minimising fugitive emissions.	[26,92]
	1	Prevent and minimise emissions as close as possible to the source.	[26,92]
	1	Disperse and dilute sufficiently in the atmosphere pollutants (e.g. apply a cone to achieve greater dispersion) that are emitted via a stack to ensure that they ground at concentrations that are deemed harmless.	[89]
	1	Select the appropriate technique for cleaning collected off-gases considering the composition, flow and conditions of the off-gas stream.	[26,92]
	1	Do not use a cap or other restriction at the stack exit.	[89]
	1	Apply an adequate insulation of stacks, vents, and process exhausts.	[89]
	1	Combine emissions into the minimum practicable number of chimneys.	[26,89,92]
	1	Perform exhaust capture and treatment for reducing amine and related odour emissions. Minimise amine emissions, and recover amine (especially from the exhausted solution abatement of chemical plants, from cold-box exhaust scrubbing liquor, and/or from scrubbing water).	[26]
	2	Verify that all emissions to air should be free from droplets.	[89]
	2	Examine the dust collection/exhaust system to understand if it was originally designed to handle larger volumes of air than necessary at present. Consider if some of the fans could be taken off-line.	[41]
	2	Tie the dust collectors to the activity: have them on only during the dust generation period and throttle them down	[41,55,74]

		during idle periods.	
	2	Maintain the differential pressure for dust collector.	[55]
	2	Use minimum effective pressure for cleaning dust collectors.	[55]
	2	Investigate and undertake remedial action immediately to problems which may have an adverse effect on emissions to air. Adjust the process or activity to minimise those emissions, and promptly record the events and actions taken.	[89]
	2	Verify that all emissions are free from offensive odour outside the site boundary, and take into account the need to render harmless residual offensive odour in the assessment of stack or vent height.	[89]
	3	Return dust collector exhaust air to buildings to reduce the need for heated make-up air.	[46]
Control of processes	2	Have systems in place to ensure that procedures are known, understood and complied with.	[42,53]
	2	Implement controlling and monitoring systems to control processes adequately under all modes of operation (preparation, start-up, routine operation, shutdown and abnormal conditions).	[42,53]
Heat recovery	3	Evaluate the possibility of waste heat recovery and recuperation (e.g. waste heat from flue gases and hot exhausts, furnace cooling system, gases from melting and heat treatment furnaces, heat losses of heat treatment furnaces, die casting machines, moulds or cores production, metal solidification, hot sprue boxes, hot raw castings after shake out, sand cooling, and air leaving dust collectors).	[12,22,26,28-31,40,41, 46,47,52,53,55,59,63,6 9,74,92,106-108]
	3	Use the waste heat to preheat combustion air, ventilation air, process gases; to heat the foundry buildings, industrial process, shower water or hot tap water, service and process water; to dry raw and input materials, scrap metal and parts, cores following smoothing; to generate electricity and cooling energy; to deliver it to the local district heating system; to produce steam, hot water and air; to drive air-conditioning units; to store heat.	[26,28-31,40-42,46,52, 53,55,63,69,74,86,96]
Decommissioning	1	Update the site closure plan (including the removal or the flushing out of pipelines and vessels, plans of all underground pipes and vessels, the removal of asbestos or other potentially harmful materials, testing of the soil and the need for any remediation) as material changes occur, but even at an early stage.	[26]

Table S2. Management practices specific for each foundry process step.

Process step	Theme	Type	Practice	References
Melting	**Equipment layout**	1	Choose the furnace position so that the molten metal can be transferred at a specific point (e.g. analysis test place, pouring location) and with minimum distance between each equipment.	[12,13,46,55,59,105]
		1	Locate day storage facilities adjacent to the furnace plant and, where small furnace and manual charging systems are involved, on the platform itself.	[74]
		1	Optimise the travel of the charging bucket and the ladle as the shortest, quickest way.	[41,78]
		1	Supply equipment with a large power usage from a high voltage supply as close as possible.	[42]
		3	Relocate combustion air intake to recover heat from other processes.	[41]
	Maintenance	1	Have a spare furnace lid in good repair ready for quick exchange when required.	[41]
		2	Maintain refractories and furnace insulation in optimal condition, according to manufacturer recommendations, performing infrared inspections to determine electrical and refractory problems prior to failures, carrying out repairs and maintenance of refractories during the annual facility maintenance shutdown.	[3,30,41,50,52,55,63,69,78,87,96,105]
		2	Inspect and maintain in good condition the furnace cover and seal cover gaps, repairing diligently even a small opening.	[41,50,105,109]
		2	Implement burner preventive maintenance program on make-up air units.	[46]
		2	Equip and properly maintain teapot inlet and pouring spouts.	[109]
		2	Monitor and document lining performance, refractory practices, and reasons for failures. Regularly assess refractory wear, applying visual inspection, physical measurement and instrumental monitoring programmes (e.g. furnace and inductor case temperatures, power consumption and electrical characteristics, cooling water circuit temperatures).	[26,30,41,42,61,74,78,92,109]
	Planning and scheduling	2	Reduce holding times in melting furnace to a minimum and the necessary overheating of the metal to compensate for delays in casting for achieving the optimal timing of liquid metal delivery and in casting the mould.	[12,26-29,53,61,63,74,75,78,92,105]
		2	Optimise scheduling and arrange melting programmes for induction furnace to adopt a continuous melting without any cooling-down periods in between, increase the furnace utilisation rate, reduce cold start melts, and	[11,12,26,30,41,52,58,59,63,74,75,107]

		minimise melting delays.	
	2	Reduce the amount of metal that must be melted properly estimating the weight of metal cast by lessening defective casting ratio and decreasing the amount of remaining melt in ladle and furnace.	[61,83,86,105]
	2	Consider ladle travelling distance for keeping the tapping temperature lower.	[105]
	2	Balance the demand for, and the supply of, molten iron.	[74]
	2	Reduce analysis time, cut down the idling time, perform quickly preliminary furnace test and temperature measurement, eliminate the waiting time for crane, and decrease the furnace repairing time.	[13,105]
	2	Schedule production so that each furnace operates near maximum output.	[41]
	2	Synchronise the operation and make quick transfers between the preheater and the furnace.	[41]
Heat recovery	3	At the end of the day, place metals into the hot furnace and close the lid to allow them to absorb sensible heat during the night.	[74]
Tidiness and housekeeping	2	Keep recuperator surfaces clean.	[41]
	2	Clean the furnace daily to reduce the accumulation of oxides in the furnace.	[55]
Insulation	1	Reduce heat losses from furnace openings: ensure that furnace lids are well-insulated and fit well, maintain a good tight fit between the cover and the furnace body, guarantee a good seal of furnaces and on the doors and spout covers when furnace is closed, and seal off other possible air access paths around melting furnace lids and slagging doors.	[12,13,26-30,41,50,55,59,63,69,74,78,83,108]
	1	Apply water cooling of the furnace wall for avoiding the usage of refractory lining.	[26]
	1	Add thermal insulation to those system parts that are not insulated or that have insufficient insulation.	[30,41,50,52,55,63]
	1	Choose (considering operating temperature, charge type, slag, furnace and ladle design, melting practices) and use adequately high-quality and correctly installed refractory lining and select suitable lining materials. Evaluate the possibility to use ceramic, also in sandwich fashion with other refractory materials, or cured refractories.	[12,26,28-30,41,46,50,52,55,61,63,78,109]
	2	Minimise the access to the melting furnace (through the spouts and skimming doors), the number of times the lid is off during the melt and the duration of the uncovered periods (e.g. open the lid only for charging and tapping the melt,	[26,28-30,39,41,42,46,50,52,63,69,74,92,105,108,109]

		take samples through a hole made in the cover or drill a sampling port through the furnace lid, when sampling the molten metal or measuring its temperature; otherwise, sample the molten metal at pouring, if the metallurgy allows it).	
	2	Keep a slag on the molten metal, reducing radiation losses from the top surface.	[12,27]
Procedures and training	2	Train personnel and make necessary preparation so as to charge materials and adjusting agents regulator as quick as possible.	[74,105]
	2	Optimise the sampling, testing and adjusting procedures.	[26]
	2	Maintain records to determine any trends in operating performance.	[28,29,46,109]
Power management	1	Use medium frequency power and upgrade low frequency systems to medium frequency.	[26,28,29,55,58,74,92,96,105,108]
	1	Check harmonics levels at furnaces and compensate with installation of active monitoring and conditioning component such as filters and capacitors.	[12,42,87]
	1	Consider specific starter-blocks for cold start-up for mains frequency units.	[26,74,105]
	1	Oversize cables to equipment.	[42]
	1	Reduce the length of flexible power leads and configure them in a 'diamond' type configuration.	[69]
	2	Melt with residual molten metal in case of low-frequency furnace.	[105]
	2	Re-charge medium frequency furnaces and apply power immediately following tapping.	[74]
	2	Maintain the furnace full during melting (to draw maximum power) and minimise the tapping time.	[74]
	2	Supply the full power for maximum time during melting.	[12,13,26-29,55,63,74,78,87,92,105]
	2	Reduce the power in the furnace using potentiometer settings as soon as no solid scrap remains in the bath or just before this.	[27]
	2	Operate mains frequency units with a molten heel of up to 2/3 of the crucible capacity.	[26,63,74,105]
	2	Switch to low-firing mode when furnace door is open.	[55]
	2	Consider off-peak melting, and shift the melting process to periods when the power demand is low.	[63,74,86]
	2	Periodically check the power factor, test (and eventually replace) capacitors (especially if the furnace is an old installation) used to correct the power factor. Correct (at its most effective when physically near to the load) and increase	[42,46,63,74]

		(according to local electricity distributor requirements) the power factor, seeking expert advice if it falls below 0.9.	
Melting temperature	2	Control and monitor the furnace temperature, the metal, and the molten metal to avoid unnecessary metal superheating and excessive temperature, and maintain minimum tapping, metal melting, and molten metal temperatures that ensure quality castings.	[12,26,28,29,41,46,55,69,74,78,92,96,105,109]
	2	Optimise high temperature melts for slag removal, founding a good balance between increasing the melt temperature and the slag removal practice.	[26,92]
	2	Do not superheat the large volume of molten metal in the main melting furnace if the pouring is done in batches. Instead, superheat, if necessary, in a smaller holding furnace just before pouring.	[41]
	2	Use oxygen enrichment to temporarily increase the heating rate when there is a need to increase productivity. This helps to reduce the amount of unburnt fuel, thereby increasing energy efficiency while reducing NO_x emissions.	[12,41,42,55,96]
Air-fuel ratio	1	Correct the air-fuel ratio to increase the furnace efficiency and reduce nitrogen oxides.	[42,55,96]
Air emission management	1	Capture the furnace off-gas and maximise the off-gas collection during the full working cycle.	[26,92,96,108]
	1	Design pollution control equipment to be able to handle the peak effluent condition, even though the peak may only persist for a relatively short period.	[26]
	2	Change or regenerate (clean) the filter media much quicker than when using clean scrap.	[26,92]
Monitoring	1	Adopt additional monitoring of the furnace flange temperature.	[28,29,41,109]
	2	Record and maintain adequately data about the measurement of the electrical characteristics of the furnace, water-cooling circuit temperatures, body and inductor shell temperatures.	[28,29,41,109]
Feedstock	1	Use cleaner carburisers.	[26,28,29,92]
	2	Carefully select and sort feedstocks and scrap, screening and sorting scrap from electronic products, painted scrap, and scrap from used vehicles. Choose scrap with low sulfur content, analyse AOX compounds prior to scrap purchase, and replace feed materials that are persistent organic pollutants or where there is a direct link between materials and releases of persistent organic pollutants from the source. Periodically review all raw materials to assess their potential impact and compare with alternatives available.	[26,61,92,94,96]
	2	Calculate exactly the required batch composition based on the analytical values of the feedstock and	[53,78,87]

		the accurate weighing and metering in the use of materials and alloy surcharges.	
	2	Avoid introduction of wet or damp metal in melt, using dry scrap. Preheat the charge/scrap/ingot/raw materials/metal loading or dry raw materials prior to use (also store feed materials dry at all times).	[12,22,26,27,30,41,50,53,55,58,74,78,96,105,107]
	2	Operate the furnace in batch mode (where any humidity is removed in the start-up process).	[55]
	2	Use compact scrap and charge raw material as dense as possible.	[12,26-29,52,55,74,92,105]
	2	Clean foundry returns and remove sand from the return material.	[26,46]
	2	Decrease diameter or thickness of material to be melted in the furnace according as the frequency becomes higher.	[105]
	2	Use and melt clean and uncontaminated scrap. Remove rust, dirt, sand and/or oil/grease. Avoid the introduction of mineral and oxide materials.	[26,28,29,69,74,78,92,105,107,109]
Slag	2	Avoid slag erosion and prevent slag build up.	[26,74,78,92,109]
	2	Prevent slag carry-over when molten iron is poured into channel holding furnaces.	[109]
	2	Remove slag regularly for minimising the radiation loss.	[87]
Charging	2	Adopt a rapid and continuous charging of the feed, topping up frequently as the charge sinks down, estimating number and capacity of storage bins (also to compensate for any period when overhead cranes are unavailable), using gated feeders or drop bottom charging buckets, and/or utilise automatic charging systems.	[26,27,30,53,74]
	2	Add charge to the level of the top of the power coil, not beyond.	[41,74,78]
	2	Avoid the free fall of materials, and minimise charging and drop height for scrap deliveries.	[26,74,92]
	2	Maintain a liquid heel (minimum amount of molten metal) inside the induction furnaces.	[12,26,55]
	2	Estimate each charge as about 10 % of crucible volume.	[78,105]
	2	Charge additional cold material successively into the furnace when the first charge starts melting.	[105]
	2	Hold channel furnaces between half and three-quarters full during long holding periods.	[109]
	2	Avoid bridging of the charges in the furnace.	[74]
	2	Consider as the maximum size of single piece of metal/scrap not more than one third of diameter of furnace crucible.	[78]
	2	Add other selected charge materials for melting 'difficult' charges (e.g. if a layer of dry solid material is charged first to provide a surface on	[74]

			which the less suitable scrap can lie and be pre-heated).	
		2	Limit the use of baled steel scrap and loose borings (machining chips).	[78]
		2	Do not use materials with sharp edges, particularly in case of heavy and bulky scrap.	[78]
		2	Charge machining chips or other fine materials into molten metal built up previously in the furnace, making use of agitation effect of molten metal.	[105]
		2	Adjust the dosage of the carburising agent together with the charge.	[53,55]
		2	Take care that the carbon content of the melt does increase unnecessarily.	[53]
		2	Follow proper charge sequence: bigger size metal first followed by smaller size and gaps must be filled by turnings and boring.	[78]
		2	Minimise melting losses by minimising contamination in the charge, charging accurately make-up and weight, optimising stirring practices.	[61]
Moulding	**Lubricants, solvents and coatings**	1	Use water-borne die lubricants and low-solvent mould and core coatings.	[89]
		1	Use water-based coatings (replacing alcohol-based ones) for the refractory coating of moulds and cores in foundries producing medium and large series. Use alcohol-based coatings for big or complex moulds and cores, and for water glass bonded sands. Use water- or alcohol-based coatings in small scale and large-scale jobbing foundries.	[26,92,96]
		1	Use water-based coatings and inorganic solvents. Use non-aromatic or alternative (based on protein or animal fat or on silicate esters) solvents for cold-box core production. Use either aromatic-based or vegetable-based solvents, for amine-hardened urethane-bonded core preparation. Use both aromatic and non-aromatic solvents in lost moulding casting.	[26,96]
		1	Provide evacuation at the coating stand when alcohol-based coatings are used.	[26]
	Binder use	1	Prevent or minimise emissions by careful selection of sand binding agents.	[90]
		1	Use inorganic binder materials (e.g. sodium silicate).	[26,55,92,110]
		2	Minimise the loss of mixed, un-cast sand.	[61]
		2	Mix only the quantity of sand that is needed.	[61]
		2	Increase operator awareness about the need to minimise sand loss.	[61]
		2	Set optimum binder levels, keeping records of the level of necessary binder addition, and monitor binder levels in reclaimed sand for adding less new binder.	[61,89]

	2	Ensure reclaimed sand has cooled prior to reuse to minimise binder burn-off during mixing.	[61]
	2	Carefully calibrate and maintain mixing equipment to achieve consistent binder levels.	[61]
	2	Maintain good inventory practices to avoid stock going out of date and stock damage or spillage.	[61]
	2	Evaluate the substitution of binders or binder solvents, monitor the development of new binders and trial them on an ongoing basis.	[26,61];
	2	Minimise the use of mixed sand by improving the sand metal ratio.	[61]
	2	Minimise binder consumption, use, additions and emissions, optimising process controls and material handling in mixer operations, controlling temperature, and applying exhaust capture measures.	[26,89,92,96]
	2	Consider sand consistency (use of a sand quality consistent with the binder system), temperature control (maintain the sand temperature in a narrow range, with regular checks and adjustment of the amount of hardener addition), mixer maintenance and cleaning, mould quality, addition rates, and mixer operation as key parameters related to good binder management.	
Sand management	1	Do green sand preparation in atmospheric mixers, or vacuum mixers with a sand capacity higher than 60 t/h.	[26]
	1	Control and optimise sand mixing (system) to improve the amount of binders and catalysts, and increase the predictability of mould and core quality and set times.	[41,61,87]
	1	Store all new or reclaimed dry sand stored outside in purpose built silos, sealed bags, or closed containers.	[89]
	1	Establish a separate collection system for resin-containing sands that are wasted before firing, to avoid high levels of binders contaminating the main sand stream.	[61]
	2	Verify that sand used is free from excessive fines.	[92]
	2	Monitor the regenerated sand quality and composition.	[26]
	2	Minimise spillage as much as possible, also preventing spillage of shell sand.	[41,61]
	2	Power-up and power-down the sand system equipment in production sequence, not all at once, when parts of it are not yet (or no longer) needed.	[41]
	2	Use new sand for the sand/metal interface only and backfill with non-reclaimed, non-mixed sand.	[61]
	3	Consider external reuse of sand waste and options for the recycling of used foundry sand for external applications (e.g. construction industry, building materials industry, and landfill construction).	[26,63,90,92,96,102,103]

	3	Reuse or recycle the captured dust into sand preparation and circuit, and/or consider its external reuse if the local market allows. Recover metal through reprocessing of the dust from abatement equipment.	[26,92,96]
	3	Minimise the sand disposal expense and the amount of sand going to disposal, by adopting a strategy of regeneration and/or reuse of chemically-bonded sand.	[26,41,90,92,96,103]
Cores	1	Substitute potentially increased machining for core-produced cavities.	[103]
	1	Harden and break uncured cold-box and cold setting core sand in a specific unit.	[26]
	1	Investigate whether turning off core-making machines using gas or power at the end of the shift is more economical than reheating of the core boxes, and enforce the implementation of the correct approach (or use timers or programmable controls).	[41]
	1	Investigate whether insertion of removable, reusable steel cores would be possible.	[41]
	1	Convert shell sand to cold box core-making.	[46]
	1	Apply amine-hardened urethane-bonded (cold-box) core production.	[92]
	2	Maintain and calibrate the monitoring and controlling equipment on the core-making machinery and supply streams, and on core drying/baking ovens.	[41]
	2	Control and analyse core defects/rejects, preparing a Pareto Chart and/or a history card, classifying high rejection few and trivial many and/or studying individual item and reason.	[41,59]
Flasks	2	Use a range of flask sizes so that each casting is done in the most appropriate flask.	[61]
	2	Insert blocks or other material to fill voids in the flask.	[61]
Ovens	1	Consider installing automatic programmable controls for the oven and for the control of the fuel consumption by the burners.	[41]
	1	Install moisture sensors on water-based wash drying ovens.	[41]
Air emission management	1	Contain, extract, capture, monitor, arrest and vent all emissions from mould and core production and sand reclamation processes to suitable arrestment plant.	[26,89,92,96]
	1	Capture, collect, and treat dust from the green sand moulding area, the vibrating screen, dedusting and cooling process stages.	[26,90,96]
Design	1	Reduce the riser weight by using riser insulation.	[41]
	2	Optimise the layout of patterns in the mould, fit a smaller pattern into the existing moulds, and check the risers' cooling rate with immersion	[41]

			thermocouples and record the temperatures to establish whether the rate of riser and patterns solidification is optimal.	
	Tidiness and housekeeping	2	Vacuum clean the moulding shop in sand moulding foundries, excluding areas where the sand has a technical or safety-related function and hand-moulding jobbing foundries.	[26,92,96]
Casting	**Design**	1	Use insulated exothermic feeders.	[53,55]
		2	Minimise the casting weight thanks to careful design of castings and gating systems.	[41,61]
		2	Minimise grinding losses, improving the casting process for reducing the need to fettle, or combining some fettling processes into the machining stage.	[61]
		2	Improve cast design by adding more units to each box.	[61]
		2	Use casting process simulation to achieve optimal use of filters, and optimisation of gating systems, of casting method and of casting removal times, and of feeder size and position.	[26,30,55,59,61,69]
	Air emission management	1	Contain, capture, extract, monitor, arrest and vent emissions from casting and cooling processes to suitable arrestment plant to meet the limits. Otherwise, in jobbing foundries, disperse and dilute as necessary to comply with visual/odour requirements.	[26,89,90,92]
		1	Fit extractor ventilators or extractor surfaces as close to the moulds as possible, without hindering the pouring process.	[26,92]
	Sand management	1	Keep sand from the core sand knock-out area separate from the other sand streams.	[61]
	Ladles	1	Improve ladle insulation and refractory materials. Use new fibre lining materials with low density, low thermal conductivity and non-wetting characteristics.	[12,28,50,55,63,69]
		1	Optimise the ladle size and adopt ladles as large as is practicable to minimise the need to transfer metal from one ladle to another and convey the metal as quickly as possible.	[26,53,78]
		1	Optimise the iron transport, the casting line, the arrangement of fusion and casting line to another and the daily operating time of the ladles for reducing the number and/or size of the ladles.	[53]
		1	Apply metal filtering to remove dross, slag and other impurities from the melt.	[61]
		2	Use clean ladles.	[26]
		2	Utilise heat-retaining covers for ladles or provide an insulated lid (e.g. lightweight ceramic-fibre, glass-wool or ceramic-wool). Alternatively to the cover, put ladles upside down when not in use.	[26,28,30,41,53,55,61,69,78,87,105]
		2	Use preheated ladle before the filling.	[12,28,52,53

				,87,92,105]
		2	Invert pouring ladles 90° or 180° prior to heating.	[46]
		2	Place an insulating blanket on top of the ladle when preheating it.	[41]
		2	Use ladles immediately after preheating.	[53]
		2	Have the ladle ready ahead of the tap time.	[41]
Finishing	**Air emission management**	1	Reduce diffuse emissions of oil-mists, when quenching baths are performed.	[26]
		1	Contain emissions, and collect dust, exhaust and off-gases during blasting, cutting, abrasive cutting, chiselling and needling, grinding, and welding. Arrest dust, and treat exhaust and off-gases.	[26,89,92]
		1	Undertake finishing processes in booths or areas with extraction of emissions or using equipment incorporating built in extraction equipment.	[89,92]
	Heat treatment furnace	1	Consult with the furnace manufacturer on the best operating conditions.	[41]
		1	Use ceramic fibre and stainless-steel mesh in a channel arrangement, for a flexible seal, for improving the door seal.	[41,63]
		1	Change the method of conveying product through the treating oven to facilitate rapid heat transfer to the product.	[41]
		1	Add insulation to the outer surface of the furnace.	[41,63]
		1	Use clean fuels (i.e. natural gas or low-level sulphur content fuel).	[26]
		1	Top hat heat treatment furnace.	[52]
		2	Prevent cold air ingress for maintaining the desired furnace atmosphere and improving temperature uniformity.	[41]
		2	Check the oxygen content in the furnace/oven and flue gases regularly.	[41]
		2	Maintain the calibration of monitoring and control instruments.	[41,63]
		2	Keep the insulation and seals around the furnace door in good repair.	[41,63]
		2	Set furnace pressure slightly higher than the normal atmospheric pressure; and maintain a positive furnace pressure.	[41]
		3	Preheat the combustion air, using any of the convenient waste heat sources in the foundry.	[41,63]
	Noise mitigation	1	Select less noisy engineering equipment.	[92]
		1	Use acoustic screens, enclosures and barriers to conceal noise sources.	[92]
		1	Fit silencers to avoid noise travelling along ducting.	[92]

Table S3. Management practices for utilities and services management.

Theme	Type	Practice	References

General	1	Optimise equipment size to ensure high capacity utilisation.	[22,42,55,111]
	1	Select energy-efficient and less noisy equipment to replace non-efficient equipment.	[21,48,55,62,78,92,110]
	2	Avoid idle running of equipment and switch it off when not in use. Run a 'switch-off' campaign to raise staff awareness about the need to turn off equipment; develop procedures and shutdown checklists to ensure that equipment shutdowns are taking place.	[21,48,55,61,62]
	2	Monitor voltages and minimise imbalances to increase motor efficiency.	[48,55,63]
	2	Foster regular equipment maintenance to avoid sub-optimal performance, included hand tools (particularly ones driven by compressed air).	[13,41,42,48,55,61,62,74,78,89,96]
Compressed air	1	In the design stage, limit pneumatical sand transportation, preferring elevators and belt conveyers.	[52]
	1	Avoid the use of compressed air and prefer alternative methods to supply low-pressure end-uses.	[53]
	1	Use air receivers large enough to meet peak demands so that compressor capacity will not need to be oversized.	[40-42,63]
	1	Prefer low vibration and low noise level air compressors.	[78]
	1	Stop the airflow to equipment no longer used as far back in the distribution system as possible.	[42]
	1	Ensure dust-free and dry air intake.	[29,50,63]
	1	Install compressor air intakes in coolest locations.	[13,21,30,41,42,50,55,63]
	1	In the design stage choose a pressure which satisfies 95 % of all needs and uses a small pressure-increasing device for the rest.	[42]
	1	Minimise the pressure drop in the distribution line (e.g. due to inadequate pipe size, choked filter elements, any obstruction, restriction or roughness in the system). The use of welded pipework may reduce frictional losses.	[29,42,55,111]
	1	Ensure that air mains slope toward drains to guarantee removal of condensed moisture.	[63]
	1	Reduce the distance the air travels through the distribution system.	[42]
	1	Recalculate the pipe diameters if there are new air demands.	[42]
	1	Store compressed air near high-fluctuating uses.	[40,42]
	2	Proactively detect and repair leaks in compressed air lines.	[21,22,30,41,42,46,50,52,53,55,63,83,86,87,110-112]
	2	Regulate compressed air pressure to the minimum required.	[21,29,30,41,42,46,50,78,111,112]
	2	Require users to justify the compressed air usage and make them accountable for that.	[41]

	2	Operate compressors with full load to the extent possible.	[29,55]
	2	Use software tools to assess energy savings possibilities in the compressed air system.	[63]
	3	Recover heat from the compressor cooling air and oil.	[29,42,46, 52,53,55,112]
Lighting	1	Position the fixture to minimise light loss from dust accumulation and so that there are no obstructions to lighting.	[41]
	1	Choose energy-efficient lighting with better ballasts, high-efficiency bulbs, and occupancy sensors.	[21,29,30,42,46,52 ,53,55,61,62, 110,111]
	1	Use simulation tools to choose which lighting system will suit best the required application by analysing the lighting distribution and glare index.	[78]
	1	Prefer localised switching in large spaces to make it possible to turn off artificial lighting in specific areas, while still operating it in other areas where it is required.	[78]
	1	Reduce lighting system voltage by separating the lighting load from other plant load to increase the operating power factor as well as the life of luminaries (lower failure rates).	[55,78]
	1	Where the environment permits, paint walls and ceilings with lighter colours and use the light reflection to improve the brightness of the workplace.	[41]
	1	Choose lighting system with larger space to height ratio to reduce the number of fittings and connected lighting load.	[78]
	1	Define lights layout at distance from corners of room.	[78]
	1	Provide adequate task-focused rather than general space lighting.	[41,42]
	2	Turn off the light during process shutdown and in unoccupied areas.	[40,46,55]
	2	Maximise usage of daylights in daytime (e.g. planning activities to optimise the use of natural light).	[41,42,55,78]
	2	Assign responsibility for turning off lights at the end of the production day, and turning them on prior to the start of shift in each department and in general areas.	[41]
	2	Reduce or switch off unnecessary outside floodlights and signs.	[41]
	2	Reduce parking lot lighting when lot is not in use.	[41]
	2	Establish a regular cleaning schedule to keep light-reflecting surfaces and lenses clean, particularly in dusty environments.	[40,41,53,61,78]
	2	Regularly clean and repaint interiors.	[78]
	2	Implement a regular re-lamping program.	[41,78]
	2	Train building occupants to utilise lighting equipment in the most efficient manner.	[41,42]
Heating, Ventilation,	1	Prefer displacement ventilation with respect to mixing ventilation to minimise air flow.	[52]

and Air Conditioning	1	Employ an energy-efficient system design and properly sized equipment.	[55]
	1	Use ventilation fans to reduce the load on heating systems and for better air circulation.	[40,53,55]
	1	Use reflective roofing, 'green' roofing or shading/windbreaks to increase energy efficiency.	[55]
	1	Minimise heat to storage areas.	[46]
	1	Install removable insulation.	[46]
	1	Equip conveyor openings, doors and other openings with plastics strips or air curtains to prevent heat loss.	[41,53]
	1	Cut small openings into large doors to allow the passage of forklift trucks and workers.	[41,53]
	1	Equip doorway with an air box or wind chamber.	[41,53]
	1	Optimise the number, shape and size of the pollutant intakes to reduce the airflow necessary for removing pollutants.	[42]
	1	Allow ventilation rate in every room to be adjusted independently according to the wishes of the occupants.	[40]
	1	Install strategically located hoods over dusty/hot areas. Make sure that they have ample dimensions so that the heat or dust does not escape into the general space.	[41]
	1	Choose improved sealed units for north-facing and highly exposed windows.	[41]
	1	Shade windows or put curtains inside or shutters outside to keep out summer heat and winter chill.	[41]
	1	Eliminate unnecessary windows and glass walls.	[41]
	1	Interlock make-up heaters to infrared heaters so they cannot run simultaneously.	[46]
	1	Use thermal insulation for ductwork and piping.	[110]
	1	Enclose fans, insulate ventilation pipes and use dampers to reduce noise.	[26,96]
	2	Train building occupants to close windows, doors and receiving/shipping bay doors in cold weather, and report high ambient temperatures rather than opening windows.	[41]
	2	When the external ambient air enthalpy is less than the indoor air enthalpy, adopt free cooling techniques making use of ambient air.	[42]
	2	Assign responsibility to turn off the fans and close the vents at the end of the production day or the week.	[41]
	2	Keep the motors on forklift trucks and other foundry vehicles well tuned, to reduce the excessive release of CO into the foundry atmosphere, which increases ventilation demand.	[41]
	2	Regularly clean filters and charge refrigerant.	[41,42,46]
	2	Keep doors closed and decrease the opening time of doors.	[41,42,53]
	2	Monitor, control, and track energy consumption to optimise consumption and help identify system problems.	[52,55]

	2	Adjust temperatures during periods of non-use.	[41,42,46,55]
	2	Improve building tightness by checking doors, roof and other openings, replacing worn out seals and restraining cracks and chinks shall.	[40,41,42,52,53,55]
	2	Delay the start of foundry ventilation at the beginning of operation until the heat of melting, pouring, shakeout, etc., has warmed the air inside.	[41]
	2	Maintain the integrity of water-impervious roof membranes through regular inspection and maintenance.	[41]
	2	Repair leaks in ventilation system.	[41,42,46,55]
	2	Implement a regular maintenance program for the pump system.	[55,78]
	3	Recover heat from local/general ventilation exhaust air.	[40,41,42,52,55]
Pumps	1	Minimise pump demand through holding tanks and elimination of bypass loops.	[42,55,78]
	1	Replace oversized pumps with properly sized ones.	[42,55]
	1	Use multiple pumps for variable loads.	[42,55]
	1	Trim impellers: reducing an impeller's diameter reduces energy added to the pump system.	[55]
	1	Avoid throttling valves and adopt more energy-efficient flow management strategies.	[42,55,78]
	1	Replace belt drives with cog belts.	[55]
	1	Properly size piping (e.g. increasing pipe diameters as part of a system retrofit reduces pumping energy).	[55,78]
	1	Use precision casting, surface coatings, or polishing to reduce pump surface roughness and increase energy efficiency.	[55]
	1	Reduce leakage through clearance reduction.	[55,78]
	1	Balance system flows and reduce pump power requirements.	[42,78]
	1	Avoid pumping head with a free return (gravity).	[78]
	1	Use siphon effect to advantage.	[78]
	1	Optimise number of stages in multi-stage pump in case of head margins.	[78]
	1	Avoid the use of too many valves and bends (especially tight bends) in the piping system.	[42]
	1	Apply coatings to the pump to reduce friction losses.	[42]
	1	Fit silencers to avoid noise travelling along ducting.	[92]
	2	Maintain proper seals to decrease seal losses.	[55]
	2	Monitor the pump system to detect problems and determine solutions to increase the system efficiency.	[42,55,78]
	2	Shut down unnecessary pumps.	[42]
Steam systems	1	Improve boiler and pipes insulation.	[42,46,104]
	1	Design and install steam distribution pipework in an energy efficient way.	[42]
	1	Size valves as large as possible.	[42]
	1	Install flue-gas isolation dampers (only to systems where there are two or more boilers with a common chimney).	[42]

	1	Isolate steam from unused lines.	[42]
	2	Minimise boiler short cycling losses.	[42]
	2	Prevent and remove scale deposits on heat transfer surfaces.	[42]
	2	Minimise boiler blowdown by improving water treatment.	[42,46]
	2	Improve and maintain steam traps of distribution systems.	[42,46,104]
	2	Repair leaks of distribution systems.	[104]
	2	Improve operating procedures and boiler controls.	[42]
	2	Improve boiler maintenance.	[42,104]
	3	Recover heat from boiler flue gas and blowdown.	[42,104]
	3	Recover steam from boiler blowdown.	[46,104]
	3	Recover flash steam of distribution systems.	[42,46,104]
	3	Increase condensate return of distribution systems for reuse.	[42,46,104]
	3	Preheat feed-water using waste heat.	[42]
Fuel	1	Co-fire with, or switch to waste and biomass.	[22,104]
	1	Switch to less carbon intensive fuels (e.g. replacing coal with natural gas).	[22,26,42,47,96,104]
	1	Use fuel with low sulphur content (e.g. natural gas) to reduce SO_2 emissions.	[26,96,113]
	3	Use warm water from furnace and sand coolers to heat supply air and domestic water. If needed, make use of a storage tank.	[40,53]
Chillers and cooling systems	1	Insulate pipes and vessels.	[46]
	1	Use a free cooling system. Using a water spray system on the fluid cooler it would be possible to use free cooling partially even when outdoor air is warmer than the return water.	[40,46,53]
	1	Piping installations in the chiller accumulator should be taking care of high temperature stratification; chilled water should be supplied to the tank with a wide cone or diffuser and return water through a cone to the upper part of the tank.	[40,53]
	2	Control the speed of the chiller circulation pump to keep pressure difference constant in the net.	[40,53]
	2	Check the condition of fins in cooling tower and do cleaning of fins on monthly basis.	[78]
	2	Control the chiller according to the temperature in the accumulator.	[53]
	2	Run the chiller circulation pump only when needed.	[40,53]
Electrical distribution system	1	Balance the system voltage to reduce the distribution losses in the system.	[13]
	1	Installing capacitors in the electrical system to maintain a high power factor, which will lead to reduced demand, better voltage, high system efficiency.	[13,62,111]
	2	Control the maximum demand by tripping non-critical loads through a demand controller.	[13,62,111]
	2	Increase utilisation rate during off peak times.	[62]

	2	Involve all employees in the electricity conservation effort: an awareness campaign fosters involvement.	[62]
	2	Track and trend power consumption based on production and nonproduction days to spot the energy wasters.	[62]
	2	Review motor burnout history and whether circuitries in the foundry need to be upgraded.	[62]
	2	Conduct thermographic inspections to detect electrical hot spots, e.g., in couplings and contacts, which indicate mechanical sources of loss.	[62]
	2	Check total electric installation of the plant for current leakages and plan for corrective steps.	[87]
Water	1	Limit the use of make-up water to critical tasks.	[41]
	1	Do not let the eyewash fountains run as a drinking water source; provide drinking fountains instead.	[41]
	1	Remove stagnant, redundant branches of the water distribution network.	[41]
	1	Consider placing a water heat exchanger system inside the foundry to help with the heating load in the winter.	[41]
	1	Reduce water heat loss or gain by proper insulation.	[41]
	1	Reduce friction losses and the associated pressure drops by streamlining and correct-sizing of water pipes.	[41]
	1	Review correct size and choice of water pumps.	[41]
	1	Install water-flow regulators for sanitary uses.	[41]
	2	Check locations and measure flow rates of all water uses in the plant to identify wasteful, non-productive usage and excessive flows.	[41,61,90]
	2	Maintain the system and repair leaks promptly.	[41]
	2	Instil good housekeeping practices in all employees.	[41,61]
	3	Recirculate water as many times as possible to prevent waste and maximise internal recycling of waste water streams (e.g. use process water from sand preparation in the moulding sand cycle or in slag granulation, use cooling water in wet scrubbing, and/or recycle tumbling water).	[26,41,90,92,96]
	3	Collect uncontaminated 'wasted' water if its generation rate exceeds the rate of the immediate reuse.	[41]
Vacuum	1	Eliminate vacuum leaks.	[46]
	1	Optimise vacuum pressure.	[46]
Vehicle movements and transportation	1	Prefer electric powered forklift trucks to mitigate noise.	[92]
	1	Select the most environmentally effective transport system as a function of product type.	[41,42]
	2	Combine deliveries with pickups or sales calls wherever possible.	[41]
	2	Minimise vehicle movements and transport activities during the night for mitigating noise.	[26,92]
	2	Do not let the engines idle: turn them off while	[41]

	waiting, and during unloading and breaks.	
2	Maintain all vehicles, including lift-trucks, in top operating condition.	[41]