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METHODS OF ENERGY EFFICIENCY ENHANCEMENT OF CENTRIFUGAL PUMPS

The article addresses the methods of energy efficiency enhancement of centrifugal pumps widely used in mining and in other industries. The methods aimed at reduction of hydraulic loss involve geometrical modification of impellers, surface treatment and hydrophobic coating. It is revealed that the change in the thickness and curvature of blades allows increasing the hydraulic efficiency by 6.5–26.5%, and the change in the number and in the arrangement of blades raises the hydraulic efficiency from 1.6 to 13% depending on the method being used. It is expedient to use the described methods together with the techniques which lessen roughness of flow passages in pumps.

Keywords: *centrifugal pump, energy efficiency enhancement methods, impeller, hydraulic efficiency, hydraulic loss*
DOI: *10.17580/em.2025.02.14*

Introduction

Centrifugal pumps enjoy wide application in water removal in opencast and underground mining, in metallurgy, as well as in petroleum, chemical and other industries [1, 2].

Centrifugal pumps ensure wide ranges of output and delivery head [3]. To ensure high delivery heads, low-speed pumps are used, with low specific speed coefficients n_s, which is governed by high resistances to be overcome in pipelines.

High outputs are ensured by high-speed pumps with high n_s to pump large volumes of liquids over small distances and heights. The factors that influence energy loss in pumps with high and low n_s include: flow friction and vortex flow, governed by an impeller geometry (**Fig. 1**) and pumped liquID properties [4, 5].

According to the research work of international science and technology organization EuroPump, pumping equipment take the second place in electric energy consumption [6, 7]. On the average, centrifugal pumps consume 10–60% of energy in industry and 3–5% of the whole energy in the country. Redesigning of pumps, their manufacture quality and operating modes can increase the pumping capacity, decrease the energy consumption and enhance thereby the pump energy efficiency [8–10]. The energy losses in centrifugal pumps can be mechanical, hydraulic and volumetric.

Mechanical losses are the energy lost in overcome of mechanical friction in bearing assemblies and face seals of a pumping unit. These losses govern the mechanical pump efficiency.

The volumetric losses (q) are the energy lost in leakage of liquID from injection zone to suction line of a pump under the action of differential pressure. These losses govern the volumetric pump efficiency.

The hydraulic losses are the energy lost in overcome of flow resistances in acting elements of a pump [11]. These losses govern the hydraulic efficiency of a pump.

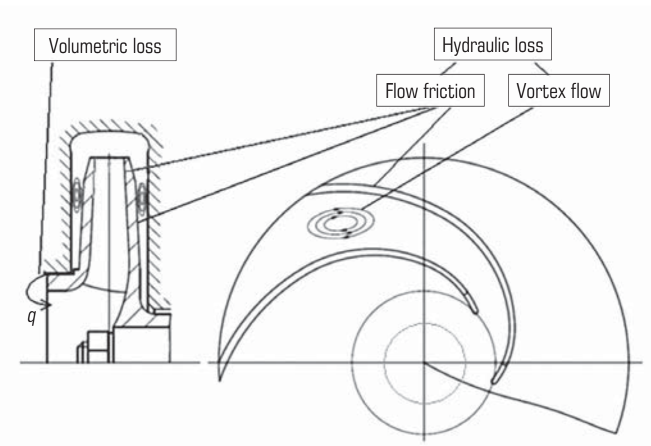

Fig. 1. Types of energy losses in centrifugal pump impeller

Table 1. Energy losses in flow passages of centrifugal pumps

Flow passages	Percent of total energy loss, %
Impeller	50–45
Guide vanes	10–15
Inlet and outlet nozzles	10
Transfer passages	20
Return passages	10

This article focuses on the methods of decreasing the hydraulic losses and increasing the hydraulic efficiency of pumps.

The study of an energy balance in centrifugal pumps [12] shows that the main losses take place in the flow passages of a pump, first of all, in the impeller (**Table 1**).

There exist many calculation procedures aimed to enhance energy efficiency of pumps [13]. The analysis with equations by Euler, Navier–Stokes, Reynolds, Kriking and others belongs to the classical techniques of research of hydraulic parameters in pumps [13–15].

The numerical analysis using ANSYS CFX, CAD and computational fluID dynamics enhances accuracy of modeling and allows solving more complex modeling problems [16]. These methods make it possible to improve energy efficiency of pumps through geometrical redesign of impellers. Also, it is possible to apply hydrophobic covers on impellers, which decrease flow resistances.

Improvement of pump energy efficiency by geometrical redesigning of impeller

The hydraulic loss reduction alongside with reaching higher delivery heads and enhanced capacity of a pump is possible using methods connected with the geometrical redesign of the pump impeller, including optimization of blade profiles in flow passages [17, 18], increase in the number of blades, minimization of diffuseness in inter-blade passages, addition of a second row of blades, as well as the change in integrity and geometry of the leading and trailing edges of blades (**Fig. 2**).

Modification of geometrical configuration of blades

Blade geometry change via thickening

This method of changing geometry of a blade of a 5-blade impeller using 3D CFD modeling [19, 20] allows gradual thickening of blades toward their center (**Fig. 3**), which makes it possible to reduce hydraulic losses in vortex and to decrease hydraulic efficiency by 14.5% and 26.5% given the pump delivery rates

0.2*Q*–0.4*Q* are maintained at the low shaft speeds, and by up to 10% in case of the higher delivery rates and shaft speeds of the pump. The color scale in Fig. 3 depicts the Stanton number St—the similarity criteria in thermal processes, which is used for the comparative analysis of heat transfer intensity in fluID dynamics.

Double-curved blades

Designing of 7-blade impellers of two-section centrifugal pumps using algorithm NSGA-II [21] produced the following results: at the shaft speed of 2600 min^{-1}, the pump delivery rate and hydraulic efficiency were increased by 9.29% and 9.01%, respectively, and at the shaft speed of 1450 min^{-1}, the increment in the listed parameters reached 10.5% and 6.52%, respectively.

Change in number and in arrangement of blades

Increased number of blades to decrease diffuseness of inter-blade passages and optimization of trailing edge angle

This method helps change head-flow characteristics of centrifugal pumps. The increase in the number of blades from 5 to 7 [22] flattens velocity profile of pressure fluid. The optimized angle of the trailing edge decreases probability of flow-separation phenomenon and vortexing, which leads to a higher efficiency by 3.5% and higher pump delivery rate by 11%. The decreased number of blades from 7 to 4 on impellers of the same diameters facilitates an increase in hydraulic losses and a decrease in delivery rate of pumps [23].

Varied blade spacing

Varied spacing of blades of impellers, aimed at decreased hydraulic losses, allows expanding the operating range of a centrifugal pump from 0.7*Q* to 1.5*Q*, increasing the general integral hydraulic efficiency by 3.5% and minimizing the shock loss [24].

Addition of second row of blades

It is possible to reduce pulsation, and to increase delivery rate and hydraulic efficiency of pumps through the decrease in diffuseness of blades at the outlet of pump impellers by means of adding the second row of blades. This approach allows increasing the pump delivery rate and hydraulic efficiency owing to decreased vortexing, flattened velocity profile and reduced pulsation by means of lowering probability of flow separation from front of a blade [25, 26].

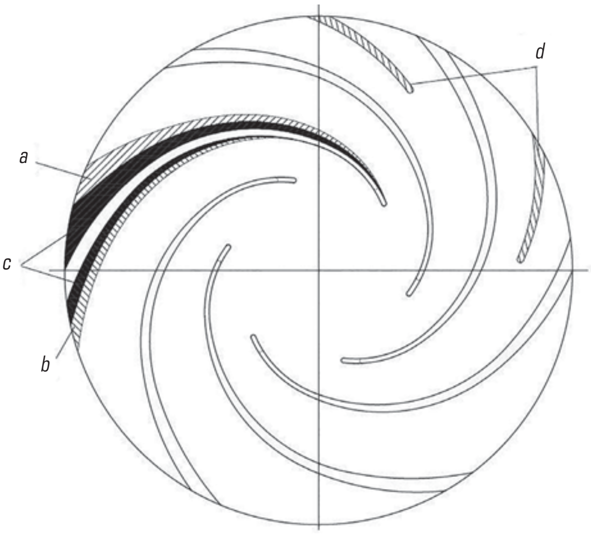

Fig. 2. Ways to reduce hydraulic losses:
a, *b*, *c*–diffusion reduction owing to changed thickness of blades; *d*–addition of second row of blades

Utilization of slots made via displacement of blades

It is possible to change hydraulic parameters of an impeller by making slots by displacement of blades and by changing geometrical parameters of blades such as: radial position (R_s), height (h_s) and slope pitch angle (θ_s). **Figures 4 *b*** and **4 *c*** show dimensions of a slot. Numerical modeling of a power fluID flow in an impeller with slots allowed an increase in the pump delivery rate from 5 to 10% owing to a decrease in the radial position of a slot (R_s), utilization of the slot height (h_s) which was 1.5% of the blade length, and utilization of the pitch angle $130 < \theta_s < 90$ [27, 28]. A slot obtained by displacement of a blade by 1.5 mm from the radial direction of the fluID flow facilitated a decrease in the energy loss and in vortexing by 13% owing to the increased pressure of the

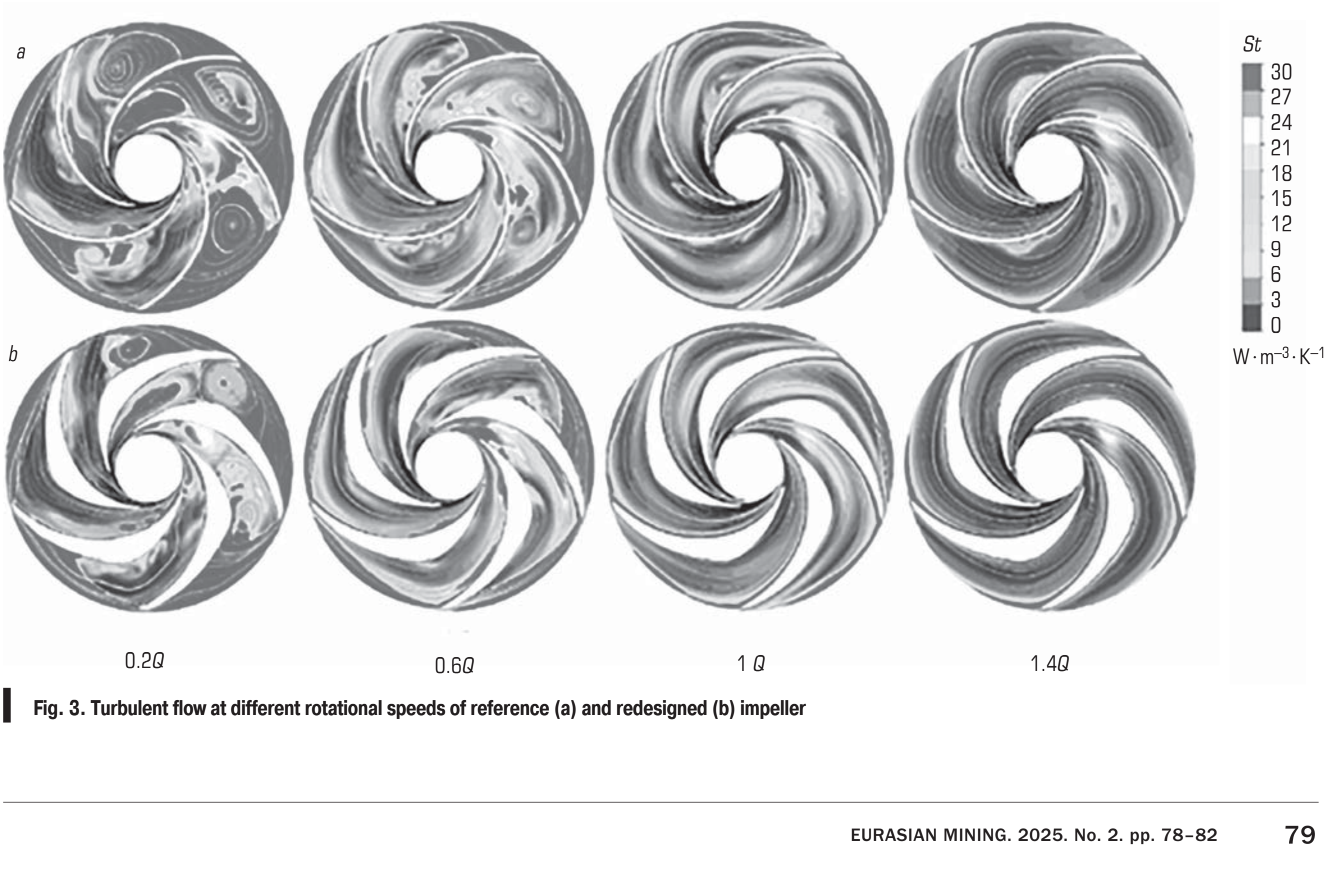

Fig. 3. Turbulent flow at different rotational speeds of reference (a) and redesigned (b) impeller

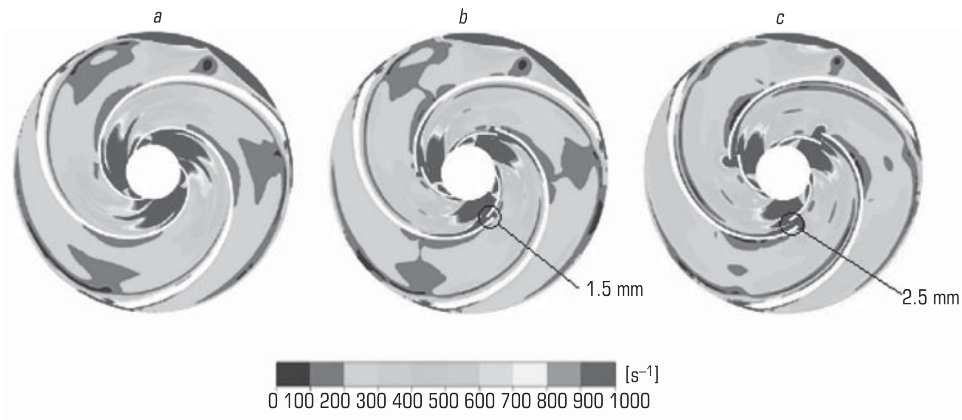

Fig. 4. FluID flow velocity patterns in impeller:
(*a*) without displacement of blades; (*b*) with displacement by 1.5 mm; (*c*) with displacement by 2.5 mm

fluID flow at the front of the blade and improved fluID flow velocity in the impeller (**Fig. 4**) [29]. The color scale in Fig 4 shows the number of complete cycles or revolutions per second S^{-1}.

Hollows on trailing edges of blades

Essential influence on vortexing is exerted by trailing edges of blades. Aimed to reduce hydraulic losses, it is proposed to change geometric lattices by making hollows on trailing edges of blades [30]: hollow diameter $d = 0.8$ mm, axial spacing of hollows $e = 2.11$ mm and radial spacing of hollows $f = 2.91$ mm (**Fig. 5**).

It is found that the hydraulic efficiency lowers by 3%, the hydraulic loss at the blade back decreases by 2.1% and the sonic pressure reduces by 4.96 dB.

Method of logarithmic spiral—changing angle of pitch, and angles of inlet and outlet of fluID flow

This method allows raising the hydraulic efficiency by 1.7% [31, 32] in case of change in the blade angle of pitch, and in case of setting the angles of 17° at the inlet and 31° at the outlet using blade profile equation (1):

$$r = r_1\left[\frac{\cos\beta_1}{\cos\left[\left(\beta_2 - \frac{\beta_1}{\circ}\right)\theta + \beta_1\right]}\right]^{\left(\frac{\psi}{\beta_2} - \beta_1\right)} \quad (1)$$

and equation of blade angle of pitch (2):

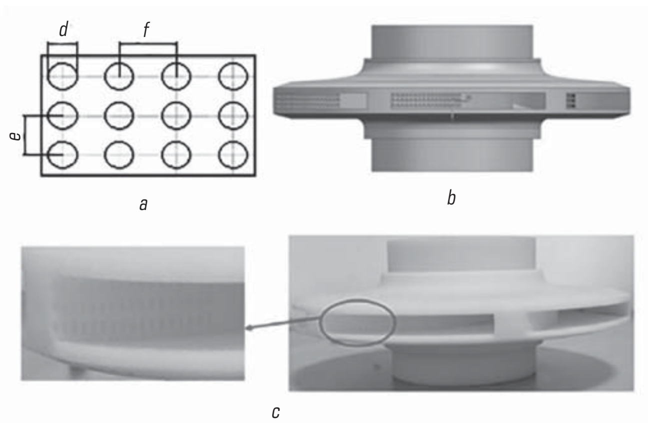

Fig. 5. Redesigned impeller:
layout of hollows on blade surface (*a*); 3D model of impeller (*b*); development prototype (*c*)

$$\varphi = \frac{(\beta_2 - \beta_1)\ln(r_2 - r_1)}{\ln(\cos\beta_2 / \cos\beta_1)}, \quad (2)$$

where r_2, r_1 are the radii of the outlet and inlet of impeller, mm; β is the setting angle of impeller, deg; β_1, β_2 are the angles of leading and trailing edges, respectively, deg; θ is the change in the blade angle of pitch ψ, deg.

Increase in blade angle of pitch from 100° to 120° and decrease in blade spacing difference at impeller inlet and outlet

Optimization of inter-blade passage influences qualitatively the velocity characteristics of centrifugal pumps and leads to the increase of 3.6% in the delivery rate by 3.6% and 1.6% in the efficiency [33].

Energy efficiency enhancement by means of reduction of impeller roughness

Hydrophobic coating

Flow friction can be decreased by means of reduction of roughness in flow passages by hydraulic coating [34, 35]. The test of centrifugal pumps with the specific speed range $n_s = 33\ldots330$ exhibited increment in the efficiency of low-speed pumps. The advantages of this approach is preservation of geometric lattice, increase in delivery rate and enhancement of energy efficiency of pumps (**Fig. 6**).

Cold curing mixture molding

Lessened roughness of surfaces of impeller made of grey cast iron placed in cold molds instead of sand casting can enhance energy efficiency and extend service life of centrifugal pumps.

Cold gas dynamic spray

Another potential way of enhancing energy efficiency and extending life of a centrifugal pump is the surface quality improvement of blades made of grey cast iron by sand molding. To that end, it is expedient to use cold gas dynamic spray which seals excessive porosity of the casting surface and improves the surface quality with attainment of the roughness parameter R_z of 40–20 μm while its initial value is 160–180 μm, through filling the hollows of micro-profile with spray material, for instance, aluminum [36]. Furthermore, cold gas dynamic spray eliminates manufacturing defects in the form of cracks on the impeller rim, revealed during mechanical processing of parts, which extends the impeller service life [37].

For the convenience, the listed methods are compiled in a table form and ranked from the highest to lowest efficiency (**Table 2**).

The methods of surface roughness reduction, described above, are applicable with any method in the table.

Conclusions

1. At the present day, numerical modeling, being more accurate and capable of solving complex problems, forces out classical calculation techniques.

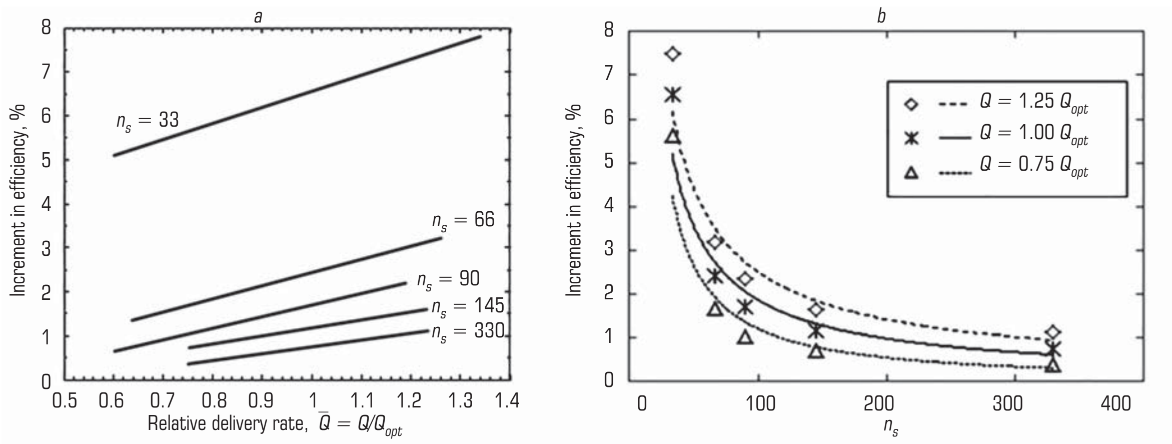

Fig. 6. Curves of efficiency of centrifugal pumps with hydrophobizated impellers:
depending on operating mode (*a*); depending on specific speed (*b*)
Q – rated pumping capacity, m^3/h;
Q_{opt} – delivery rate at maximum efficiency, m^3/h;
$\bar{Q}$ – relative delivery rate (dimensionless value) to illustrate deviation of current operating mode at rated delivery rate from optimum operation at maximum efficiency.

Table 2. Methods and hydraulic efficiency

Method	Hydraulic efficiency, %	Reference
Modification of geometrical configuration of blades		
Thickening of blades	14.5–26.5	[19, 20]
Double-curved blades	6.5–9	[21]
Change in number and in arrangement of blades		
Increase in number of blades to reduce diffuseness in inter-blade passages and optimization of trailing edge angle	3.5	[21, 23]
Varied blade spacing	3.5	[24]
Addition of second row of blades	3.5	[25, 26]
Utilization of slots made via displacement of blades	13	[27–29]
Hollows on trailing edges of blades	3	[30]
Method of logarithmic spiral—changing angle of°pitch, and angles of inlet and outlet of pumped fluid	1.7	[31, 32]
Increase in blade angle of pitch from 100° to 120° and decrease in blade spacing difference at impeller inlet and outlet	1.6	[33]

2. The modification of geometrical configuration of blades by changing their thickness and curvature allows increasing hydraulic efficiency from 6.5 to 26.5%

3. The change in number and in arrangement of blades increases hydraulic efficiency from 1.6 to 13% depending on the method being used.

4. The methods involving modification of geometrical parameters of blades and impellers are expedient to be added with the methods of reduction in surface roughness of these parts.

5. The use of the methods of hydraulic loss reduction enables higher energy efficiency of centrifugal pumps.

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FEASIBILITY OF LEAN PRODUCTION CONCEPT AT INDUSTRIAL UNDERTAKINGS IN KUZBASS

The article discusses feasibility of smart and efficient resource use in the machine works–mine cluster based on the concept of lean and low-waste manufacture. Products of the machine works (pumps, coal pumps, fans, winch arrangements, buckets, conveyors, rock-breaking tools etc.) for the mining industry feature a high resource consumption and a rather short life. The latter is governed by a set of specific factors, namely: rock pressure, rock bursts and gas outbursts, high gas and dust content of air, higher moistness of underground openings and rock mass, high abrasivity of water, air, rocks etc. As a consequence, machines, mechanisms and tools go unserviceable very fast and pass into waste. At the same time, if treated sparingly and economically, many types of production waste have a high chance of recovery up to the level of good condition and return to a production cycle, while some waste items can be brought to even a better condition with new properties. To this effect, cyclic technologies of higher resource-saving level are required. The feasibility of waste recycling and resource efficiency enhancement in the machine works–mine system is discussed as a case-study of a rock-breaking tool. The proposed structural properties and technological capabilities form a three-level waste recycling system for shearer picks, which provides conditions for prudent handling of metals involved in the process of rock fracture–steel and hard alloy. A long-term life cycle of the metals in the mining industry is ensured, at the decreased metal losses, increased level of non-waste operation of coal mines, and at the better performance of the picks. Development of new designs and technologies by mechanical engineers in cooperation with mining engineers makes the low-waste mining industry in Kuzbass realistic.

Keywords: *ongwall shearer, worn-out cutter pick, waste, utilization, downcycling, recycling, upcycling, system, modular cutter pick, module, hard alloy, resource saving*
DOI: *10.17580/em.2025.02.15*

Introduction

It is already a few decades that advanced world's economies have been adhering to the paradigm of saving production and effective resource management [1–7]. This is directed by the fact that the responsible national societies become increasingly aware of the exhaustibility of the Earth's resources, improve their environmental legislation and activate efforts of environmental agencies while business starts to comprehend benefits of husbandry and saving use of resources in production processes. The low-waste and resource-saving economic model persistently expands and deepens, involving new countries, industries and scopes of human activities [8–10]. Russian coal industry that participates in the tightening business competition in the global energy market is unable to avoID the general trends of development. Holding and consolidation of the attained market positions dictates that Russian coal companies and mines master at the earliest possible time the advanced low-waste technologies to reduce resource