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ANALYSIS OF THE BEER PRODUCTION PROCESS IN A CRAFT BREWERY WITH PROPOSED IMPROVEMENTS

Maciej JAMIŃSKI

AGH University of Krakow; mjaminski@agh.edu.pl, ORCID: 0000-0003-4416-5598

Purpose: The aim of this paper is to analyse the beer production process in a selected craft brewery in Kraków. The focus is on technological efficiency, product quality, and compliance with standards such as ISO 9001, ISO 22000, and HACCP. The study seeks to identify operational constraints and propose improvements relevant to small-scale breweries operating under market and regulatory pressures.?

Design/methodology/approach: A case study method was used in a university-affiliated craft brewery. The approach combines literature review, market data analysis, and empirical research, including direct observation, analysis of production documentation, and measurement of key technological parameters. Process performance was assessed using OEE indicators and quality compliance frameworks based on ISO and HACCP standards.

Findings: The brewery maintains high efficiency in core stages like fermentation and maturation, with tank utilisation exceeding 96%. Quality control is consistent with HACCP principles, including defined CCPs and monitored fermentation parameters. Bottlenecks were identified in bottling and tank availability. Recommended improvements include automation, ergonomic redesign, and readiness for low-alcohol beer production.

Research limitations/implications: The study is limited to a single facility, which restricts the generalizability of results. However, the methodological framework may be applied in broader studies. Future research should explore implementation outcomes, economic feasibility of upgrades, and comparisons across multiple craft breweries.

Practical implications: The paper offers actionable recommendations to improve efficiency, hygiene, quality monitoring, and product diversification. These findings support decision-making in production planning, investment in equipment, and compliance with modern consumer and regulatory expectations.

Social implications: Craft breweries contribute to local economic development, regional identity, and sustainable consumption trends. This study highlights their role in promoting product diversity, responsible production practices, and cultural value in the food and beverage sector.

Originality/value: This research integrates engineering, quality, and operational perspectives in analysing a Polish craft brewery. It provides practical insights for brewers, engineers, and policymakers focused on scalable, compliant, and sustainable craft beer production.

Keywords: beer, craft brewery, beer production process, process efficiency.

Category of the paper: case study.

1. Introduction

As one of the oldest and most widely consumed fermented beverages in the world, beer has played an important role in both cultural history and the development of food technology. Its origins date back to at least the fourth millennium BC, as evidenced by clay tablets from Mesopotamia documenting the fermentation practices of the Sumerians, considered to be among the earliest examples of food technology in human history (Hornsey, 2003). During the ancient Roman period, beer had a lower cultural status - it was associated with barbarian peoples, while wine dominated as the drink of the elite. It was not until the Middle Ages, due to the development of monastic brewing, that beer regained popularity and began to play an important role in the economy of many European countries (Nelson, 2005).

In the centuries that followed, beer established itself as one of the pillars of local traditions and industry, especially in central and western European countries such as Germany, Belgium, the Czech Republic and Poland (Unger, 2004). A turning point in the history of brewing was the enactment of the so-called Reinheitsgebot - the Bavarian Purity Law - in 1516, which imposed strict restrictions on beer ingredients. According to this decree, only three raw materials could be used in the production of beer: water, barley malt and hops (Wilson, 2006). Although this decree did not include yeast, its importance to the fermentation process was not fully understood until the 19th century, thanks to the work of Louis Pasteur, who proved the microbiological basis of alcoholic fermentation. This discovery ushered in a new era in brewing technology, leading to the development of controlled and reproducible production methods (Gal, 2008).

In the Polish lands, beer played an important role in everyday life as early as the Middle Ages, being one of the most commonly consumed fermented beverages. Historical sources indicate that beer production was widespread both in towns and in rural areas. Many urban centres had several breweries each, some of which were in the hands of the bourgeoisie, craft guilds or monasteries. Jan Długosz, in his Rocznik (Annals), stressed that beer was an everyday part of the diet during the Piast dynasty - mainly due to the unavailability and high cost of wine, which remained the drink of the elite (Długosz, 2009).

Over the following centuries, the role of beer in the structure of alcohol consumption in Poland began to change gradually. At the end of the First Republic, vodka, whose production was simpler, cheaper and effectively supported by the propination system, which gave landowners exclusive rights to produce and sell alcohol to peasants, became increasingly popular. This phenomenon had long-lasting social and economic effects, contributing to the marginalisation of brewing as a food industry.

During the period of the People's Republic of Poland, the development of the brewing sector was significantly limited by the policy of central planning. Lack of investment, low innovation and outdated technological infrastructure resulted in limited availability and low quality of beer on offer (Kosiński, 2008). It was only the political transformation initiated in the 1990s that created conditions for the dynamic development of the beer market. The liberalisation of the economy, the inflow of foreign capital and the implementation of modern technologies contributed to the modernisation of existing production facilities, increased efficiency and diversification of the assortment (Zorska, 2005). This change was significant not only from an economic point of view, but also from a cultural and consumer point of view.

Today, Poland is one of the leading beer producers in Europe, both in terms of production volume and consumption. According to the Central Statistical Office (GUS) (2024), annual beer consumption per capita oscillates around 90 litres, which places Poland among the world leaders. The domestic beer market is dominated by three main players - Kompania Piwowarska, Grupa Żywiec and Carlsberg Polska - which together control over 80% of the market share (Deloitte, 2021). The activities of these concerns are based on automated, highly integrated production of bottom-fermented beers, mainly of the lager type, which constitute the core sales segment.

Parallel to the activities of large producers, the craft brewery sector is developing dynamically, responding to growing consumer expectations in terms of variety, quality and innovative sensory qualities. This trend, part of the worldwide "craft beer revolution" trend, has resulted in the emergence of hundreds of new operators producing top-fermenting beers, often inspired by American, Belgian or Nordic styles (Deloitte, 2021).

Changing consumer preferences are contributing to an evolving demand structure, with more and more people abandoning conventional lagers in favour of beers with a more complex flavour profile (Aquilani et al., 2015). According to market analyses, the craft beer segment has increased its share by around 18% over the last three years, demonstrating its growing importance in the structure of domestic consumption. At the same time, the market is showing signs of saturation, leading to intensified competition between both conglomerates and smaller producers. In this situation, the key success factor becomes not only the innovativeness of the offer, but also the efficiency of technological processes, the quality of raw materials and the ability to build lasting relationships with consumers.

Unlike industrial breweries, craft breweries operate on a much smaller scale, which requires a different approach to optimising production processes and quality management. Also, the range of products on offer at smaller breweries is far more extensive than at conglomerate breweries. Precise fermentation control, raw material selection and batch repeatability are key technological challenges for this sector. (Kunze, 2023)

The beer production process consists of several key stages, such as wort brewing, fermentation, lagering, filtration and bottling, the optimisation of which has a direct impact on the quality and character of the finished product (Kunze, 2023). In craft breweries, individual recipes and less repeatability are of particular importance, giving rise to the need for precise analyses of production parameters and the effectiveness of the sanitation procedures used (Salanță et al., 2020). Despite the impossibility of making major changes to the beer production process, it is constantly being improved by, among other things, the development of new equipment (Baiano, 2020) or new laboratory discoveries (Materials of the School of Fermentation Technology 1998-2024).

The purpose of this study is to analyse the beer production process in one of Kraków's craft breweries in terms of its efficiency, quality and compliance with industry and company standards. The study includes a detailed assessment of key production stages and identification of potential technological improvements that could improve product quality and increase operational efficiency. Technological parameters of the brewing, fermentation, filtration and bottling process were analysed, with a focus on critical control points (CCPs) and repeatability of quality indicators. The work is of an applied nature and can serve as a starting point for further optimisation research and benchmarking in the SME brewing sector.

2. Research methods

The initial stage of the study was a systematic review of the literature on the subject, with the aim of acquiring the well-established theoretical and empirical knowledge necessary to develop a model for the analysis of the beer production process in a craft brewery. This review covered scientific publications, industry studies and technical standards on both classical technological steps and contemporary aspects of quality and process efficiency management.

Special attention was paid to issues related to the successive phases of the production process, such as barley malting, mashing, boiling with hops and wort filtration, fermentation, lagering, secondary filtration and beer bottling. The diversity of technologies used in craft breweries is also analysed, including the use of unmalted raw materials, the specifics of top and bottom fermentation and the importance of unfiltered end products in the context of beer styles. The literature review also included the characteristics of the craft brewery sector in Poland, taking into account its organisational structure, scale of production, business models (stationary, contract and restaurant breweries) and current consumer and technological trends observed in the brewing industry. The analysis included the development of the segment of top-fermenting beers, non-alcoholic products and so-called experimental beers, as well as the impact of economic variables on the condition of the sector.

In parallel, secondary data from industry reports, statistical databases (e.g. GUS, PARPA) and industry organisations (e.g. ZPPP Browary Polskie) were analysed. Data on the level and structure of beer consumption in Poland, dynamics of the number of active breweries, changes in consumer preferences and legal and technical conditions were assessed. Quality standards, including national and international guidelines (e.g. PN-A-79098, ISO 9001, ISO 22000), defining requirements for the technological process and the finished product, were also taken into account.

The empirical study proper was a case study conducted at the Górniczo-Hutniczy Brewery in Kraków, Q2-Q3 2022. The study used qualitative and quantitative methods, including: participatory observation, analysis of process documentation, measurement of technological indicators and functional assessment of equipment and work organisation. Direct observation was conducted continuously as part of the research collaboration with the brewery, while measurement and data analysis were based on the plant's internal documents, process sheets and production monitoring records.

The reference framework for assessing process efficiency was the Overall Equipment Effectiveness (OEE) indicator model, commonly used in the analysis of production equipment performance. This indicator allows a synthetic evaluation of the availability of production resources, operational efficiency and the quality of the product batches produced. This approach enabled the identification of bottlenecks, organisational inefficiencies and potential areas of improvement in the planning, scheduling and execution of the brewing and bottling process.

2.1. Beer production process

The beer production process is a complex sequence of technological operations, the number and scope of which may vary depending on the classification used in literature and industrial practice. In general, four main phases can be distinguished:

1. malting of barley,
2. wort production,
3. fermentation and maturation,
4. final stabilisation of the beer, usually by filtration and pasteurisation (Poreda, 2010; Simonffy et al., 2014).

Each of these stages is an integral part of brewing technology and has a direct impact on the physicochemical and sensory properties of the final product. Depending on the technological approach, this process can be broken down into between four and even ten sub-stages.

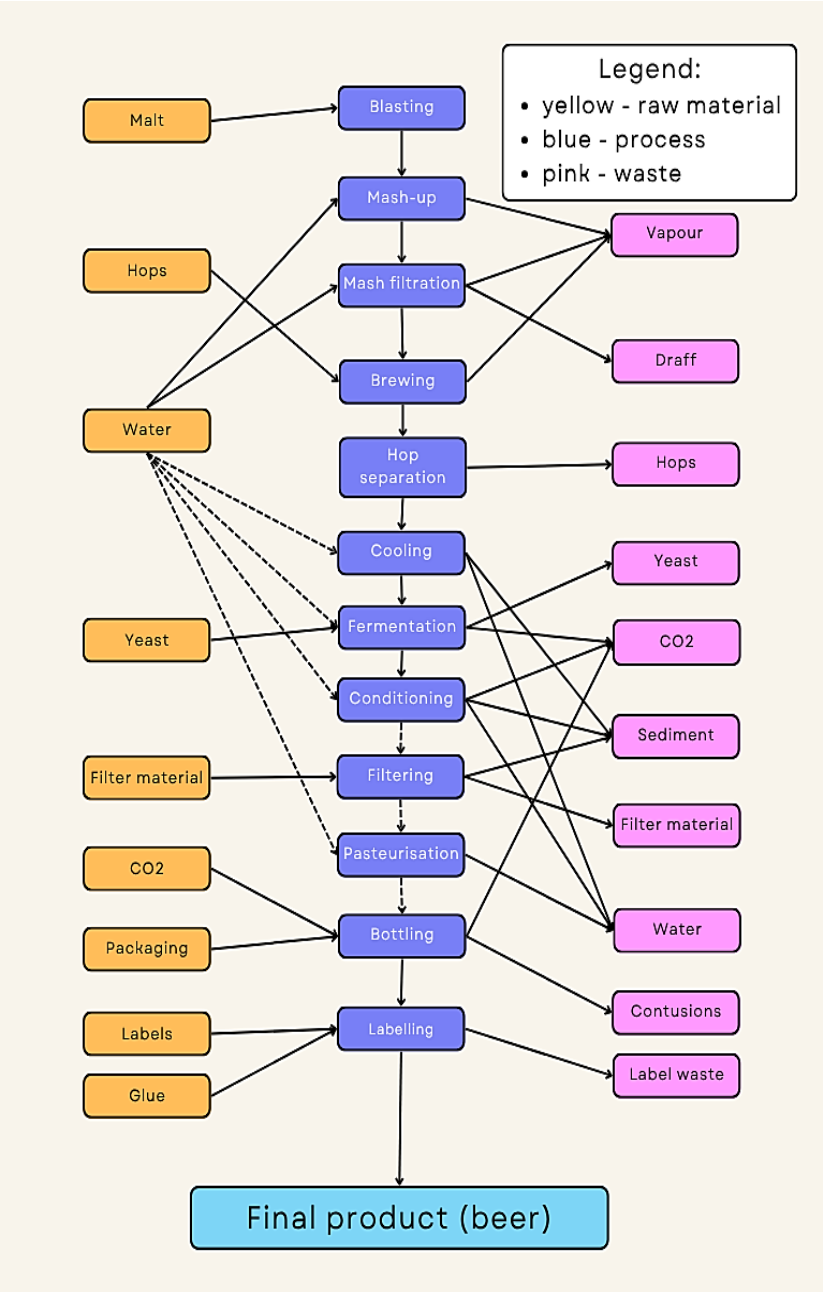

Figure 1. The beer production process.

Source: own work.

2.1.1. Brewing beer (wort production)

The brewing process, carried out in the brewhouse, is the central stage in the production of wort - an intermediate product that determines the extract and chemical composition of the finished beer. The sequence of technological operations includes the following stages:

- mashing - involving thermal treatment of a mixture of barley malt and optional unmalted raw materials in mash tubs. The aim is enzymatic hydrolysis of starch to fermentable sugars and dissolution of extractive compounds (Harrison et al., 2019);
- filtration of the mash - carried out in a filter vat to separate the liquid phase (wort) from the mash;

- wort boiling with the addition of hops - carried out in a brewing boiler. This process allows isomerisation of the alpha-hops acids, sterilisation of the wort and evaporation of undesirable volatile aroma fractions (e.g. DMS) (Sterba et al., 2024; Dai et al., 2023);
- separation of sediment and hop residues - carried out in a whirlpool, where sedimentation of solid fractions takes place by centrifugal force;
- cooling of the wort - to a temperature suitable for the selected strain of fermentation yeast (usually 8-12°C for bottom fermentation and 16-22°C for top fermentation). Cooling is done using plate heat exchangers (Harrison et al., 2019);
- aeration of the wort - using sterile air or pure oxygen to ensure adequate levels of dissolved oxygen necessary for yeast cell proliferation in the initial stage of fermentation (Briggs et al., 2004).

Throughout the process, at various stages, a brewery employee performs a number of quality checks on the wort produced (e.g. sugar content, pH, temperature measurement). The duration of one brew - understood as a complete wort production cycle - varies depending on the mashing method used (infusion, decoction) and the capacity of the brewing line, and is on average between 4 and 7 hours (Pazera, 1998).

2.1.2. Alcoholic fermentation

Fermentation is one of the key stages in the technological process of beer, during which the biochemical conversion of fermentable sugars contained in the wort into ethanol and carbon dioxide takes place. This process is carried out with brewer's yeast (most commonly *Saccharomyces cerevisiae* or *Saccharomyces pastorianus*) and takes place under strictly controlled conditions due to its fundamental importance for the physicochemical and sensory parameters and stability of the finished product.

Depending on the scale and type of production, fermentation can be carried out:

- traditional method - in open fermentation tanks, which allows observation and manual control of the process,
- industrial method - in closed cylindroconical tanks (CCT), with the possibility of automatic control of temperature, pressure and fermentation level.

A typical fermentation process involves the following operational steps:

- assignment of the yeast inoculum to the cooled and aerated wort,
- monitoring of process parameters, including temperature, actual extract density and apparent attenuation,
- controlled discharge of excess CO_2 and possible removal of surface foam,
- harvesting of yeast biomass at the end of active fermentation, for disposal or reinoculation.

The duration of fermentation depends on a number of factors, including: the beer style chosen, the yeast strain, the temperature at which the process is conducted and the desired sensory profile. At this stage of beer production, the key parameters to be controlled are the amount of CO_2 present in the vessel and the temperature. In brewing practice, fermentation of

bottom-fermented beers typically takes 8-14 days, while top-fermented beers can be ready in 4-7 days (Kunze, 2023; Briggs et al., 2004).

2.1.3. Ageing (beer maturation)

Maturation, also known as lagering, is the final stage of the fermentative-biochemical transformation of the wort into a beer ready for bottling. This process plays a key role in stabilising the product both chemically, microbiologically and sensorially. The main objectives of maturation include:

- elimination of undesirable compounds such as diacetyl, aldehydes and higher alcohols, which can negatively affect the sensory quality of the final product,
- fixing the flavour and aroma profile, including the smoothing of bitter notes and the development of desirable esters and phenols (depending on the beer style),
- saturation of the beer with carbon dioxide naturally, by secondary fermentation of residual sugars or by diffusion in closed tanks.

Maturation is carried out in lagering tanks (usually cylindrical and conical) at a controlled temperature close to 0°C, which promotes sedimentation of suspended solids, colloidal stabilisation and clarification of the product. The duration of this stage depends on the beer style, its initial extract and the producer's requirements and can range from a few days (e.g. for light session beers) to several months (for strong, spontaneously fermented beers or specialty beers such as German-style lager) (Briggs et al., 2004; Kunze, 2023).

Effective management of the maturation process is essential to ensure the repeatability and quality of the final product and to meet consumer requirements and industry standards.

2.1.4. Beer filtration

Beer filtration is a technological step aimed at removing colloidal suspensions, residual yeast cells and particulate matter in order to obtain a clear, microbiologically and visually stable final product. This process affects not only the aesthetics but also the shelf life of the beer, reducing the risk of secondary fermentation in the package and microbial turbidity.

In industrial settings, filtration is carried out using specialised systems such as:

- plate filters (e.g. diatomaceous earth filters),
- candle filters,
- microfiltration systems, allowing clarification without pasteurisation.

In the practice of craft and restaurant breweries, however, filtration is used selectively or omitted altogether. For many beer styles - in particular wheat, Hefeweizen-type or craft beers - the presence of a fine yeast and protein suspension is a desirable sensory characteristic and an element of product authenticity.

In the case of unfiltered beers, control of microbiological and physico-chemical stability is based on proper fermentation and lagering and a strict sanitary regime during bottling. It is worth noting that the decision to carry out filtration depends not only on technological aspects, but also on the assumptions of the beer style and the marketing strategy of the producer (Koprya, 2017; Kunze, 2023).

2.1.5. Bottling and final stabilisation

Beer bottling is the final stage of the technological process, consisting in filling unit containers - such as glass bottles, aluminium cans or KEG-type bulk containers - with the finished, stabilised product. At this stage, the product must meet quality and microbiological requirements for safe storage and distribution (Habschied et al., 2022).

To extend shelf life and ensure consumer safety, beer is often subjected to additional microbiological stabilisation, most commonly by:

- - thermal pasteurisation (tunnel or jet pasteurisation), which involves briefly heating the beer to 60-72°C (Wray, 2015).
- - microfiltration - mainly used in unfiltered beers, allowing mechanical removal of micro-organisms without the use of high temperature (Klyuchnikov et al., 2020; Cristea et al., 2012).

The bottling operation must be carried out under a high sanitary regime, taking into account cleaning-in-plant (CIP) procedures, quality control of packaging and monitoring of residual oxygen levels, which can negatively affect the oxidative stability of the beer (Devolli et al., 2016).

From a production engineering point of view, efficient bottling involves minimising raw material losses, ensuring uniform CO_2 dosing and maintaining consistent volume and pressure in unit packs. In smaller craft breweries, this process is often carried out using semi-automatic equipment with limited capacity, requiring greater operational supervision and manual control (Rachwał et al., 2020; Sperandio et al., 2017).

Quality assurance in the beer production process requires a comprehensive approach including both the control of technological parameters and the implementation of quality management systems compliant with current national and international standards.

The basic document regulating the quality requirements for beer in the Polish market was the PN-A-79098 standard, in force until 2004, which defined, among other things, the generic classification of beer, requirements for colour, extract, alcohol content, clarity, taste and aroma, as well as permissible deviations of physicochemical parameters. This standard served as a reference for both industrial producers and craft breweries (PN-A-79098:1995).

At a system level, the implementation of the ISO 9001 standard, which defines the requirements for an organisation's quality management system, is important. In the context of a brewery, this includes the following: documentation and supervision of production processes, risk management, process approach and customer satisfaction monitoring. This system promotes standardisation and reproducibility of production and enables data-based decision making.

In parallel with standard quality assurance procedures, the brewery applies a food safety management system based on the principles of HACCP (Hazard Analysis and Critical Control Points), integrated with the requirements of ISO 22000. The system is designed to systematically identify, evaluate, and control biological, chemical, and physical hazards that

may occur throughout the beer production process. Within this framework, the brewery defines Critical Control Points (CCPs), establishes critical limits for key technological parameters (e.g. fermentation temperature, pasteurisation duration), and implements continuous monitoring procedures along with predefined corrective actions in case of deviation. ISO 22000 ensures that HACCP is embedded within a broader risk-based food safety management structure, providing traceability, documentation, and process validation across the entire production chain.

The implementation and adherence to the above standards allows not only to ensure the high quality and health safety of the product, but also to build consumer confidence and strengthen the brewery's competitive position in the market.

2.2. Beer market and consumption in Poland

The beer market in Poland is characterised by a wide variety of organisational forms of production activities. Breweries operating in the market can be divided into three basic categories:

- stationary breweries - producing for their own needs and on behalf of other entities; in 2021, there were 260 such breweries operating in Poland,
- contract breweries - which do not have their own brewing facilities, outsourcing the production process to external facilities (in 2021 there were 86 units of this type), and
- restaurant breweries - combining the function of a catering establishment with the production of beer served directly on site (Piwna Zwrotnica Report, 2022).

Despite the significant growth in the number of independent producers, the ownership structure of the market is highly concentrated. As can be seen in Fig. 2, the three largest brewing groups - Kompania Piwowarska, Grupa Żywiec and Carlsberg Polska - together control over 78% of the domestic beer market (Deloitte, 2021). This consolidation took place mainly in the 1990s, as a result of the economic transition, the privatisation of state-owned enterprises and the liquidation of many local brewing plants.

The largest producer is Kompania Piwowarska, which is owned by the Japanese group Asahi Breweries. The company was established in 1999 and comprises three main breweries: Tyskie Browary Książęce (Tychy), Lech Browary Wielkopolskie (Poznań) and Browar Dojlidy (Białystok).

Second place goes to Grupa Żywiec, controlled by Dutch giant Heineken. The company was established in 1998 as a result of the acquisition of the Brewpole group, which included breweries in Elbląg, Leżajsk and Warka.

The third largest entity is Carlsberg Poland, part of the Danish Carlsberg group. The Polish branch was established in 2001 as a result of the consolidation of breweries in Brzesko, Sierpc and Szczecin.

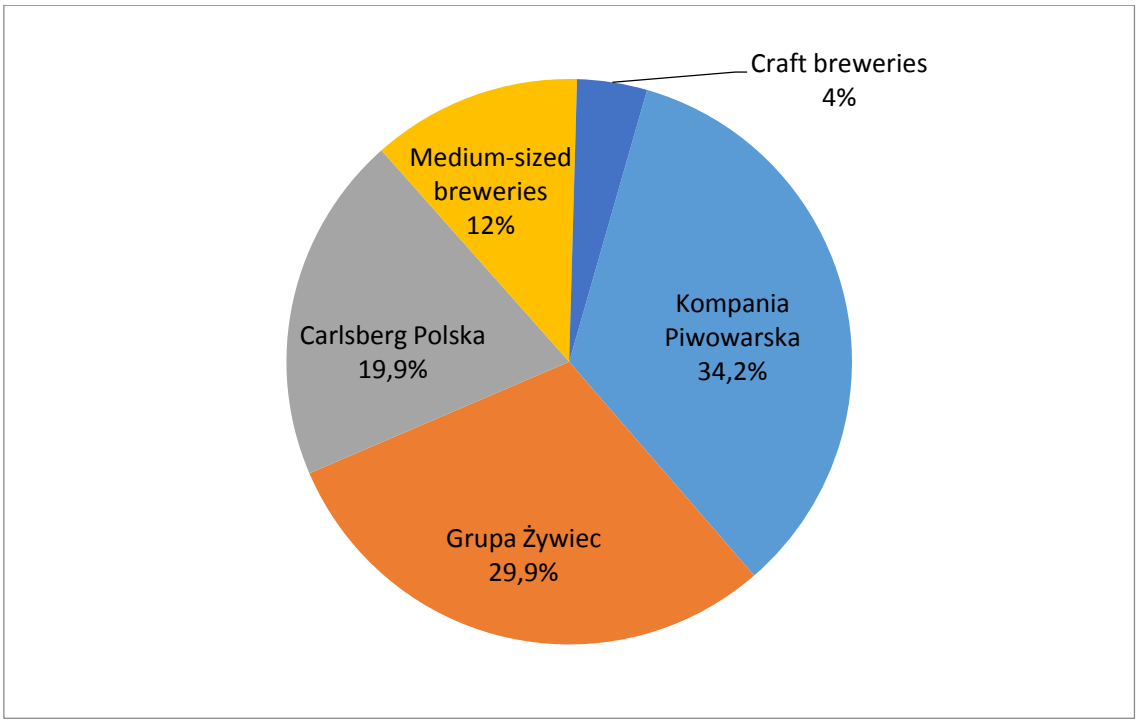

Figure 2. Structure of the Polish beer market in 2021.

Source: Summary analysis of selected indicators of the impact of the brewing industry on the Polish economy and environment, *Podsumowanie analizy wybranych wskaźników wpływu przemysłu piwowarskiego na polską gospodarkę i otoczenie.* Warsaw: Deloitte, 2021.

Parallel to the activities of large concerns, the sector of craft (kraft) breweries is developing dynamically. In Poland, a craft brewery is most often considered to be an entity whose annual production does not exceed 200 000 hectolitres. Although the term has been used relatively recently, this segment is one of the most innovative and developing branches of the brewing industry.

According to data from the Central Statistical Office (GUS) (2023) (National economy entities registered in the REGON register, declaring their activity (according to PKD 2007 - 11.05.Z (Manufacture of beer), the largest number of craft breweries operates in the Mazowieckie (55), Dolnośląskie (43) and Śląskie (38) provinces, which correlates with population density and the presence of large urban agglomerations.

The history of beer consumption in Poland dates back to the times of the first state organisms. Although for centuries beer was not a culturally or economically dominant beverage, the political changes of the 1980s and 1990s enabled its return to widespread consumption (GUS, 2024). Currently, Poland is one of Europe's leading beer producers (Figure 3), but per capita consumption has been declining in recent years.

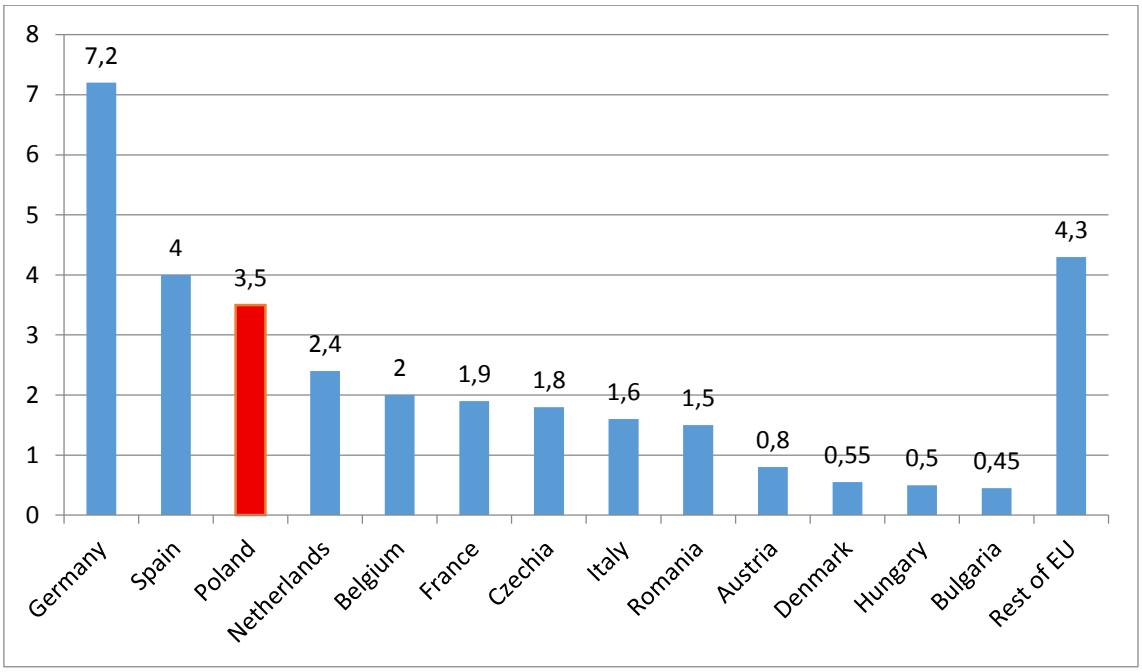

Figure 3. Beer production in Europe [bilions hl].

Source: own work https://ec.europa.eu/eurostat/databrowser/bookmark/04fb9f6b-2b43-44b1-be71-fdd7c208325b?lang=en&page=time:2023

After 28 years of a 329% increase in beer consumption, the record level of 100.5 litres per capita was reached in 2018 (Fig. 4). Since then, a downward trend has been evident, with consumption in 2023 at 87.4 litres (compared to 152 litres/year in the Czech Republic, 106 litres/year in Austria and 88.8 litres/year in Germany) (GUS, 2024; Kirin, 2024). This trend is explained by changes in consumer preferences, the impact of the COVID-19 pandemic and economic pressures. Despite this, beer remains the dominant segment of the alcoholic beverages market in Poland, with over 60% of adult Poles declaring that they consume it regularly (Browary Polskie, 2025).

Particularly noteworthy is the growing popularity of non-alcoholic beers, which are increasingly becoming an alternative to traditional alcoholic beverages. This change reflects global health and cultural trends related to reducing alcohol consumption.

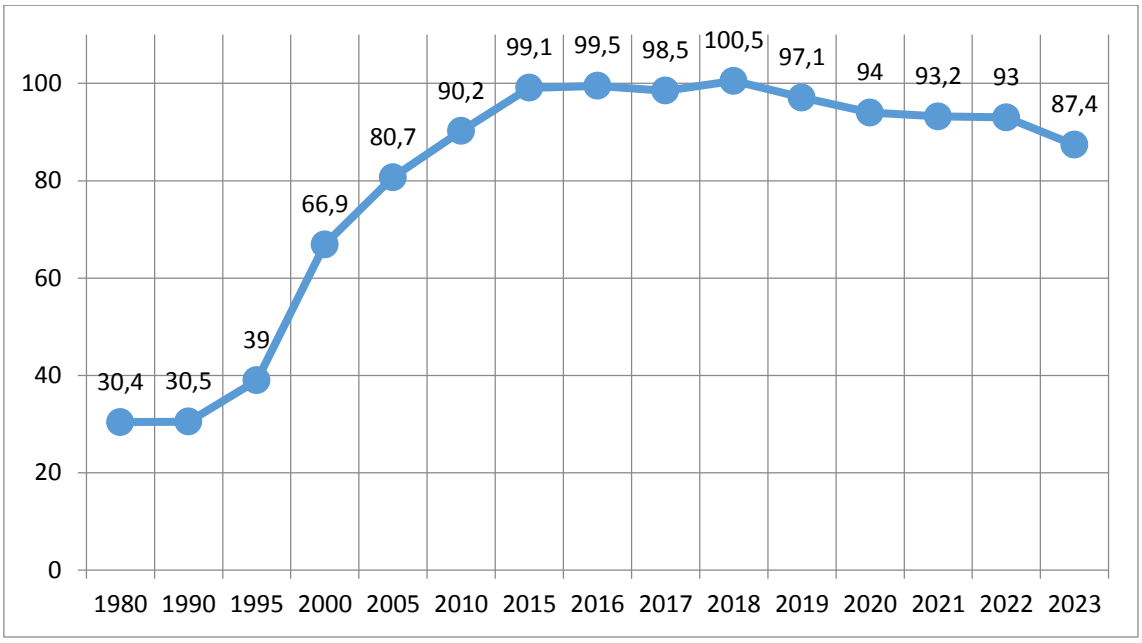

Figure 4. Average beer consumption in Poland per capita in litres.

Source: own work.

The growth of interest in beers with an atypical sensory profile and beverages with reduced alcohol content (the so-called NoLo segment: no- and low-alcohol beverages) observed in recent years is one of the key factors stimulating the development of the craft beer market in Poland. Craft beers have started to be perceived by consumers as synonymous with high quality, authenticity and localness, which has contributed to consolidating their position in the premium segment (Heyd et al., 2020).

The dynamic growth of this sector, however, faces significant economic and regulatory barriers. Between 2015 and 2023, the price index for alcoholic beverages in Poland rose to 133.1 and the increase in energy costs reached 215.4 in the same period (GUS, 2024), significantly affecting the profitability of small breweries operating at a limited scale of production. This is compounded by changes in fiscal policy (e.g. excise duty increases), increased logistics costs and increasing social pressure related to responsible alcohol consumption and public health concerns (Järvinen et al., 2017).

According to data from the Association of Brewing Industry Employers Polish Breweries (2024), the year 2023 saw a decline in beer sales of 6.9%, which negatively affected the financial standing of many producers, especially those operating in the craft model. Despite these difficulties, the increase in the share of non-alcoholic products in the total sales volume remains noticeable. Over the last decade, the consumption of non-alcoholic beer in Poland has increased tenfold, which places the country in third place in Europe in terms of production volume in this segment - with a share of 9.3% (Browary Polskie, 2025).

3. Formulas – second level numbering

As a beer production facility operating under the craft brewery formula, the Górniczo-Hutniczy Brewery is characterised by a simplified organisational structure, adapted to the small scale of production and the high degree of specialisation of the team. At the date of the survey (2022), the plant employed a total of 10 employees, including: 2-man management, 4 brewers responsible for the technological process and 4 administrative staff. Work at the brewery takes place in a single-shift system, which, given the current production volume and premises conditions, is an optimal solution from an organisational and cost perspective.

The management of the brewery has a strategic and decision-making function, coordinating activities related to production planning, contacts with suppliers and relations with the owners (joint-stock company). In terms of operations, the managerial and executive functions are largely integrated - the brewers are responsible for both running the technological processes (brewing, fermentation, lagering, bottling), as well as quality control and internal and external logistics. In practice, this means that each member of the production team performs a number of functions: planning production orders, operating equipment, controlling fermentation parameters, sensory control and preparing products for dispatch or collection.

The administrative department performs support functions, focusing on financial and accounting tasks, marketing, customer communication and the organisation of day-to-day operations (e.g. procurement of raw materials, packaging management, contact with wholesalers and sales outlets). Under conditions of low automation and high operational variability, this kind of interdisciplinary functional structure enables organisational flexibility while maintaining operational continuity.

The Górniczo-Hutniczy Brewery, established in 2020, is located on the campus of the AGH University of Krakow. It serves not only a production and commercial function, but also an important teaching and research role. Due to its location, technological infrastructure and organisational links with the university, it is a unique example of the implementation of the entrepreneurial university model and the so-called “living lab”. The concept is to integrate the academic environment with the industrial infrastructure to foster innovation, knowledge transfer and practical training.

As part of its educational activities, the brewery makes its technological facilities available for laboratory classes, engineering and diploma projects, as well as apprenticeships for students of food technology, chemical engineering, biotechnology, industrial analytics and production management. Students have the opportunity to participate directly in production processes, quality control, development of new recipes and monitoring of technological parameters in accordance with the principles of good manufacturing practice (GMP) and the ISO 22000 system.

Due to the local scale of operations and the state-of-the-art nature of the installation, the Mining and Smelting Brewery exhibits characteristics of low-carbon and environmentally sustainable production. The brewery's operating model takes into account both the efficient use of resources and the reduction of environmental impacts throughout the product life cycle (from raw material to distribution), which is in line with the principles of the closed-loop economy (GOZ) and the European Commission's recommendations for a sustainable food system (Fetting, 2020).

In terms of raw materials, the brewery prefers products of local origin or those produced within the facilities of the university. An example is the use of honey from an apiary belonging to the AGH as an additive to honey beer. This kind of integration of local resources reduces the carbon footprint associated with transporting raw materials and supports regional agriculture. Also, the hops used are sourced from plantations located in Poland (Polish Hops company), which fits in with the idea of shortening supply chains and supporting sustainable logistics.

In terms of waste management, the brewery uses solutions that reduce organic and industrial waste. After fermentation, the yeast is analysed for viability every time; part of the biomass is recovered and used to re-inoculate the wort, and the rest is disposed of in accordance with organic waste regulations. By doing this, both waste and the need for new yeast cultures are reduced.

Brewing takes place in monthly planning cycles so as to produce beer according to the current monthly demand. In 2022, the brewery brewed 123 brews (a total of 1251.7 hl of beer), resulting in 10.25 brews per month, assuming 2 brews per day. The brewing time for one brew of beer at the Mining and Smelting Brewery averages about 4 hours, which is at the lower end of the range of values reported in the literature for a 10 hl plant.

The “Braublock” brewing installation from Kaspar Schulz used by the brewery enables brewing to be carried out in a technologically efficient manner while maintaining high quality standards. The short duration of the process is not the result of shortening or simplifying the stages, but the result of appropriately organised work of the brewing team, rational production planning and the alignment of operational activities (e.g. preparation of raw materials for the next batch during the current brew).

Brewing takes place according to a monthly production schedule, which allows the number of brews to be adjusted to current distribution demand. During the analysed period (year 2022), the brewery made 123 brews, which is an average of 10.25 brews per month, with 2 brews made per day. Such a production rate, while maintaining a standard brewing time and full technological regime, testifies to good work organisation and efficient use of operational resources. It should be emphasised that the brewing installation allows the realisation of up to two brews per day at full load, which leaves a reserve of production capacity in case of an increase in demand.

In addition, due to the local reach of distribution, the beer is not transported over long distances - the primary sales channels include selected catering outlets and specialist shops in and around Kraków. This approach reduces CO_2 emissions associated with transport and reduces energy consumption in last-mile logistics. Goods are released from the warehouse according to the FIFO principle (first in - first out), which minimises the risk of out-of-date products and consumer losses.

In addition, the brewing process is carried out in accordance with the principles of Good Manufacturing Practice (GMP). Full control over temperature, wort volume and microbiological purity of the brewhouse demonstrates adherence to process safety principles, which remains in line with the ISO 22000 system guidelines. Despite the lack of formal ISO 9001 certification, the practices used comply with the quality management assumptions set out in this standard.

The beer production process at the Mining and Metallurgical Brewery uses a system of ongoing control of technological parameters, supplemented by periodic analyses carried out by an external analytical laboratory as part of inter-university cooperation. Such a model allows the repeatability of physicochemical parameters to be maintained.

During the wort production stage, brewers perform ongoing monitoring of basic process indicators such as temperature, duration of individual mash breaks and base wort extract (°Plato). Standard measurements also include pH, density and wort volume after filtration. These data are recorded and compared with reference values depending on the beer style, according to the technology charts developed at the brewery.

Once the fermentation process is complete, selected beer samples are sent to an external specialist laboratory, which performs analyses of key quality indicators. Among the parameters tested are:

- alcohol content by volume (% v/v),
- actual extract and apparent extract,
- basic wort extract,
- actual and apparent attenuation.

The data obtained serve both to verify compliance with the recipe and industry standard and to validate fermentation processes. Collaboration with an external laboratory ensures high analytical quality and repeatability of results, while benefiting from independent verification of batch parameters. An example of a summary of laboratory tests, brewery declarations and industry standards can be found in Table 1.

The final stage of quality control is the sensory evaluation of the finished product, carried out after the beer has been bottled, kegged or tapped. A tasting panel, made up of brewers and staff involved in the process, carries out an organoleptic evaluation covering appearance, clarity, aroma, flavour, fullness and balance of bitterness and sweetness. Sensory evaluation allows any irregularities not apparent in the instrumental analysis to be picked up and is an essential complement to the quality control system.

A summary of the installation and beer production at the brewery can be found in Table 2.

Table 1.
Comparison of laboratory data with manufacturer's declarations and industry standards

Parameters	Source of information		
	Laboratory data	**Producer's declaration**	**Beer style sheet**
Style	Blond Ale	Blond Ale	Blond Ale
Alcohol content [%]	5,4	5,2	3,8-5,5
Initial extract [°P]	12,5	12,5	9,5-13,5
Bitterness [IBU]	-	1/5 (~ 20)	15-28
Final extract [°P]	2,3	-	2-3,2
Colour	Light	Light	Light

Note. The beer style sheet is taken from a list of beer styles compiled by the BJCP (Beer Judge Certification Program).

Source: own work on information from BGH and BJCP (BJCP 2021 Style Guidlines).

Table 2.
Summary of beer production parameters.

Parameters	**Value**
Mashing capacity	10 hl
Time per brew	~4 hrs
Number of tank-fermenters	10 × 20 hl
Type of yeast	dry
Brewing frequency	approx.2 brews per day (123 brews per year)
Bottling system	manual with a capacity of 250-300 bottles per hour
Quality control	on site and in an external laboratory

Source: own work.

4. Study results

The production system in place at the Mining and Smelting Brewery can be characterised as a hybrid of the "Make to Stock" (MTS) model, which is used for the beer on tap, and the flexible "Make to Order" (MTO) model, which is used for special order batches and seasonal beers. Production scheduling is mainly done in a forward scheduling mode, taking into account the constraints imposed by the availability of fermentation and lager tanks and recipe parameters. This model allows production volumes to be adjusted dynamically according to changing demand, but is highly sensitive to logistical disruptions and lack of capacity reserves.

Maximum potential production should be investigated using the formula (Singh et al., 2021):

$$Capacity\ utilization\ (CU) = \frac{\text{Real Capacity}}{\text{Installed Capacity}} \times 100\% \quad (1)$$

Maximum production volume, assuming:

- single-shift operation, five days a week, a maximum of 250 working days per year (including public holidays) and
- production of two brews per day, is:

$$250\ days\ \times \frac{2\ \times 10hl}{day} = 5000\ hl \tag{2}$$

When substituted into the formula:

$$Capacity\ utilization\ (CU) = \frac{1251{,}7\ hl}{5000\ hl} \times 100\% = 25{,}03\% \tag{3}$$

The maximum production volume on fermentation and lagering, taking into account the lagering of the beer over a period of 8 weeks (the average time for all styles produced at the brewery) is:

$$\frac{52\ weeks}{8\ weeks}\ \times 10 \times 20\ hl = 1300\ hl \tag{4}$$

$$Capacity\ utilization\ (CU) = \frac{1251{,}7\ hl}{1300\ hl} \times 100\% = 96{,}28\% \tag{5}$$

According to the above calculations and the Theory of Constraints (Goldratt, 1984), the fermentation and ageing stage is the structural bottleneck of the production process at the plant under analysis. The limited number of tank-fermenters (10 × 20 hl) and an average lagering time of 8 weeks determine the maximum production volume, which under current conditions does not exceed 1300 hl per year. A further increase in capacity would require a physical expansion of the space or the use of larger tanks (e.g. 40 hl), with investment and architectural implications. However, despite this constraint, the installation of 4 additional 40hl tanks would allow an 80% increase in annual capacity.

Currently, the beer bottling process at the Mining and Smelting Brewery is carried out using a semi-automatic two-station bottling machine (Fillmaster Five model), with a capacity of 250-300 bottles per hour. With a capacity of one fermentation-labelling tank of 20 hl, it takes an average of seven to eight hours to fully bottle the contents into 500 ml bottles, assuming one-person operation. In addition, the labelling process is done manually or with a separate semi-automatic machine, which also generates comparable working time (up to 8 hours) required to prepare one batch of products ready for storage or sale.

The planned solution to improve this stage of the technological process is the installation of an integrated, automatic filling and labelling line with a capacity of 800-1000 bottles per hour. This type of installation enables beer to be filled, capped and labelled simultaneously, with significantly less manual labour. In the case of a 20 hl tank, the bottling and labelling time would be reduced to around 2.5-3 hours, meaning a reduction in total operating time of up to 65-70% compared to the current operating model.

In addition, due to the greater stability of the operational parameters (constant flow, volume repeatability, uniform pressure), the automated line would increase the homogeneity of the final product and reduce the risk of losses due to spillage, oxidation or improper bottle closure. A constant filling height and an automated air evacuation system (CO_2) further improve the microbiological quality and foam stability of the finished beer.

From an organisational perspective, the use of such a line would require the presence of two employees to operate the line (supervision of bottle feeding and collection and packaging), but this does not involve highly qualified staff. In addition, the automation of this stage would allow better management of the workforce in other parts of the brewery, especially in the area of preparation of the next brews or warehouse logistics.

The manual operations identified in the production area, such as the collection of malt at a temperature of 75°C or the manual transport of malt over long distances and differences in levels, generate significant accident risks and excessive physical strain on employees. According to the ISO 11228-1:2003 guidelines for the manual handling of loads, these conditions are to be considered non-ergonomic. The installation of installations for the automatic ejection of malt and subsystems to facilitate hose reeling (wall-mounted reels) would contribute to reducing occupational risks and improving working comfort.

In the context of the observed increase in consumer interest in the low- and non-alcoholic beer segment (the so-called NoLo category), the Mining and Smelting Brewery could consider the possibility of launching a non-alcoholic beer. However, this would require a detailed technological and economic analysis, taking into account infrastructure constraints and potential investment costs.

One method of producing non-alcoholic beer is to use a thermal or vacuum de-alcoholisation facility, allowing the removal of alcohol from the finished beer without significantly affecting its sensory profile. However, this technology involves a very high capital investment. The cost of purchasing and installing an industrial dealcoholisation installation exceeds PLN 1.7 million, not counting the cost of adapting the brewery infrastructure (supporting installations, liquid circulation modernisation, technical space), which makes this solution uneconomic in the conditions of craft production of limited scale.

An alternative to alcohol removal technology is the use of specialised yeast strains with limited fermentation capacity that produce minimal amounts of ethanol (less than 0.5 per cent by volume). This approach produces non-alcoholic beer without the need for dealcoholisation, significantly lowering the investment threshold. However, consideration must be given to the need to purchase and maintain separate strains of micro-organisms, which can generate additional operational costs due to the need for isolated storage, cyclic multiplication or continuous acquisition of new cultures. To ensure microbiological safety and to avoid contamination between product lines, it would also make sense to dedicate a separate fermentation tank or dedicated fermentation plant for this type of process. A brief summary of the above section can be found in Table 3.

Table 3.
Summary of proposed recommendations.

Area	Identified issue	Proposed improvement	Impact on production
Fermentation and maturation	Occurrence of a bottleneck in fermentation and lagering tanks	Acquisition of additional 40 hl fermenters with external installation	Increase in annual production capacity
Bottling and labeling	Manual handling and transport	Implementation of an automatic bottling line	Reduction of cycle time by approx. 70%
Ergonomics	Manual removal of spent grains at 75°C	Installation of an automatic spent grain discharge system	Improved occupational health and safety
Ergonomics	Risk of injury due to unprotected hoses left on the floor	Installation of wall-mounted automatic hose reels	Improved occupational health and safety
Product portfolio	Lack of alcohol-free beer in the brewery's offering	Installation of de-alcoholization equipment or development of a <0.5% ABV beer recipe	Expansion of the product range

Source: own work.

5. Discussion and conclusion

The purpose of this study was to conduct a comprehensive analysis of the beer production process in the operational environment of a craft brewery, with particular emphasis on technological, organizational, and quality-related aspects. The case study of Górniczo-Hutniczy Brewery in Kraków enabled the identification of the characteristic features of medium-batch production in a small-scale brewing facility focused on product quality and the local distribution network.

The application of diversified research methods – including participant observation, process documentation analysis, and technological indicator measurement – allowed for a reliable evaluation of production effectiveness based on the OEE (Overall Equipment Effectiveness) model. This approach facilitated the identification of critical stages of the process, including

production bottlenecks such as time-consuming manual bottling and labeling, manual removal of spent grain, and limitations related to fermenter capacity and storage space.

The results indicate that despite the small scale of operations and limited technical resources, the brewery demonstrates a high level of efficiency in the fermentation and maturation stages (with tank utilization at 96.3%) and maintains stable production quality in compliance with ISO 9001 and ISO 22000 requirements. At the same time, the identification of operational inefficiencies enabled the formulation of several organizational and technological improvement proposals, including the installation of an automatic bottling line, ergonomic management systems for hoses and spent grain, and the implementation of a CO_2 recovery solution from fermentation.

From a strategic perspective, the study also discussed potential development directions for the enterprise, including the formation of a purchasing group, expansion of fermentation infrastructure, and introduction of alcohol-free beer into the product portfolio. The analysis highlighted technological and investment barriers to the implementation of such products, suggesting the use of low-attenuating yeast strains as the most economically feasible solution for small breweries.

In conclusion, the findings of this study confirm that achieving high efficiency and consistent quality in a craft production environment is possible not only through capital investment but also through the effective use of available resources, thoughtful work organization, and the implementation of process-based management principles. The insights presented herein may serve as a practical reference for other small and medium-sized breweries seeking to enhance their operational effectiveness within the modern craft brewing sector.

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