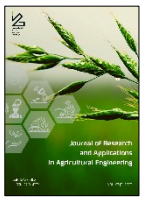
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Barriers to the production of spare parts for agricultural transport vehicles from semi-finished cast products: an expert perspective

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The manufacture of spare parts for agricultural transport equipment from cast blanks involves various barriers affecting the quality of finished products and their operational proper-ties. The aim of this study is to identify and assess these barriers from the perspective of enter-prises engaged in machining operations. The empirical basis of the study is a survey conducted among spare-parts manufacturers. The analysis covers barriers related to the quality of cast blanks, difficulties encountered during machining, quality assurance of finished parts, and problems revealed during assembly and operation. The adopted approach makes it possible to assess the significance of individual barriers, identify relationships between them, and establish their hierarchy. The findings may provide a basis for identifying areas requiring improvement in enterprises manufacturing spare parts for agricultural transport equipment.

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1. Introduction

The efficiency of agricultural transport means depends largely on the availability of spare parts (Kennedy et al., 2002; Lengu et al., 2014) that meet specific dimensional, quality and functional requirements (Antosz & Ratnayake, 2019; Bacchetti & Saccani, 2012; Chaudhuri et al., 2021). These components are operated under conditions of variable loads, vibrations, dust, humidity and contact with factors accelerating wear and corrosion. Their quality therefore affects not only the durability of the repaired units, but al-so the reliability, safety, and continuity of use of the machines (dos Reis et al., 2023). In this context, the production of spare parts from cast semi-finished products, used, among others, for the production of bodies, housings, hubs, wheels, brackets, and elements of running and drive systems, is of particular im-portance (Perzyk et al., 2000).

A casting is a semi-finished product whose properties directly impact the ability to achieve the required features of the finished part. Dimensional and shape variability, uneven material allowance, non-uniform hardness, internal defects, and varying surface conditions can hinder its proper mounting and machining (Skarbiński, 1966). These problems increase the risk of excessive tool wear, scrap, the need for rework, and extended production time (Olszak, 2017). So-me casting defects are revealed only during the removal of subsequent layers of material, which limits the possibility of their early detection (Godlewski, 1955).

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Subtractive machining (Grzesik, 2016) plays a crucial role in shaping the final properties of spare parts (Stephenson & Agapiou, 2016). Its goal is to achieve the required dimensions, tolerances, surface positioning, holes, threads, and grooves, as well as the appropriate surface quality (Grzesik, 2018). In the case of cast semi-finished products, meeting these requirements can be difficult due to the instability of the starting material, deformations occurring during mounting or machining, and documentation that does not match the actual casting properties. Barriers emerging during the manufacturing phase can subsequently result in problems with part fit du-ring assembly, premature wear, or damage during use (Paman et al., 2022, 182-191). Barrier assessment should not be limited solely to the machining process. It is necessary to consider the entire chain of dependencies, including the quality of the delivered semi-finished product, the production of the spare part, the inspection of the finished product, and its subsequent assembly and operation. Part traceability is also crucial, enabling the linking of complaints or failures to a specific production batch and the delivery of castings. Information derived from assembly, service, and use can provide the basis for improving material requirements, manufacturing technology, and quality control methods.

In the literature, barriers related to casting quality, machining, and part operation are most often considered separately. However, their interconnections from the perspective of agricultural spare parts manufacturers are analysed to a limited extent. The hierarchy of problems occurring at individual stages of production and their impact on the quality and operational properties of finished parts also remains insufficiently understood. This justifies the need for research enabling an integrated assessment of these conditions.

The aim of this study is to identify and assess barriers encountered during the production of spare parts for agricultural transport vehicles from cast semi-finished products, with particular emphasis on issues affecting the quality of finished products and their operational properties. The study was based on self-assessment conducted by representatives of companies conducting subtractive machining. Respondents rated the importance of individual barriers on a scale of 1 to 5, where 1 indicates no problem, and 5 indicates a very significant problem.

The adopted approach allows for the identification of barriers related to cast semi-finished products, difficulties encountered during production, problems related to the quality of finished parts, and irregularities revealed during assembly and operation. It also allows for the development of a hierarchy of barriers and the differentiation of these barriers based on company characteristics, the type of material processed, the group of parts manufactured, and the machining technology used. The obtained results can form the basis for formulating actions to reduce production problems, improve the quality of spare parts, and improve their durability and reliability..

2. Starting point

The starting point for this discussion is the assumption that a company producing spare parts does not perform the entire casting process, but receives the casting as input material for further processing. Therefore, the manufacturer's direct influence on the material's structure, casting accuracy, and the presence of internal defects is limited. At the same time, the pro-cessing company is responsible for the dimensional accuracy and quality of the part delivered to the customer.

The production of spare parts differs from the production of components intended for initial assembly. It can be carried out in smaller batches, based on documentation for previously developed designs, and with limited availability of identical semi-finished products. This re-quires maintaining interchangeability, meaning the ability to use a new part without making significant changes to the repaired assembly. Therefore, reproducing the required geometric and functional characteristics despite the variability of the delivered castings becomes crucial.

A barrier is defined as any condition that hinders the production of a part that complies with the requirements, increases the scope of corrections and inspections, or increases the risk of problems during assembly and use. Barriers may stem from the semi-finished product, machining conditions, quality control method, information flow, or limited ability to link an operational problem to a specific production batch.

The basic unit of analysis is therefore the spare part manufactured from the cast semi-finished product, while the research perspective is defined by the company conducting the sub-tractive machining. The assessment is not based on the technological process itself, but on the significance of the problems encountered by the manufacturer – from casting acceptance to obtaining information about the part's behaviour during use.

This approach allows for the organization of barriers into four related areas: the properties of the cast semi-finished product, the production of the spare part, ensuring the quality of the finished product, and assembly and operation. This division forms the basis for the design of the research tool and the subsequent

interpretation of the scores provided on a scale of 1 to 5.

3. Research material and method

3.1. Research gap

In the literature, barriers related to casting quality, machining and part operation are most often analysed separately. There is a lack of research covering the problems related to the cast semi-finished product, the production of spare parts and their subsequent assembly and use. The perspective of producers of spare parts for agricultural means of transport and the hierarchy of barriers affecting the quality and operational properties of these products remain insufficiently recognized.

3.2. The purpose of the work

The aim of this work is to identify and assess barriers encountered during the production of spare parts for agricultural transport vehicles from cast semi-finished products, with particular emphasis on issues affecting the quality of finished products and their operational properties. Achieving the main objective required the implementation of the following sub-objectives:

- Identifying barriers related to the quality, properties, and repeatability of cast semi-finished products used for the production of spare parts.
- Assessing difficulties encountered during the production of spare parts from cast semi-finished products using subtractive machining methods.
- Identifying problems associated with achieving the required dimensions, shape, surface quality, and fit of spare parts.
- Assessing barriers affecting the quality and preparation of finished spare parts for assembly and use.
- Identifying problems encountered during the assembly, operation, and servicing of spare parts.

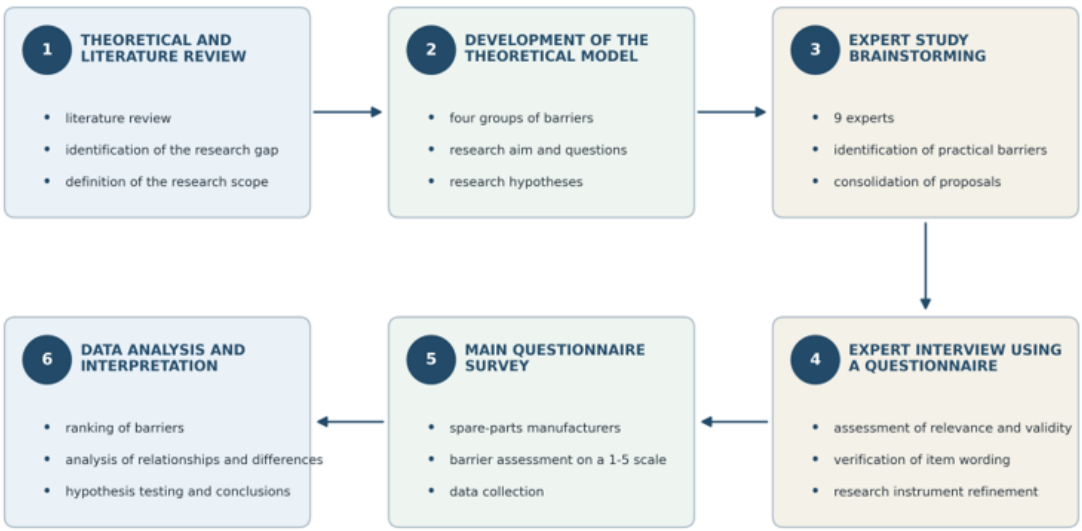
3.3. Research question

What barriers limit the production of spare parts for agricultural transport vehicles from semi-finished cast parts and what is their significance for the quality and operational properties of finished products?

3.4. Study implementation scheme

The research was planned as a sequence of interconnected theoretical, experimental and empirical stages (Figure 1).

Figure 1. Scheme of research implementation

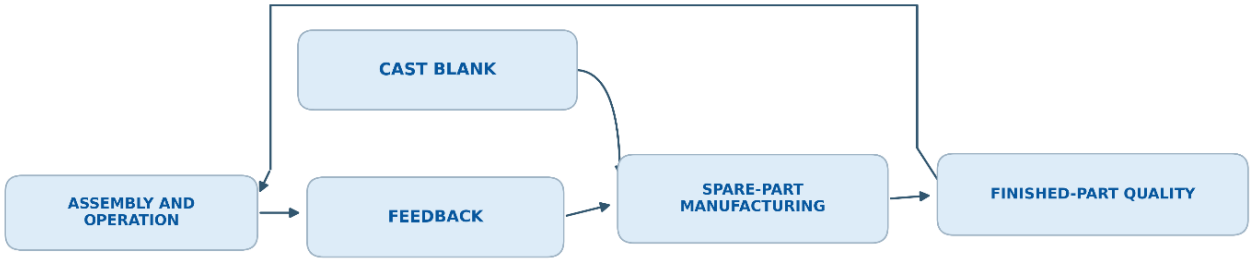


Source: own study

The starting point was the perspective of a company that does not conduct a casting process, but uses a cast semi-finished product as input material for the production of spare parts using sub-tractive machining methods. The adopted framework allowed for a transition from identifying the problem in the

literature, through identifying barriers encountered in company practice, to their quantitative assessment. The literature analysis served to clarify the terminological foundations and identify factors that may limit the production of spare parts. It also allowed for the identification of a research gap resulting from the separate approach to casting, machining, quality, and operational problems. Based on the literature research results, a theoretical model was developed as a starting point for further work. The model is based on the assumption of a relationship between the quality of the semi-finished product, manufacturing difficulties, the quality of the finished part, and problems revealed during its use. It was assumed that problems arising in one area can influence assessments made in other areas. The model also incorporates feed-back from assembly, service, complaints, and part use (Figure 2).

Figure 2. Areas of theoretical and cognitive research



Source: own study

The next stage consisted of an expert survey conducted with nine individuals with knowledge or experience in the production, quality control, assembly, or operation of cast parts. The first part of the study utilized a brainstorming method. Its goal was to gather the broadest possible set of barriers actually encountered in company practice. Experts identified problems related to the quality of castings, their preparation for processing, achieving the required part characteristics, inspection of finished products, and irregularities revealed during assembly and use.

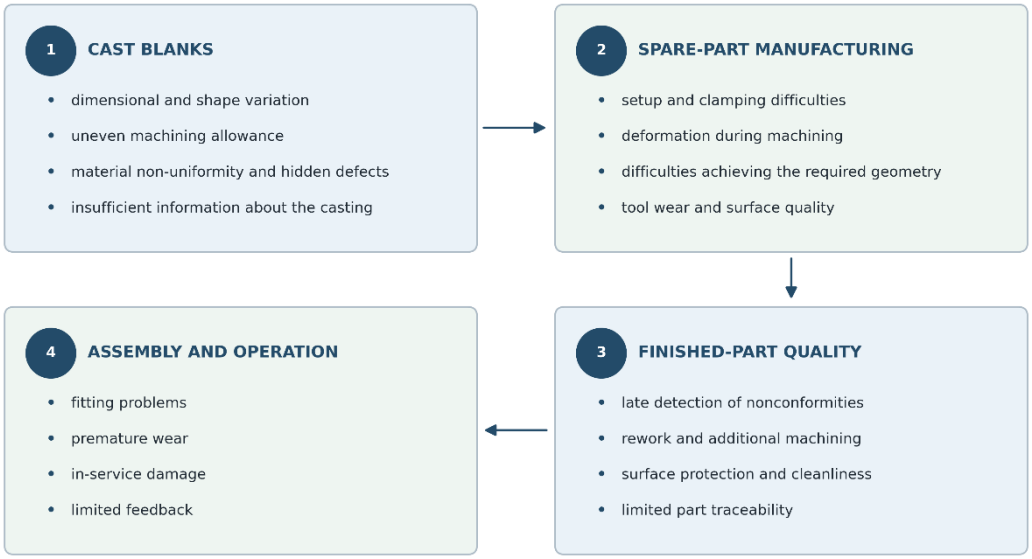
The reported barriers were organized by combining propositions of similar importance and eliminating duplication. They were then assigned to areas identified in the theoretical model. The experts primarily assessed:

- the significance of individual barriers;
- the consistency of the barriers with company practice;
- the clarity and understandability of the formulations;
- the completeness of the adopted research areas;
- the relevance of the questions to the study's objective.

Based on the theoretical model and the results of the expert study, an appropriate research tool was developed for spare parts manufacturers who perform subtractive machining of cast semi-finished products. The survey included 30 questions addressing four groups of barriers (Figure 3).

Each barrier is rated on a scale of 1 – not a problem, 2 – a small problem, 3 – a moderate problem, 4 – a major problem, and 5 – a very major problem. An additional response, "ND," is provided, indicating that the barrier does not apply to the company or that the respondent does not have sufficient data to assess it. The adopted framework leads from theoretical problem identification to empirical assessment of barriers by producers. At the same time, the expert sur-vey serves as a link between literature findings and company practice, increasing the content validity of the survey.

Figure 3. Basic groups of barriers



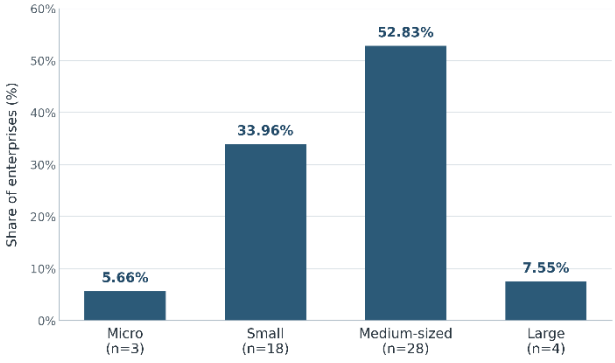
Source: own study

4. Research results

4.1. Characteristics of the surveyed enterprises and expert profile

A total of 53 experts representing purposefully selected companies producing spare parts (replacements) for agricultural transport vehicles participated in the study. Medium-sized enterprises comprised the largest group – 28 entities, representing 52.83% of the sample. Small enterprises were the second largest category – 18 entities (33.96%). In total, small and medium-sized enterprises constituted 86.79% of the study population. Large enterprises accounted for 7.55% (4 entities), while microenterprises accounted for 5.66% (3 entities). The sample structure therefore indicates a clear dominance of the SME sector, which comprised 92.45% of respond-ents.

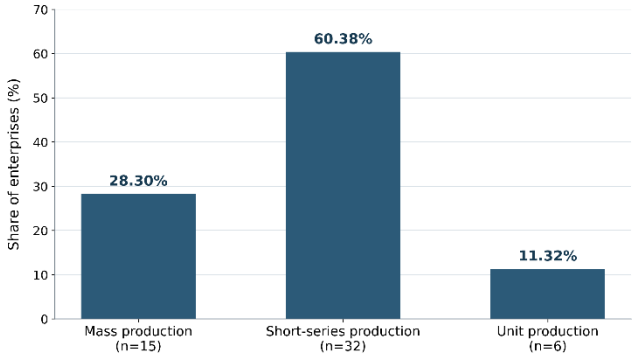
Figure. 4. Characteristics of the surveyed enterprises according to their size



Source: own study based on research

The surveyed group was dominated by enterprises conducting short-run production – 32 entities (60.38%). Mass production was indicated by 15 enterprises (28.30%), while single-unit production was indicated by 6 entities (11.32%). The results indicate that the identified barriers to spare parts production were assessed primarily from the perspective of enterprises implement-ing short and varied production runs (Figure 5).

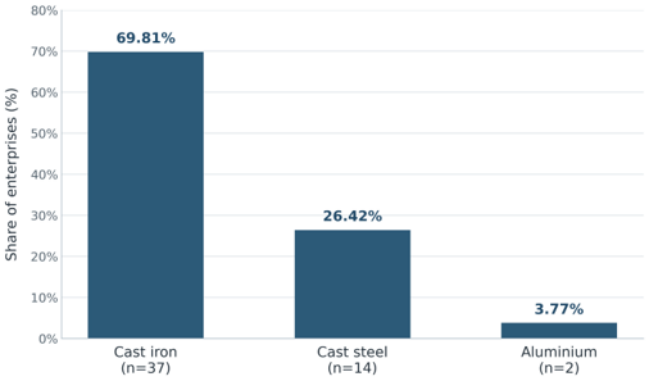
Figure 5. Characteristics of the surveyed enterprises according to the type of production



Source: own study based on research

The surveyed sample was dominated by companies processing primarily iron castings – 37 entities, or 69.81%. Steel castings were indicated by 14 companies (26.42%), while aluminium castings were indicated by only 2 entities (3.77%). In total, iron and steel castings accounted for 96.23% of responses.

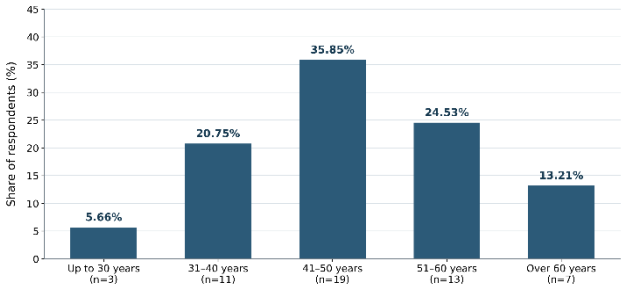
Figure 6. Characteristics of the surveyed enterprises according to the type of casting processed



Source: own study based on research

The largest group consisted of respondents (expert sampling) aged 41-50 – 19 individuals (35.85%). The next groups included individuals aged 51-60 – 13 individuals (24.53%) and 31-40 – 11 individuals (20.75%). Respondents over 60 years of age constituted 13.21% of the sample, while those under 30 constituted 5.66%. The age structure indicates a predominance of respond-ents with potentially significant professional experience and practical knowledge of the issues related to the production of spare parts from cast semi-finished products (Figure 7).

Figure 7. Characteristics of the surveyed experts according to age

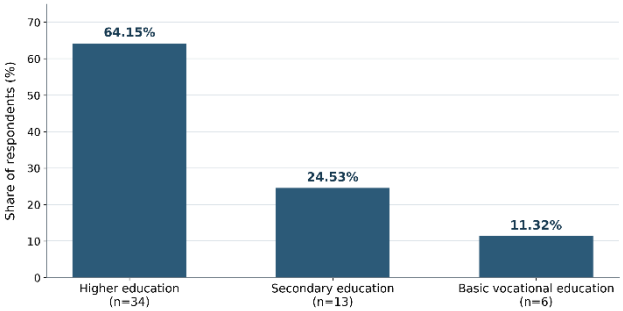


Source: own study based on research

The study group was dominated by individuals with higher education – 34 respondents (64.15%). Thirteen individuals (24.53%) had secondary education, while six (11.32%) had vocational education. This structure indicates a high level of formal preparation of respondents to assess barriers encountered in the process of manufacturing spare parts from semi-finished cast products.

The survey respondents were a purposively selected group of 53 experts professionally in-volved in the production of spare parts from semi-finished cast parts. The primary selection criterion was practical knowledge of the problems encountered during the machining of castings and the assessment of the quality of finished parts. Purposeful sampling was based on the specialized nature of the study subject, which required knowledge unavailable to randomly selected respondents. The combination of practical experience, formal training, and direct connection to the analysed production area allows the respondents to be considered competent experts. Their assessments therefore provide a reliable basis for identifying, prioritizing, and analysing barriers to the production of spare parts for agricultural transport vehicles from semi-finished cast parts.

Figure 8. Characteristics of the surveyed experts according to their education



Source: own study based on research

4.2. Results

The results of a study examining barriers to the production of spare parts from cast semi-finished products are presented in Table 1. The analysis was conducted by considering specific problem groups and their perceived importance by respondents. The results enabled the identification and prioritization of the most important barriers in the area under study.

The obtained results indicate that barriers related to the quality of cast semi-finished products are of moderate importance to companies engaged in subtractive machining. The average rating for the entire group of problems was approximately 3.05 on a five-point scale, indicating that the analysed difficulties occur in practice, but their significance varies depending on the type of problem.

The highest-rated barrier was excessive dimensional and shape differences between successive castings, for which the average was 3.49. A total of 47.2% of experts considered this problem to be significant or very significant, while 41.5% assigned it moderate significance. This result indicates that the geometric uniqueness of semi-finished products poses a significant obstacle to the organization of machining. It can necessitate more frequent adjustments to ma-chine settings, changes in the base and clamping methods, and the individual adjustment of machining

parameters to individual castings. This problem becomes particularly significant in the short-run production environment prevalent in the surveyed companies. Hidden defects, such as cracks, pores, and voids, which only become apparent during machining, ranked second with an average score of 3.40. 45.3% of respondents considered them a significant or very significant barrier. The significance of this problem stems primarily from their late appearance, often after some of the costs associated with preparation and initiation of machining have been incurred. Hidden defects can lead to part rejection, the need for re-processing, material losses, and disruptions in order fulfilment.

Table 1. Problems related to cast semi-finished products

No.	Barrier or problem	1	2	3	4	5	average grade
		%					
1.	Excessive differences in dimensions and shape between successive castings.	3.8	7.5	41.5	30.2	17.0	3.49
2.	Too little or uneven material allowance to be removed.	15.1	30.2	39.6	9.4	5.7	2.60
3.	Variable material hardness and uneven surface condition of castings.	9.4	17.0	35.8	20.8	17.0	3.19
4.	Corrosion, contamination or damage to castings delivered for processing.	5.7	18.9	30.2	24.5	20.8	3.36
5.	Hidden defects, such as cracks, pores or cavities, which only become apparent during processing.	7.5	15.1	32.1	20.8	24.5	3.40
6.	Lack of full information about the material, origin and quality of the delivered casting.	32.1	32.1	20.8	9.4	5.7	2.25

Source: own study based on research

Corrosion, contamination, and damage to castings delivered for machining were assigned a similar level of importance. This barrier received an average score of 3.36, with 45.3% of experts rating it 4 or 5. The result indicates the importance of storage, transport, and preliminary preparation conditions for castings. Poor surface condition of the semi-finished product can necessitate additional cleaning, hinder proper part mounting, and increase the risk of tool damage.

Variable material hardness and uneven surface condition of castings reached an average score of 3.19. This problem was rated as high or very high by 37.8% of respondents, while 35.8% considered it moderate. Variability in material properties affects machining stability, tool life, surface quality, and the ability to maintain repeatable technological parameters. This barrier can therefore generate both quality issues and increased manufacturing costs.

Too low or uneven material removal was rated significantly lower, with an average of 2.60. This problem was rated as high or very high by 15.1% of respondents, while 45.3% as-signed it low or very low importance. This may indicate that machining allowances are sufficient in most companies or that problems in this area are incidental. At the same time, the high share of moderate ratings (39.6%) indicates that this issue cannot be completely ignored.

The lowest rating was given to the lack of complete information about the material, origin, and quality of the delivered casting, with an average of 2.25. As many as 64.2% of respondents considered this problem to be unimportant or of little importance, while only 15.1% considered it to be significant or very significant. This result may indicate that the surveyed companies generally receive sufficient information about semi-finished products, use reliable supply sources, or have their own procedures to mitigate the effects of information gaps.

The hierarchy of assessments shows that the greatest difficulties directly concern the physical quality and repeatability of castings, particularly their geometry, the presence of hidden defects, and surface condition. Barriers related to material documentation and machining allowances are of lesser importance. The results therefore justify focusing improvement efforts on in-coming casting inspection, improving their dimensional repeatability, early detection of internal defects, and improving the transport and storage conditions of semi-finished products.

Table 2. Difficulties in the production of spare parts

No.	Barrier or problem	1	2	3	4	5	average grade
		%					
1.	Unclear, incomplete, or frequently changed requirements for the finished replacement part.	18.9	22.6	35.8	13.2	9.4	2.72
2.	Difficulty in reproducibly aligning the casting due to uneven raw surfaces.	20.8	17.0	41.5	13.2	7.5	2.70
3.	Part distortion during clamping or material removal.	17.0	20.8	37.7	18.9	5.7	2.75
4.	Remaining raw surface fragments in areas requiring machining.	18.9	39.6	32.1	5.7	3.8	2.36
5.	Difficulty in reproducibly achieving the required part dimensions.	30.2	43.4	22.6	1.9	1.9	2.02
6.	Difficulty maintaining the correct positioning of surfaces, holes, threads, or grooves.	43.4	28.3	22.6	1.9	3.8	1.94
7.	Excessive tool wear or deterioration of the machined part surface finish.	17.0	24.5	41.5	7.5	9.4	2.68

Source: own study based on research

The results presented in Table 2 indicate that difficulties encountered during the production of spare parts were rated relatively low. The arithmetic mean of all analysed problems was 2.45 on a five-point scale. This means that the barriers examined are present in company practice, but are generally not dominant or critical. None of the assessed difficulties achieved a mean score equal to or higher than 3.00.

Part deformation during clamping or material removal received the highest rating, with a mean score of 2.75. This problem was considered a major or very major barrier by 24.6% of respondents, moderate by 37.7%, and low by 37.8%. This result indicates that deformation can be a noticeable difficulty, especially when machining parts with low rigidity, complex shapes, or uneven material allowance distribution. This problem can impact manufacturing accuracy, clamping stability, and necessitate additional inspection operations. Second place went to un-clear, incomplete, or frequently changed requirements for the finished spare part, with an average score of 2.72. 22.6% of experts rated it 4 or 5, while 35.8% considered it a moderate problem. This result demonstrates that barriers to spare part production are not solely due to material properties and machining processes, but can also result from insufficient documentation preparation, ambiguous definition of part parameters, or changes to requirements introduced during or-der processing. A similar rating was given to the difficulty of repeatable casting alignment due to uneven raw surfaces, with an average score of 2.70. This problem was rated moderate by 41.5% of respondents, and severe or very severe by 20.7%. Casting surface irregularities can complicate the selection of machining bases and ensure stable mounting. At the same time, the predominance of ratings from 1 to 3 indicates that companies are, in most cases, able to limit the effects of this problem through the use of clamping methods, employee experience, or individual adjustments to settings.

Excessive tool wear or deterioration of the surface smoothness of the machined part received an average rating of 2.68. Respondents' ratings focused primarily on a moderate level (41.5%), while 16.9% of respondents considered this barrier to be significant or very significant. This problem may be related to variations in casting hardness, the presence of moulding sand residue, the surface condition of the semi-finished product, and incorrect selection of machining parameters. However, this value does not indicate that excessive tool wear is a common or critical problem in the surveyed companies.

Remaining raw surface fragments in areas requiring machining received a lower rating (average rating of 2.36%). Only 9.5% of respondents considered this problem to be significant or very significant, while 58.5% assigned it low or very low importance. This may indicate that machining allowances were generally selected correctly and the scope of operations was effectively prepared. In individual cases, however, this problem may result from the dimensional non-repeatability of castings or incorrect positioning of the blank.

Difficulty in consistently achieving the required part dimensions was assigned relatively low importance – an average of 2.02. As many as 73.6% of experts rated this barrier as 1 or 2, while only 3.8% rated it 4 or 5. This result suggests that the surveyed companies generally have the appropriate competencies, equipment, and control solutions to maintain the required dimensional accuracy.

Difficulty in maintaining the correct position of surfaces, holes, threads, or grooves received the lowest rating – an average of 1.94. Ratings of 1 and 2 accounted for 71.7% of responses, while only 5.7% of experts considered this problem to be significant or very significant. This result indicates a relatively high level of mastery of operations related to ensuring the accuracy of the geometrical elements of the part.

The study shows that the greatest difficulties in the production of spare parts relate not so much to achieving the required dimensions and relative positioning of the machined elements, but rather to the preparation and stabilization of the semi-finished product at the initial stage of processing. Part deformation, variability of raw surfaces, and ambiguity of requirements for the finished product are particularly significant. At the same time, the lower average ratings for this group of barriers compared to problems related to cast semi-finished products – 2.45 and 3.05, respectively – indicate that companies have better control over the manufacturing process itself than the quality and repeatability of the resulting castings. Reducing barriers should therefore focus primarily on properly preparing requirements, improving base and clamping methods, and preventing deformation.

Table 3. Quality problems and preparation of the finished product

No.	Barrier or problem	1	2	3	4	5	average grade
		%					
1.	Delayed detection of defects and discrepancies in the finished spare part.	17.0	24.5	39.6	13.2	5.7	2.66
2.	Frequent rework, additional machining, or re-measuring.	20.8	30.2	32.1	13.2	3.8	2.49
3.	Difficulty in thoroughly removing burrs, chips, and other machining residues.	22.6	32.1	28.3	13.2	3.8	2.43
4.	Corrosion or damage to finished surfaces during storage and transport.	28.3	30.2	32.1	9.4	-	2.23
5.	Difficulty in linking the finished spare part to the casting delivery and inspection results.	22.6	28.3	34.0	9.4	5.7	2.47
6.	Requirement of additional adjustments to the spare part during assembly.	26.4	35.8	24.5	9.4	3.8	2.28

Source: own study based on research

The results presented in Table 3 indicate that quality issues and difficulties related to the preparation of the finished product do not constitute the dominant barrier group in the surveyed companies. The arithmetic mean of all analysed issues was 2.43 on a five-point scale. None of the factors reached a mean of 3.00, which allows us to conclude that the surveyed companies generally manage quality assurance and the preparation of spare parts for storage, transport, and assembly. At the same time, the results indicate the existence of specific areas requiring further improvement.

The highest-rated problem was the late detection of defects and nonconformities in the finished spare part, with an average of 2.66. This issue was considered a major or very major barrier by 18.9% of respondents, moderately important by 39.6%, and slightly or very unimportant by 41.5%. The relatively high ranking of this factor may indicate that some nonconformities are detected only during the final inspection, when most of the material and production costs have al-ready been incurred. Late identification of defects limits the ability to quickly correct the pro-cess and increases the risk of rework, part rejection, or order delays.

Second place was occupied by the need for frequent rework, additional machining, or re-measurements, with an average of 2.49. A total of 17.0% of respondents rated this issue as high or very high, 32.1% as moderate, and 51.0% assigned it low or very low importance. This result indicates that rework is not common, but in some companies it can reduce productivity, increase labour intensity, and interfere with the timely production of spare parts.

The difficulty in linking the finished spare part to the delivery of the casting and inspection results received a similar rating, with an average of 2.47. The problem was considered significant or very significant by 15.1% of respondents, while 34.0% rated it as moderate. This result indicates the need to maintain part traceability throughout the manufacturing process. Link-ing the finished product to a specific casting batch, machining parameters, and inspection results facilitates determining the causes of nonconformities and taking corrective actions. Incomplete traceability can be particularly important for defects that only become apparent during assembly or operation.

The difficulty in thoroughly removing burrs, chips, and other machining residues reached a mean score of 2.43. This barrier was considered significant or very significant by 17.0% of respondents, while 54.7% assigned it low or very low importance. This result suggests that finish-ing operations are generally carried out effectively. However, it should be emphasized that even occasional residues left after machining can affect the correct assembly, operational safety, and reliability of the finished part. The need for additional adjustments to the spare part during assembly was rated lower – an average of 2.28. Ratings of 1 and 2 accounted for a total of 62.2% of responses, with only 13.2% of respondents rating 4 or 5. This result corresponds to the low ratings for difficulty in obtaining the required dimensions and correct positioning of the part's geometric elements. Therefore, it can be assumed that most finished parts maintain dimensional consistency, allowing for assembly without additional adjustments.

The lowest rating was given to the risk of corrosion or damage to finished surfaces during storage and transport – an average of 2.23. This problem was rated as significant by 9.4% of respondents, while none of the respondents assigned it a rating of 5. At the same time, 58.5% of experts considered its importance to be low or very low. This may indicate the use of effective surface protection methods, appropriate packaging, and appropriate storage and transport conditions for finished parts. The hierarchy of ratings shows that the most important quality problems are primarily related to the detection of nonconformities and the need for corrective action. Difficulties related to securing, assembly, and final preparation of parts are of lesser importance. From the perspective of process improvement, it is therefore justified to shift quality control to earlier stages of production, increase the frequency of in-process inspections, and develop trace-ability that allows for linking the finished product to the casting batch and inspection results.

A comparison of the three groups of barriers analysed so far indicates that quality problems and finished product preparation achieved an average score similar to the difficulties encountered during part production – 2.43 and 2.45, respectively – and significantly lower than the problems associated with cast semi-finished products, which averaged 3.05. This means that the main source of difficulties is located before the actual processing begins, primarily in the quality, condition, and repeatability of the delivered castings. The surveyed companies, however, demonstrate a relatively greater ability to control the production process itself and the quality of finished parts.

Table 4. Problems revealed during installation and use

No.	Barrier or problem	1	2	3	4	5	average grade
		%					
1.	Insufficient feedback from the assembly, service, or use of a spare part.	17.0	15.1	39.6	18,9	9.4	2.89
2.	Difficulty in determining the production batch to which a complaint or failure relates.	13.2	20.8	28.3	28,3	9.4	3.00
3.	Premature wear of surfaces interacting with other components.	17.0	18.9	30.2	28,3	5.7	2.87
4.	Damage to parts due to the loads occurring during machine operation.	20.8	17.0	34.0	22,6	5.7	2.75
5.	Loss of required dimensions, shape, or fit during use.	20.8	28.3	30.2	17,0	3.8	2.55
6.	Slow implementation of changes after identifying recurring defects or complaints.	18.9	28.3	24.5	20,8	7.5	2.70

Source: own study based on research

The results presented in Table 4 indicate that problems revealed during the assembly and use of spare parts are of moderate importance to the surveyed companies. The arithmetic mean of all barrier ratings was 2.79 on a five-point scale. This is higher than for difficulties encountered during production and quality issues with the finished product. This indicates that companies have relatively better control over internal production operations than problems revealed after parts are handed over for assembly or use.

The highest-rated barrier was the difficulty in determining the production batch associated with a complaint or failure, with an average of 3.00. This was considered a major or very major problem by 37.7% of respondents, moderate by 28.3%, and low by 34.0%. The varying responses may indicate uneven levels of development of traceability systems across the surveyed companies. The inability to link the faulty part to a specific casting batch, machining process, and inspection results limits the ability to determine the source of the discrepancy and determine whether the problem is isolated or recurring.

Second place was occupied by the lack of sufficient feedback from assembly, service, or use of the spare part – an average of 2.89. A total of 28.3% of respondents rated this barrier as high or very high, while 39.6% assigned it moderate importance. This indicates that information regarding the performance of parts under real-world operating conditions is not always effectively communicated to the manufacturer. This hinders the assessment of product durability and reliability, the identification of recurring defects, and the implementation of improvement measures.

Premature wear of surfaces interacting with other components was rated similarly – an average of 2.87. This barrier was considered high or very high by 34.0% of respondents, moderate by 30.2%, and low by 35.9%. Premature wear can be related to the material properties of the casting, machining accuracy, surface quality, lubrication conditions, and actual operating loads. From a manufacturer's perspective, determining the exact cause of the problem can be difficult, especially with limited access to operational data.

Part damage due to loads occurring during machine operation achieved an average score of 2.75. This problem was rated as high or very high by 28.3% of respondents, while 34.0% considered it moderate. This result indicates that operational failures do occur, but they are not common. They can be caused not only by material defects or manufacturing errors, but also by overloading, improper assembly, or using parts in conditions other than those intended.

Introducing changes too slowly after identifying recurring defects or complaints achieved an average score of 2.70. 28.3% of respondents considered this problem a high or very high barrier, while 47.2% considered it of low or very low importance. The results indicate that some companies effectively respond to identified nonconformities, but in other cases, the flow of in-formation and the implementation of corrective actions may be too slow. Delays increase the risk of the same problem recurring in subsequent production batches.

Loss of required dimensions, shape, or fit during use received the lowest rating, with an average of 2.55. 20.8% of respondents rated the problem 4 or 5, while 49.1% considered the problem minor or very minor. This result may indicate that the geometric characteristics of the part generally remain intact during operation. However, it does not rule out instances where de-formation, wear, or dimensional changes limit the proper interaction of the part with other ma-chine components.

The hierarchy of barriers shows that a greater problem than damage and changes to the part's properties is the limited ability to obtain, organize, and use operational information. The highest rankings were occupied by the difficulty of linking complaints to production batches and the lack of feedback from assembly, service, and use. This indicates the need to develop mechanisms for parts traceability, record complaint data, and systematically transfer information to areas responsible for casting procurement, production preparation, machining, and quality control.

Comparison of all four groups indicates that problems related to cast semi-finished products received the highest ratings, with an average of 3.05. Problems encountered during assembly and use ranked second, with an average of 2.79. Lower scores were given to difficulties dur-ing manufacturing, with an average of 2.45, and to quality problems and finished product preparation, with an average of 2.43.

The results indicate that the main barriers occur at the process entry point and after the part is put into service. Problems occurring in areas directly controlled by the manufacturer are relatively less significant.

The obtained results justify the need to treat spare parts production as a system encompassing not only casting processing but also the quality of deliveries and subsequent performance of the parts in service. Closing the feedback loop is particularly important: from semi-finished product delivery, through manufacturing and inspection, to assembly, service, and use. This approach can facilitate the identification of defect sources, shorten complaint response times, and reduce the risk of recurring problems.

5. Discussion

The obtained results allow us to look at the production of spare parts from cast semi-finished products as a system encompassing four interrelated areas: material supply (Lysons, 2004; Bendkowski, & Radziejowska, 2005; Kowalska, 2005), production transformation (Czerwonka & Podgórski, 2025; Grabowska, 2019; Kowal et al., 2024), quality assurance (Borys, et al., 2024; Budzyński, 2016; Hamrol, 2023) and operation (Sawczuk et al., 2022; Ścieszka & Żołnierz, 2012). Not only the efficiency of individual operations is crucial, but also the quality of the links between these areas. Barriers are primarily focused on the organizational boundaries of the process - between the supplier and the manufacturer, and between the manufacturer and the user of the part.

The relatively lower intensity of difficulties in areas directly controlled by the manufacturer demonstrates the companies' developed ability to compensate for the heterogeneity of semi-finished products. Employee knowledge, the clamping methods used, the selection of machining parameters, and dimensional control allow for limiting the impact of casting variability on the conformity of finished parts. However, this does not mean that material variability is without economic consequences. Its effects can be absorbed by the process in the form of additional preparation time, increased tool wear, additional measurements, or the need to individually adjust the operation.

The results therefore reveal the difference between the ability to obtain a consistent product and the efficiency of its production. A company can effectively ensure the required geometric characteristics of a part while incurring additional costs resulting from the uniqueness of castings. Therefore, the conformity of the final product alone is not a sufficient measure of pro-cess efficiency. The assessment should also include the labour intensity of production preparation, changeover time, the number of additional measurements, tool wear, the level of defects, and the scope of rework.

An important cognitive conclusion concerns the nature of information problems. The low significance of defects in basic material documentation coincides with greater difficulties in maintaining information continuity after the part is handed over for assembly and use. This means that the barrier is not solely the availability of data, but the ability to link it throughout the product lifecycle. Information about the material, process, inspection, complaints, and operational behaviour may exist within the enterprise, but remain dispersed and not used as a coherent basis for decision-making.

From a quality management perspective, this indicates the need to move away from control focused on individual stages towards closed-loop quality management. In this approach, da-ta from assembly, service, and operation should be related to the specific semi-finished product, its processing method, and inspection results. Only by maintaining this continuity can we distinguish material defects from manufacturing errors, improper assembly, or unintended operating conditions.

The study also indicates that improvement limited solely to machining stations may not yield the desired results. If the primary sources of variability lie outside the technological core of the process, further optimization of cutting parameters or final inspection will be limited. Collaboration with casting suppliers, agreeing on acceptance criteria, risk-based input inspection, and standardization of data provided by service and users are becoming increasingly important.

The results should be interpreted with the limitations of the study in mind. The purposive sampling approach allowed for the acquisition of assessments from individuals with practical knowledge, but limits the possibility of statistically generalizing the results to the entire population of companies. The study was based on expert self-assessment, therefore presenting the perceived importance of barriers rather than their directly measured technical and economic im-pacts. It also does not allow for the formulation of conclusions about causal relationships. Further research should combine expert assessments with objective metrics such as reject rates, number of complaints, additional processing time, tool life, and nonconformance costs. It is also worthwhile to examine the differences in assessments based on the type of alloy being pro-cessed, production scale, and company size. This would allow us to determine whether the identified barriers are universal or dependent on technological and organizational conditions.

6. Research conclusions

The research led to significant conclusions:

- The production of spare parts from castings should be analysed as a system that ex-tends beyond the boundaries of the machining process. Its efficiency is also deter-mined by the quality of the semi-finished product and the ability to utilize information derived from assembly and operation (Vignat et al., 2010).
- The technological core of the process is relatively well-mastered by the studied companies. Production competencies enable the production of parts that meet requirements despite material

variability, but may involve hidden costs associated with compensating for this variability.

- The greatest potential for improvement lies at the interface between the company and its suppliers and users. Reducing barriers therefore requires interorganizational coordination, not just the improvement of internal operations (Zhang et al., 2021).
- A key management problem is the disruption of information continuity throughout the part lifecycle. Data availability alone does not provide the opportunity for learn-ing if complaints and operational incidents cannot be linked to the casting's origin, processing process, and inspection results.
- The priority of improvement actions should be preventing problems, not merely re-solving their effects. This requires supplier qualification, defining casting acceptance criteria, risk-based incoming inspection, and early detection of defects.
- Assessing process effectiveness should not be limited to the dimensional conformance of the finished part. It should be supplemented with measures of efficiency, quality costs, material losses, additional labour, and product performance in service.
- The research's cognitive contribution lies in demonstrating that barriers to the pro-duction of spare parts from cast semi-finished products are primarily systemic and in-ter-process in nature. Reducing these barriers requires integrating supply management, production, quality, and operational information within a single improvement loop.

7. Summary

The aim of this work was achieved by identifying, assessing, and prioritizing barriers to the production of spare parts from semi-finished cast parts. In answering the research questions, it was determined that the greatest limitations concern the quality and repeatability of delivered castings and the flow of information from assembly and operation. Difficulties encountered dur-ing machining and preparation of the finished product are of lesser importance, indicating relatively good mastery of the processes under the manufacturer's direct control. The results confirm that improvement should focus on the quality of deliveries, part traceability, and the utilization of feedback from use..

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