Інше

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APPROACHES TO SCALING PROTECTIVE GLASS MANUFACTURING FOR MOBILE DEVICES

Summary. *This article analyzes approaches to scaling the business of manufacturing protective glass for mobile devices. The stages of the technological chain—mechanical grinding and polishing, ion-exchange chemical tempering, application of multifunctional coatings, and laser edge treatment (LET)—are examined alongside strategies for business expansion in this field. It demonstrates how supply-chain and partner-ecosystem models, together with multicriteria decision analysis (AHP, PROMETHEE), can inform optimal investment and market-selection decisions. A step-by-step industrialization plan—from pilot line to mass production—is outlined, leveraging Lean/Six Sigma and digital IoT/MES solutions. To ensure consistent quality, a comprehensive control system is proposed, incorporating optical inspection and continuous equipment-parameter monitoring. The scientific novelty lies in integrating technological, organizational-management, and digital approaches to achieve sustainable capacity growth without compromising protective-glass quality. The insights presented will interest researchers and practitioners in industrial engineering, operations management of high-tech manufacturing, strategic planning, and venture investment in the consumer-electronics sector.*

Key words: *protective glass, production scaling, ion exchange, laser edge treatment, AHP, PROMETHEE, quality control, IoT.*

Introduction. The relevance of this study stems from the rapid expansion of the electronic-device segment and the consequent demand for innovative screen-protection solutions capable of preserving the structural integrity of display modules under mechanical stress and harsh operating conditions. In this context, protective glass plays a critical role; its development relies on understanding the failure mechanisms of glass coatings and improving their strengthening methods [1].

The aim of this article is to identify approaches to scaling protective-glass production for mobile devices that combine advanced technological processes with multicriteria decision-making methods.

The scientific novelty lies in integrating technological, organizational-management, and digital approaches to achieve sustainable capacity growth without compromising glass quality.

The author's hypothesis posits that combining multicriteria evaluation of technological alternatives with systematic quality management will reduce production costs and defect risks during scale-up, while maintaining the protective glass's performance characteristics.

The research methodology is based on a comparative analysis of existing publications in which authors examined current approaches to scaling businesses in protective-glass manufacturing.

Materials and Methods. In contemporary literature, several key research strands directly impact the scaling of protective-glass production for mobile devices. For instance, a review on the DiverseDaily portal examines chemical-strengthening techniques, ion-exchange tempering, and application of protective coatings to manufacture durable, scratch-resistant mobile-screen glass [2]. Delbari S. A. and Hof L. A. [9] show how combining Industry 4.0/5.0 approaches with circular-economy principles enables the recycling of glass frit into new sheets, delivering resource efficiency and a fully closed production loop.

Another research vector explores functional coatings and composite materials. Marra F. et al. [3] introduce a scalable graphene-nanoplatelet ink for screen-printing flexible, conductive layers in smart-textile sensors. Gualandi I. et al. [4] investigate conducting-polymer chemical sensors for sweat analysis, demonstrating the potential of thin-film additive methods to embed sensing capabilities directly into glass substrates.

A third theme focuses on digitalizing manufacturing processes and enhancing workplace safety. Aksüt G., Tamer E., and Alakaş H. M. [1] apply multicriteria decision methods to evaluate wearable-device use in industrial environments. Häikiö J. et al. [5] explore IoT-based safety monitoring, highlighting how sensor networks and data analytics provide real-time visibility into production-floor conditions. Syberfeldt A., Danielsson O., and Gustavsson P. [7] develop AR-product assessment guidelines for "smart" factories, formalizing criteria for selecting augmented-reality solutions and benchmarking existing implementations.

Finally, human-factor and implementation-strategy studies uncover behavioral and organizational barriers to adopting protective technologies. Sapbamrer R. and Thammachai A. [6] identify the training and cultural hurdles that inhibit technology uptake on the production line. Under the AT2030 program and ATscale partnership, Chaudron M. et al. [8] craft product narratives for industrial eyewear, underscoring the role of storytelling and multi-stakeholder engagement in scaling assistive solutions.

Thus, the literature spans materials-science methods, advanced manufacturing processes, digital decision-support, IoT and AR tools, as well as socio-technical deployment strategies and user-centric storytelling. Yet it pays insufficient attention to harmonizing functional-coating integration into mass production and to the economic evaluation of scaling approaches that leverage closed-loop systems and digital technologies.

Results and Discussion. High-quality aluminosilicate glass—valued for its combination of strength and optical clarity—is widely used as the base material for mobile-device protective screens [1]. Prior to thermal and chemical tempering, blanks undergo multi-stage grinding and polishing using diamond abrasives and pastes, which both smooth the surface and remove microdefects that could initiate cracking in the tempered glass [2]. Geometric control at this stage is critical for scalability: even minor deviations lead to elevated scrap rates in downstream processes.

The key method for enhancing mechanical properties is ion-exchange chemical tempering. Blanks are immersed in molten potassium nitrate, where smaller sodium ions (Na^+) at the surface are replaced by larger potassium ions (K^+), creating a compressive-stress layer that increases flexural strength. After tempering, multifunctional coatings—including oleophobic and hydrophobic fluoropolymer layers—are applied to guard against fingerprints and abrasive wear [4]. To further boost impact resistance, Laser Edge Treatment (LET) is employed.

Table 1 illustrates the main technological stages involved in scaling protective-glass production for mobile devices.

Table 1

The main technological stages of scaling the production of protective glasses for mobile devices

Stage	Method	Key Effect
Mechanical grinding and polishing	Diamond abrasives, polishing pastes	Removes microdefects; ensures surface smoothness
Application of multifunctional coatings	Fluoropolymer compounds	Protection against fingerprints and abrasion
Laser Edge Treatment (LET)	High-precision pulsed laser	Eliminates microcracks

Source: compiled by the author based on the analysis of [1; 2; 4]

One of the factors critical to successful scaling is a reliable and flexible supply chain. Table 2 outlines the characteristics of each scaling phase for protective-glass production and the tools employed.

Table 2

Scaling phases and key tools

Phase	Main Tasks	Tools and Methods
Pilot line	Equipment installation and commissioning; IQ/OQ/PQ	IQ/OQ/PQ; Training Within Industry (TWI)
Ramp-up	Personnel training; process flow optimization; parameter variance reduction	Lean/Six Sigma; MES
Mass productio n	Full automation; continuous quality control; capacity scaling	IIoT; IIoT analytics; periodic AHP monitoring

Source: compiled by the author based on the analysis [2; 5; 6; 8]

For successful scaling of protective-glass manufacturing, it is essential to implement a multilayered quality-control system that combines standard testing with modern digital solutions.

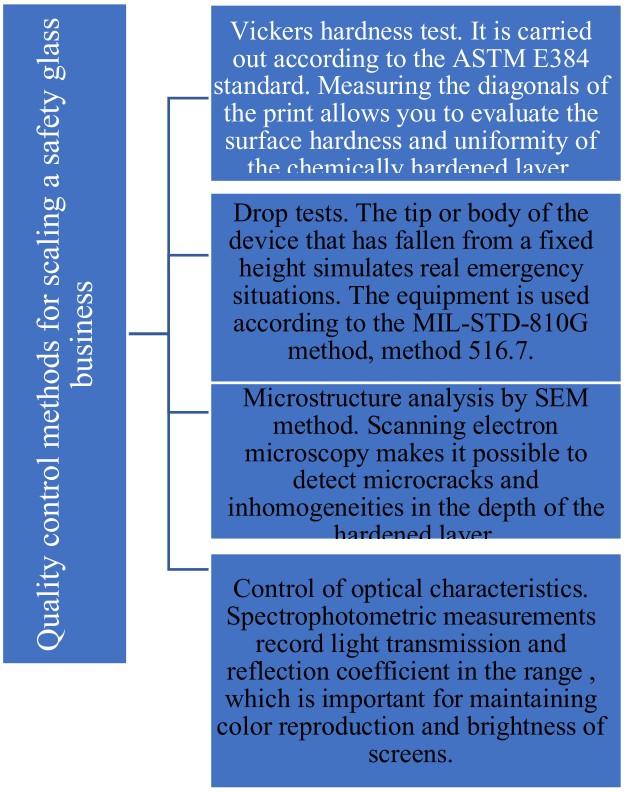

Fig.1. Quality control methods for scaling a business for the production of safety glasses [1; 9]

Digital solutions act as a catalyst, permeating both the technological and organizational-management layers. Implementing IoT and MES systems does more than collect data; it creates a digital footprint for every product and every process step. This enables real-time monitoring of deviations from target parameters during grinding, tempering, or coating application (technological aspect), while simultaneously providing the information needed for informed managerial decisions (organizational-management aspect). Examples include predictive equipment maintenance or optimization of production flows according to Lean principles. In this way, digitalization transforms traditional manufacturing operations into controlled, transparent processes, and organizational methods gain a powerful tool for data-driven analysis and decision-making [2; 3].

The core of integrating technological, organizational-management, and digital approaches for sustainable capacity growth without compromising protective-glass quality is ensuring consistent product quality amid increasing production volumes—a business imperative for maintaining competitiveness. Here, the synergy is most apparent. Advanced processes (for example, LET for edge strengthening or precision polishing to minimize defects) establish the basis for high quality. Organizational-management mechanisms—such as a comprehensive quality-control system at every stage, the PDCA (Plan-Do-Check-Act) cycle for systematic problem solving, and engaging personnel through Kaizen workshops—foster a quality-focused culture. Digital tools (automated optical inspection, continuous equipment-parameter monitoring via IoT sensors, and integration of data into a unified MES–SCADA system) deliver objective, timely, and comprehensive assessments of product and process compliance with standards. For example, IoT-sensor data on the temperature profile of chemical-tempering furnaces (digital aspect) are immediately analyzed by the MES. When deviations are detected, corrective actions are automatically triggered according to quality-management protocols (organizational-management aspect), preventing the release of a batch of glass with compromised strength (technological aspect).

Integration of the collected data into a unified MES–SCADA system provides full traceability of production batches, automatic report generation, and the ability to intervene immediately when parameter thresholds are exceeded [5].

At the core of building a quality culture and continuous improvement is the PDCA (Plan–Do–Check–Act) cycle, which enables the planning, implementation, verification, and adjustment of measures to reduce defects and increase productivity.

Monthly cross-functional workshops for defect analysis and process-optimization proposals drive employee engagement and foster the generation of innovative ideas based on Kaizen principles.

Regular laboratory testing of new coating formulations and LET parameters, followed by pilot validation on the production line, ensures a continuous influx of technological innovations and strengthens the company's competitive position [1; 2].

Thus, the scaling model proposed here is not merely the sum of three approaches, but rather a holistic, dynamically evolving system. Within this system, technological innovations are developed, managed, and controlled through advanced organizational practices and are exponentially amplified by end-to-end digitalization. Sustainable capacity growth is achieved through deep optimization of manufacturing processes and adaptive resource planning, while high quality is maintained via proactive, data-driven management and a culture of continuous improvement integrated at every level of the production system.

Conclusion. The methodology presented proves effective for scaling the production of protective glass for mobile devices. First, the combination of high-precision mechanical preparation, chemical tempering, and laser edge treatment yields components with superior strength, minimal surface roughness, and enhanced impact resistance. Second, applying multicriteria decision-making methods (AHP and PROMETHEE) enables well-justified selection of technological investments and target markets, thereby minimizing financial risks and shortening the time required to move innovations into mass production. Third, deploying a digital quality-control system—incorporating IoT sensors, MES, and "smart" wearable devices for operators—ensures that defect rates remain consistently low.

The practical significance of this work lies in its roadmap for introducing and adapting advanced technological solutions based on multicriteria evaluations, which allows protective-glass manufacturers to rapidly scale capacity while preserving high product quality. Future research should explore the development of flexible, self-healing glass and leverage artificial-intelligence techniques and digital-twin models to forecast and optimize manufacturing processes.

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