Sustainable Biodiversity Development – Improving the Production Process as an Example of Sustainable Management

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Abstract

This paper explores the integration of sustainable biodiversity development principles into the production of polyurethane beehives as a model of eco-friendly management. Beginning with an overview of pollinator ecosystem services and their alignment with the UN Sustainable Development Goals, the study details the manufacturing process of thermally insulated polyurethane hives, emphasizing quality control, material handling, and process stability. A plant-level analysis identifies inefficiencies—particularly operator overload and disorganized warehousing—and proposes interventions including workforce expansion, a clear division of tasks, and implementation of 5S workplace organization. The impact of these measures is quantified through Overall Equipment Effectiveness (OEE), revealing improvements in availability (from 88.76% to 89.89%), performance rate (from 37.12% to 84.36%), and overall OEE (from 31.24% to 68.37%), despite a temporary dip in product quality due to staff onboarding. The study concludes that combining sustainable product design with lean production practices not only enhances operational efficiency but also supports pollinator health and biodiversity conservation, laying the groundwork for continuous improvement and competitiveness in green manufacturing

Keywords: *sustainable development, sustainable development goals, sustainable biodiversity, polyurethane beehive production, production process optimization, 5S methodology, overall equipment effectiveness OEE*

INTRODUCTION

Pollination by bees is a key mechanism determining the reproductive dynamics of angiosperms, directly influencing the structure, stability, and functioning of both agroecosystems and wild flora. The foraging activity of honey bees and wild pollinator species enables the efficient transfer of substantial quantities of pollen between flowers, facilitating both self- and cross-pollination processes. This plant–insect interaction leads to full seed and fruit development, and numerous ecosystem studies indicate that up to 35% of global crop production depends on pollination services provided by bees, implying that their demographic decline could trigger significant deficits in the global food supply [1].

Ecological mechanisms associated with pollination include increased floral biodiversity, enhanced soil quality through stimulated nutrient cycling, and strengthened ecosystem resilience to stressors such as droughts and pathogen invasions. Long-term studies show that apiaries serve not only as bioreactors transferring plant genes but also as indicators of environmental health, since changes in bee populations often correlate with habitat degradation and intensified agricultural practices. Moreover, increased pollinator activity has been shown to raise humus content and improve soil structure, confirming the crucial role of bees in maintaining soil fertility [2].

Sustainable development plays a key role in ensuring a balance between economic growth, environmental protection, and social well-being, making it an essential element in the pursuit of a better future — not only in Europe, but also in countries such as China, Vietnam, and other regions around the world [3-6].

The concept of sustainable development gained global significance in 1987, when the United Nations published the report Our Common Future, which defined it as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. Since then, it has become the foundation of global strategies, including the 2030 Agenda and the 17 UN Sustainable Development Goals.

Sustainable development is of fundamental importance across all sectors of the economy — from industry and services to the energy sector — and is especially crucial in the raw materials industry, agriculture, and food processing, where responsible resource management has a direct impact on the environment and the quality of life in societies.

From the perspective of implementing the UN Sustainable Development Goals, protecting and strengthening bee populations is reflected in at least three priorities of the 2030 Agenda.

Goal 1: No Poverty emphasizes the importance of micro-scale beekeeping enterprises, where the development of local apiaries provides vital income for rural communities. Investments in beekeeping training, adoption of circular-economy principles for bee products (honey, propolis, wax, royal jelly), and support in market access generate new economic channels, contributing to farm diversification and increased financial resilience.

Goal 2: Zero Hunger highlights that enhanced pollination services correlate with higher yields of cereals, vegetables, and fruits, essential for combating malnutrition in regions with limited agricultural resources. Agroecological production models show that establishing bee forage in buffer zones and within-field wooded areas can boost yields by 20–30%, improving the caloric and nutritional availability of food for local populations [7].

Goal 15: Life on Land pertains to the need to protect and restore ecotones and habitats rich in nectar- and pollen-producing plants. Preserving diverse rural landscapes—such as grasslands, flower meadows, and forest patches—supports beekeeping and maintains trophic structure and biotic balance in both agricultural and forest ecosystems. Long-term monitoring of floral density and pollinator abundance underpins assessments of conservation and restoration program effectiveness.

In light of global challenges 8] —climate change, habitat fragmentation, pesticide emissions, and emerging bee pathogens—strategic investments in interdisciplinary research on disease epidemiology, bee genetic resilience, and sustainable integrated pest management are environmental policy priorities. Developing beekeeping practices centered on prevention, biopreparations, pollinator-friendly agronomy, and adaptive genetic management of apiaries can minimize colony losses and safeguard bee ecosystem services.

Additionally, providing bees with optimal living conditions is essential. In modern apiculture, polyurethane hives are gaining importance due to their excellent thermal insulation, which maintains stable internal temperatures in winter and protects against excessive heat in summer. The polyurethane coating also controls humidity and reduces mold risk, while ensuring structural durability and weather resistance. Consequently, polyurethane hives contribute to improved colony health, higher pollination efficiency, and increased honey production [9].

A critical factor for ongoing success is stakeholder education—from farmers and local authorities to consumers. Training programs, social-educational campaigns, and support for civic initiatives such as urban gardens and flower meadows raise ecological awareness and encourage pollinator-friendly practices. Integrating agroecological policies at regional and national levels, along with international cooperation in knowledge and technology exchange, will secure pollination services and ultimately strengthen global food security, biodiversity conservation, and the balance of terrestrial ecosystems.

Beehive Production Process

In the face of increasing challenges related to ecosystem disintegration and declining bee populations, the development and implementation of innovative technologies in apiculture have become key areas of interdisciplinary research. The production of polyurethane hives offers a versatile operational tool, combining advanced polymerization processes with a thorough understanding of ecological and social needs. The use of polyurethane materials with an optimized cellular structure not only guarantees excellent insulating and mechanical properties—resulting in a stabilized microclimate inside the hive—but also minimizes microcracks and deformations under extreme temperature, humidity, or barometric pressure fluctuations. This resilience correlates inversely with the mortality rate among young worker bees, contributing to the increased survival of bee colonies even in urban and degraded landscapes.

The manufacturing process for polyurethane hives comprises a series of meticulously planned stages, each carried out under the highest standards of precision and quality control. The process begins with the preparation of raw materials: isocyanate—a specialized chemical mixture of proprietary composition supplied by a trusted vendor—and polyol, ordered in three color variants for the company's needs. The pigment added to the polyol serves only aesthetic purposes and does not affect the mechanical or chemical properties of the components.

The first step on the production floor is to withdraw the pigmented polyol from IBC tanks placed on heated platforms that maintain the liquid's proper viscosity. The material is then conveyed to injection molding machines via specialized nozzles and a pump system that regulates constant pressure and temperature.

On the molding lines are three injection carousels, each equipped with ten molds of varying shapes and sizes. Thirty molds can be filled at once, ensuring high throughput. When switching component types, mold changeovers—lasting about 30 minutes—are performed simultaneously on all idle molds to prevent downtime and optimize resource use.

Before injection, each mold undergoes thorough cleaning—both manually and with compressed air systems and cleaning agents—to prevent surface defects and structural flaws. Then, under pressures of several hundred bars, the polyol–isocyanate mixture is injected into the mold. A chemically controlled curing reaction follows at a regulated temperature, with a cure time of approximately 45 minutes.

A critical factor is the precision of mold closure: the operator has only 40 seconds from the moment the components are mixed to engage the closing mechanism—any delay risks foam leakage, necessitating mold cleaning and work interruption.

After curing, the finished part is carefully removed from the mold and manually trimmed to remove excess material using special knives and milling tools, requiring both experience and an aesthetic eye to maintain dimensional accuracy and smooth edges.

The next phase is stabilization: components are placed on a staging area under controlled humidity and temperature for at least 48 hours. During this time, a visual quality inspection checks for mold completeness, structural integrity, and any surface defects. Depending on product specifications, metal reinforcements, fiberglass mesh, or other additives may be installed to enhance durability and functionality.

Stabilized components are then stacked on pallets and transported by forklift to high-bay storage. The final step is packaging the finished parts in PVC film to protect them from moisture and mechanical damage during transit.

PRODUCTION ANALYSIS FROM AN OPTIMIZATION PERSPECTIVE

The plant analysis revealed several areas in need of comprehensive improvement measures aimed at both optimizing production processes and increasing employee satisfaction. The most critical issue proved to be the excessive workload placed on a single worker, who was responsible for operating injection machines, removing parts from molds, trimming flash, performing equipment changeovers, and storing components. Such task concentration led to a significant drop in operational efficiency, prolonged individual production cycle times, and an increased likelihood of errors and downtime.

In response to the identified challenges, it was proposed to hire two additional employees, allowing for a more balanced distribution of duties. The recruitment process was conducted

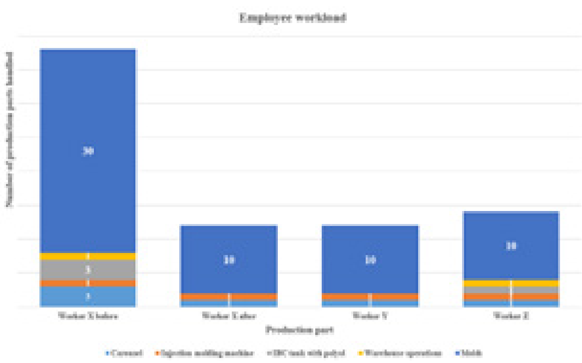

Fig. 1. Employee Workload Chart
Rys. 1. Wykres obciążenia pracą pracownika

Tab. 1. Performance analysis
Tab. 1. Analiza wydajności

	Before	After
Produced quantity [pcs]	58	116
Operation cycle time [min]	20	20
Operation count coefficient [pcs]	125	125
Time spent [min]	25	22
Efficiency [%]	37.12%	84.36%

in stages, focusing on attracting candidates with the technical qualifications and manual skills necessary for machine operation and basic assembly work. At the same time, the former lead operator was promoted to team supervisor. This not only relieved him of an excessive number of operational tasks but also strengthened his role within the organizational structure, resulting in increased engagement and a greater sense of responsibility for achieving objectives.

The onboarding of new staff enabled a more precise and flexible division of tasks, tailored to each individual's competencies. Employees were trained according to a unified induction program covering injection-machine operation, safe part removal from molds, and post-process quality-control methods. Simultaneously, the promotion of the lead operator to supervisor allowed for task delegation, oversight of mold-change schedules, and short-term work planning. As a result, the team acquired a clear hierarchical structure in which every member knows their responsibilities and coordination rests with the manager. These changes led to improved on-time order fulfillment and increased team cohesion and motivation.

The reorganization produced a distinct division of duties and greater process transparency, contributing to improved workplace ergonomics and faster task completion. This transformation exemplifies the effective use of human resources to streamline the production process.

To visualize employee workload distribution, the following analysis is presented.

The above chart presents a comparison of employees' scopes of responsibility before and after hiring additional staff in the company. In the original arrangement, all tasks rested on a single worker (denoted X), who alone operated three carousels, three injection molding machines, the IBC polyol tank, the warehouse, and the full set of molds assigned to each carousel. In total he was responsible for 38 functional units, which led to severe overloading.

As a result of the reorganization, two additional operators (Y and Z) were hired, and duties were evenly distributed among three people. Each operator was assigned one carousel, one injection molding machine, and its set of molds—i.e., ten functional units per person. In addition, Worker Z took responsibility for the IBC polyol tank and warehouse operations.

These changes yielded a more balanced workload, clarified lines of responsibility, and increased operational efficiency. The previously overburdened Worker X was relieved, and the entire production process stabilized and became more transparent.

Further observations of the production process revealed significant shortcomings in warehouse organization and the consequences of overproduction. The current method of storing components—in piles, without clear categorization, and in arbitrary locations—lengthened search times, caused frequent picking errors, and generated unnecessary downtime. To streamline the warehouse, it was proposed to implement a Just-in-Time approach, synchronizing deliveries with actual production needs. Plans also call for purchasing and installing pallet racking and modular shelving, which will allow zoning by component type, usage frequency, or size. This will ensure transparent, repeatable storage, shorten production-preparation times, and reduce damage caused by improper handling. While these solutions are still in the planning phase, their implementation represents a crucial step toward better organization and minimization of warehouse losses.

Another key improvement is the adoption of the 5S methodology—a system for workplace organization and standardization. Previous practices fostered the accumulation of unnecessary tools and materials, creating clutter, hampering machine cleaning, and undermining ergonomics. The rollout began with Sort (eliminating all unneeded items), followed by Set in Order (systematically arranging the necessary tools). Early results are already evident: production-line layout is clearer, dust and debris on molds have decreased, and workstation ergonomics have reduced worker fatigue.

Initial resistance among some staff to changing habits has given way to an appreciation of the benefits of an organized work environment. Regular 5S audits according to a fixed schedule enable progress monitoring and rapid correction of any deviations. Consistent adherence to 5S will be crucial for raising quality and reliability levels and fostering a culture of continuous improvement throughout the plant.

OBTAINED RESULTS

To assess the effects of the organizational changes—including staffing modifications and the partial implementation of the 5S methodology—the OEE (Overall Equipment Effectiveness) metric was employed. This tool enables a comprehensive evaluation of operational efficiency by analyzing the utilization of available production resources. Calculating OEE allows for precise determination of actual productivity and identification of key factors contributing to performance loss, such as downtime, limited machine speed, or product defects.

The OEE metric served as the basis for comparing conditions before and after the improvements were implemented, allowing determination of the impact of the changes on the production process and highlighting areas requiring further optimization.

Availability analysis was based on the formula defining the ratio of the difference between total available time and unplanned downtime to the total available time. This made it possible to evaluate the effect of stoppages and breakdowns on resource utilization efficiency. The nominal working time remained unchanged at 445 minutes, but unplanned downtime was reduced from 50 to 45 minutes. As a result, actual operating time increased from 395 to 400 minutes, and the availability factor improved from 88.76% to 89.89%. Even a modest increase of 1.13 percentage points indicates a positive impact of the initiatives—especially in repetitive, multi-shift production processes, where every minute counts.

The performance rate, calculated as the ratio of actual output multiplied by the cycle time to the time expended, reflects the organizational efficiency of processes. This rate plays a crucial role in assessing operational effectiveness by indicating the extent to which working time is utilized relative to the number of units produced. It also highlights potential areas for further improvement. The table below summarizes the results before and after the implementation of the measures—namely, the hiring of additional personnel—aimed at enhancing efficiency.

After hiring additional staff, the number of finished products increased from 58 to 116 pieces, with the operation cycle time kept constant at 20 minutes and the operation count coefficient unchanged at 125 pieces. Shortening the cycle time from 25 to 22 minutes, combined with higher output, drove the performance rate up from 37.12% to 84.36%, confirming the tangible impact of the staffing measures on efficiency.

Quality was evaluated as the ratio of correctly produced units to the total output. Before the changes, this rate was 94.83% (55 conforming units out of 58); after onboarding the new operators, it fell to 90.16% (110 conforming units out of 122). The rise in defective units (from 3 to 12 pieces) can be attributed to the adaptation period of the new employees, which requires additional training. Despite this temporary quality dip, the absolute number of conforming products grew, indicating an overall positive effect of the changes.

Calculating all individual factors yielded an overall OEE that climbed from 31.24% to 68.37%. Such a significant improvement testifies to the effectiveness of the measures undertaken—workforce reorganization, resource rationalization, and personnel expansion. The biggest contributor to the OEE gain was the boost in performance rate, although the slight rise in availability also played a role. The initial decline in quality during operator ramp-up is transient and can be mitigated through targeted training programs and ongoing quality checks.

Next steps should focus on strengthening quality and operational stability by standardizing work procedures, implementing on-station quality control, and monitoring process data in real time. Investments in skills development, automation, and detailed planning will enable further gains in efficiency and competitiveness.

Revising the organizational structure by adding operators allowed for a balanced division of tasks, reduced individual overload, and minimized losses in line with Lean principles. The experienced operator's promotion to team leader improved communication, motivation, and knowledge transfer. Task synchronization and shorter handover times between production stages reduced micro-stoppages and enhanced process flow. Despite initial adaptation challenges, the reorganization delivered higher availability and performance and laid the groundwork for continuous process improvement, creating a more modern and flexible production environment.

CONCLUSIONS

Pollination by honey bees and wild pollinators plays a fundamental role in the reproduction of angiosperms, directly affecting the stability of both natural and agricultural ecosystems. By transferring pollen between flowers, seed and fruit formation occurs, determining the availability of plant-based resources and influencing global food security. Ecosystem literature indicates that as much as one third of the world's crop production depends on pollination services—so a noticeable decline in bee colony numbers can lead to serious food-supply deficits and disrupt the functioning of both agricultural landscapes and wild habitats.

Protecting and supporting pollinator populations benefits floral biodiversity, since diverse plant communities form more stable and resilient ecosystems. Through stimulating nutrient cycling and increasing soil organic matter, these plant–insect interactions improve soil structure, which in turn enhances water-retention capacity during droughts and supports self-purification by eliminating fungal pathogens.

In the context of the UN Sustainable Development Goals, bee conservation has multifaceted importance. Supporting local apiaries and small beekeeping enterprises creates new income sources in rural areas, helping to reduce poverty by diversifying economic activities. At the same time, intensified pollination services translate into higher yields of cereals, vegetables, and fruits, improving food availability and combating malnutrition. Caring for nectar-rich habitats—such as flower meadows, intra-field tree belts, and forest-field ecotones—helps preserve biodiversity and protects the genetic resources of plant species, aligning with the objectives of terrestrial ecosystem conservation.

Contemporary beekeeping faces challenges including climate change effects, habitat fragmentation, pesticide overuse, and emerging bee pathogens. In response, interdisciplinary research is being developed on bee genetic resistance, disease epidemiology, and integrated plant protection based on biopreparations. Preventive practices and modern polyurethane hives with optimized cellular structure ensure a stable internal hive microclimate year-round, reducing losses from winter cold or summer heat and minimizing mold growth and moisture condensation.

In a facility producing polyurethane hives, precise injection of the isocyanate–polyol mixture, strict control of temperature conditions, and rigorous mold-cleaning procedures before each cycle are critical. An organizational analysis of the production process revealed an overload on a single operator, which was corrected by hiring two new workers and promoting the former specialist to team supervisor. The implementation of 5S methodology improved workplace order and ergonomics, reduced mold contamination, and motivated the staff to maintain quality standards.

The results of these improvements were measured using the OEE metric. Machine availability increased, unplanned downtime decreased, and production efficiency jumped thanks to better resource utilization and shorter cycle times. Although the adaptation period of the new employees temporarily lowered product quality, the total number of conforming units rose significantly, driving OEE from 31.24% to 68.37%. Based on these results, it is recommended to continue training programs, implement on-station quality-control systems, and further automate processes, which over the long term will sustain the upward trend and strengthen the plant's competitiveness. Moreover, manufacturing polyurethane hives is vitally important because it provides bees with safe, stable shelter, supporting colony health and their ability to deliver key ecosystem services.

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Zrównoważony rozwój bioróżnorodności – doskonalenie procesu produkcyjnego jako przykład zrównoważonego zarządzania

Niniejszy artykuł bada integrację zasad zrównoważonego rozwoju bioróżnorodności z produkcją uli poliuretanowych jako modelu przyjaznego dla środowiska zarządzania. Rozpoczynając od przeglądu usług ekosystemowych zapylaczy i ich zgodności z Celami Zrównoważonego Rozwoju ONZ, badanie szczegółowo opisuje proces produkcji uli poliuretanowych z izolacją termiczną, kładąc nacisk na kontrolę jakości, obsługę materiałów i stabilność procesu. Analiza na poziomie zakładu identyfikuje nieefektywności — w szczególności przeciążenie operatorów i niezorganizowane magazynowanie — i proponuje interwencje, w tym rozbudowę siły roboczej, jasny podział zadań i wdrożenie organizacji miejsca pracy 5S. Wpływ tych środków jest kwantyfikowany za pomocą ogólnej efektywności sprzętu (OEE), ujawniając poprawę dostępności (z 88,76% do 89,89%), wskaźnika wydajności (z 37,12% do 84,36%) i ogólnego OEE (z 31,24% do 68,37%), pomimo tymczasowego spadku jakości produktu z powodu przyjmowania pracowników. Badanie wykazało, że połączenie zrównoważonego projektowania produktów z praktykami produkcji szczupłej nie tylko zwiększa wydajność operacyjną, ale także wspiera zdrowie zapylaczy i zachowanie bioróżnorodności, kładąc podwaliny pod ciągłe doskonalenie i konkurencyjność w zielonej produkcji.

Słowa kluczowe: *zrównoważony rozwój, cele zrównoważonego rozwoju, zrównoważona bioróżnorodność, produkcja uli poliuretanowych, optymalizacja procesu produkcyjnego, metodologia 5S, ogólna efektywność sprzętu OEE*