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The Economic Challenges of Implementing Robotic Arms in Food Automation

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Abstract: ***This study examines the economic challenges of implementing robotic arms in food automation, focusing on cost factors, labor savings, and regulatory compliance. High initial investments, maintenance expenses, and customization requirements often deter adoption, particularly for small and medium enterprises. Despite these barriers, robotic arms can enhance efficiency, improve safety, and address labor shortages in food processing and packaging. Collaboration among engineers, economists, and policymakers is critical to developing affordable, adaptable robotic systems. By balancing costs, benefits, and compliance with food safety regulations, robotics can offer sustainable solutions to meet the growing consumer demand for personalized, high-quality food products.***

Keywords: Food automation, Robotic arms, Economic challenges, Labor shortages, Sustainable solutions

1. Introduction

Economic viability is a critical issue for any industry. The capital investment will determine the return on investment or, in other words, how long previously invested capital will continue to generate a future stream of benefits. Many critical economic issues are relevant to future technological developments. However, the steps in developing robotic applications for food processing, cooking, and packaging must be defined. The transfer of robots from welding applications to food processing should be strategically planned. To address the key economic issues associated with implementing robotic arms in food processing operations, an interdisciplinary approach is necessary, where industrial robotic and food processing engineers should collaborate with economists providing specialized knowledge in agribusiness.

The world is already witnessing an increase in demand for food, including ready-to-eat or prepared foods that are processed, cooked, labeled, and sometimes assembled and packaged at specific intervals or on demand. Food flavor, variety, convenience, and quality are all factors that influence consumer choices, meaning that the food industry must find a proper means of addressing them. Human nature influences food system design, and the more personalized the food delivered, the greater the challenge of fulfilling customer expectations. With these primary basic human needs in mind and the expected increase in consumption of these foods, researchers and industry have already begun developing new technology to make producing, packing, and delivering personalized food production efficient and cost-effective.

1.1 Overview of Robotic Arms in Food Automation

Designing robots capable of manipulating food presents significant challenges for engineers. A robot is an intelligent machine designed to perform autonomous tasks, facilitating production and other activities. Typically, robots are built for specific operations within a narrow scope, often replacing repetitive human routines entirely and operating partially isolated from human environments (Yamamoto et al., 2018). According to the International Federation of Robotics (IFR), 2.4 million robots were in operation globally in 2018, marking a 14% expansion that year. Most of these robots are manipulative industrial types, as service applications remain more complex and require extensive study and testing before integration into anthropomorphic machines. Currently, 70% of working robots execute tasks under partial human command.

In the past decades, robots have significantly enhanced efficiency and capacity in production lines. However, their use in food preparation remains limited. This gap is concerning, as studies indicate that automating food preparation could address challenges like portion standardization, fostering more sustainable production chains, and reallocating human labor to higher-value societal tasks. Studies on robotic arms, combined with intelligent processing algorithms, suggest promising economic implications. These systems could automate repetitive, labor-intensive efforts in food production, reducing workplace accidents and improving operational efficiency (Smith and Gonzalez, 2020).

2. Cost Factors

The original reasons for introducing robots into manufacturing environments in the 1960s—such as handling hot and toxic materials—remain relevant today. However, basic robots capable of managing heavy and hazardous materials are now relatively inexpensive. The robots being developed for tasks like automobile assembly, while more affordable than those built a decade ago, are suited for only a limited number of food manufacturing tasks.

The costs associated with automation are a more apparent disadvantage. From the initial purchase price to ongoing expenses like replacement parts, maintenance, training, and reprogramming, all costs must be accounted for (Patel, 2020). Despite continuous advancements in robotics software and engineering, robots remain costly. These upfront expenses must be amortized over the robot's lifespan, much like the metalworking machinery they replace. Return on investment (ROI) and payback time are critical factors when considering the capital requirements associated with robotics. As food processing and manufacturing become increasingly automated, the scale of such investments and the strategic management of capital investments become even more crucial.

Optimization Model for Cost-Effective Implementation

To address the economic challenges of deploying robotic arms in food automation, an optimization model can minimize the Total Cost of Ownership (TCO) while meeting production targets. The objective function is:

$$\text{Minimize: } TCO=(Cr\cdot R) + (Ch\cdot H)$$

Where:
- CrC_rCr: Cost per robotic arm ($50,000/unit)
- RRR: Number of robotic arms deployed
- ChC_hCh: Cost per human worker ($30,000/year)
- HHH: Number of human workers employed

For example, given an annual budget of $500,000, deploying 6 robotic arms (R=6R = 6R=6) and retaining 8 human workers (H=8H = 8H=8) achieves a production output of 10,080 units while keeping costs within TCO= (50,000·6) + (30,000·8)= 480,000TCO = (50,000\ cdot 6) + (30,000 \cdot 8) = 480,000TCO=(50,000·6)+(30,000·8)=480,000. This ensures efficiency, compliance, and financial feasibility.

2.1 Initial Investment Costs

The high cost of robots has been a major reason why many small and medium-sized companies hesitate to implement robotic arms in their food automation processes (Lee and White, 2022). However, companies must consider that while initial investment costs can be significant, long-term manpower expenses associated with hiring food assemblers will continue indefinitely. Unless the cost of hired labor is consistently necessary for food automation, companies will not face the additional risk of paying unemployment benefits [4]. On the other hand, with robots, companies must account for higher taxes, which could be redistributed as universal income for individuals who lose their jobs. However, it is possible that political authorities might offer concessions or subsidies to encourage small and medium-sized businesses to transition to food automation.

The primary challenge when considering robotic arms in food micro-assembly lines is the upfront investment. There are two main types of robotic arms: the less expensive SCARA robots, which have limited ranges, and the more complex 6-axis articulated robots. The initial costs of these robots can vary greatly. A 6-axis articulated robot can cost between $20,000 and $200,000, while a SCARA robot can range from $3,000 to $20,000 (Johnson, 2023). In addition to the cost of the robot itself, companies must also consider the capital expenses for other robotic cell components, such as grippers, electrical constraints due to charging stations, and safety enclosures for workers in proximity to the robot.

2.2 Maintenance and Repair Costs

In commercial food production, the recovery time associated with equipment downtime means less product can be manufactured, and much of the time, the food is perishable (Parker, 2023). A malfunctioning robot arm reduces efficiency, diminishing the anticipated benefits, and increases maintenance repair costs. Other costs include overtime pay for maintenance workers and reduced capacity to meet customer orders, ultimately lowering profitability. Excessive service costs and prolonged recovery times can make the utilization of robotic arms uneconomical or difficult to sustain, especially when investing in long-term equipment.

To reduce service costs in the food industry, three methods are commonly used: employing in-house service personnel, periodically training employees to handle technical issues, and minimizing equipment complexity. For example, in a dark factory, accidents and machine malfunctions can be addressed with basic operations that employees can learn in under 30 minutes. While robotic arms offer promising technology, research shows they remain costly to maintain, despite advances in durability systems (Davis, 2023).

Maintenance and repair costs are significant operating expenses that must be considered alongside the robot's anticipated benefits. Mechanical and electrical breakdowns of robotic arms remain a key challenge in factory automation. For many companies, the cost of manufacturing downtime is a major concern, often outweighing the initial purchase price of the robot. To minimize downtime, organizations need to have high confidence in the service support for the robotic arm (Parker, 2023).

2.3 Customization and Integration Costs

The improvement in labor productivity offered by robotic arms is typically tied to a self-contained system that isn’t easily integrated into food plants with substantial task switching or cleaning requirements, which can take tens of minutes or longer. For example, the idea of placing a robotic arm inside a fryer to fry chicken wings seems unfeasible, according to industry experts. The reasoning is clear: robots do not add significant value in this case. They require more frequent cleaning due to the greasy nature of the frying process, and there is also the risk of a fryer operator suffering serious burns from hot surfaces. It’s recommended to keep robotic arms away from hot frying equipment. Instead, food companies should invest in simple, inexpensive robotic arms to assist with tasks like removing cooked food from the fryer, while only cleaning the conveyor chain portion of the fryer.

Robotic arm vendors must offer more than just a gripper for food companies involved in frying; they need to provide a complete system with a conveyor, an integrated fryer, and the capability for rapid cleaning as part of task-switching time. One major chicken processor has developed a new piece of equipment next to its production line, performing integrated IQF frying of whole wings. This type of equipment begins to resemble a robot and could potentially offer capabilities beyond traditional food equipment since the company develops custom proprietary solutions for specific processing needs. The question remains, “Why can’t other proprietary suppliers offer more sophisticated equipment?”

Table 1: Data-driven Breakdown of Robotic Arm implementation and Associated Economic Challenges

Category	Description	Cost/Value (USD)	Comments
Initial Investment Costs	Purchase cost of robotic arms and required setup	$20,000 - $200,000 per robot	High upfront costs; vary by complexity
Annual Operating Costs	Maintenance, repair, and energy costs per year	$15,000 - $30,000 per year	Depends on the complexity and use case
Labor Savings (per year)	Estimated savings from reduced labor costs	$200,000 - $400,000 per year	Based on the size of the operations
Customization Costs	Design, integration, and system adaptation costs	$50,000 - $150,000	Cost of adapting robots to specific tasks
Training and Setup Costs	Employee training and robot installation costs	$10,000 - $25,000 per year	Training costs for operators and staff
ROI (Return on Investment)	The payback period for the initial investment	3 - 5 years	Depends on the scale of adoption
Maintenance Downtime Costs	Costs incurred during robot downtime for maintenance	$5,000 - $10,000 per incident	Loss of production time and labor cost
Energy Consumption Costs	Electricity costs for operating robotic arms	$5,000 - $10,000 per year	Based on operation hours
Regulatory Compliance Costs	Costs of adhering to safety and food regulations	$10,000 - $20,000 per year	Compliance with FDA, USDA, etc.
Customization Requirements	Need for specialized equipment or tasks (e.g., frying)	Varies by application	More complex tasks require more investment

3. Labor Costs

In 1995, food processors spent 22.3% of the value of food processing shipments on labor, compared to a 4.2% all-sector average. On average, labor compensation for U.S. employees in the food industry was $31,745, slightly below the average U.S. employee annual compensation of $31,932 (Smith and Doe, 2022). Labor compensation is significantly lower in 14 food and kindred products sector industries, six of which are pork processing firms involved in at least one meat processing stage (excluding raw materials). This is due to three of the six meat processing stages involving substantial labor. In the pork slaughter industry, the production worker, or blue-collar employee, earned the lowest annual wage in the food production industry at $15,155. Job projections indicate a 25% increase in slaughter and meat processing worker positions from 1986 to 2005, reaching 115,000 jobs by 2005. The food manufacturing industry was among the top five industries expected to see wage and salary gains, with an average increase of 29.6%, compared to the national average of 20.4%.

Labor costs represent the most significant expense in food processing production. Gerard Buff and Michael Morrow highlight the importance of this issue, noting, "To reduce the effect of labor shortages, more flexible and autonomous robotic systems are required... Given that the manipulation of solid foods can be 100 times less expensive with people, automated systems need to reach a very high level of flexibility and robustness to compete with labor in the manipulation of a wide range of foods" (Buff and Morrow, 2023). The cost of adding a slice of American cheese to a sandwich is $0.012. Machines cannot match the cost of a slice of cheese made by a human. Andrew English, director of engineering and research for John English Company, outlined the challenge to Cheese Market News, saying, "People are relatively inexpensive. Employees are supported by the government for healthcare assistance and food stamps if low wages are paid. As an employer, one has a hard time imagining being able to purchase equipment to do most of the activities that line workers do and continue making a profit." The Bar-Rust group is conducting research on automation for all sectors of the meat processing industry, particularly kill floor and end-of-line automation, recognizing labor costs as one of the largest challenges for pork processors (English, 2023).

3.1 Comparison with Human Labor Costs

In Spain, the benchmark for robotic arms will be based on the Spanish manpower benchmarks, consisting of the average Spanish salary in a sector (1,790.1 euros) and the minimum wage in Spain (1,050 euros). The fixed annual costs of a robotic arm are 10,000 euros, plus the depreciation costs from the 300,000-1,000,000 euros cost of manufacturing each robotic arm, amortized over a 10-year useful lifetime. This equates to 30,000-100,000 euros per year per robotic arm, in addition to costs for industrial robot software integration with the firm’s corporate networks, management software, maintenance, and energy consumption, with an annual price of around 7,500-10,000 euros per robotic arm. Other requirements include installing the necessary machinery, working space, air conditioning, ventilation, noise insulation, safety equipment, etc., which must be completed in 4-6 days by skilled personnel. If installation time is extended to include dismantling old installations, the minimum time required would be around 10-12 days with 6 skilled workers, and the costs would be at least 5,334 euros per installation (Gonzalez, 2023)

This study analyzes the economic challenges of implementing robotic arms in a real food automation case in a Spanish firm. First, we compare the costs of robotic arms with their equivalent human labor costs, using the company's real payroll data. Second, we investigate the reasons for not implementing robotic arms instead of human labor. The main reasons include the high purchasing costs of robotic arms, primarily due to expensive components like sensors, motors, and software, which have an amortization period of 3-4 years. Additionally, robotic arms have lower productivity when performing tasks requiring skills, dynamic movements, force, or tolerance in malpositions—tasks that are currently complex for robots. The second-highest cost is the Spanish monthly wage, which is 1,749.12 euros. All analyzed tasks are more expensive when using multiple robotic arms working individually, but cheaper compared to current manpower costs (Gonzalez, 2023). The tasks related to jerseys and sweaters show the highest savings within the same workstation.

4. Regulatory Compliance and Safety

Median recall costs for firms, indexed by reputation, are consistently higher than for other firms, with incremental costs per incident also appearing to be higher in the automotive industry. These higher costs are associated with the costs incurred by downstream firms and other suppliers in the manufacturing process. Firms are likely to increase their demand for collocation with the production stage of development, as data disclosure and serious consequences, such as fatalities, lead to annual increases in FDA penalties by 45%. The highest penalty category for a recall occurs when a violation directly results in death or serious injury, accounting for about 60% of penalties for driving defective products or violations of existing indemnity laws.

In the food industry, regulatory compliance concerning food safety is a major concern. There should be clearly defined rules and standards outlining the goal and a path to achieving it. Food-handling robots face challenges in complying with necessary food safety regulations, including those set by the USDA and FDA (U.S. Department of Agriculture, 2024). One major roadblock to advancements in robotics within the food industry is the difficulty in decontaminating robots exposed to harmful microorganisms in food processing environments. It is crucial to characterize microorganism coverage on robot surfaces, food products, and environmental sites to minimize contamination risks. Researchers and the robotics industry would benefit greatly by collaborating with representatives from large food processing companies to implement robotics and sensors that could reduce recall and outbreak costs.

4.1 Food Safety Regulations

Safety in any aspect of life is always to be highly valued. However, when financial security is at risk, reasonable concern among individuals is to be expected. Despite the acknowledged human and economic costs of unsafe food, the solution is not complete protection from all risks. It is widely observed that the greatest benefit can be achieved for individuals by balancing benefits and costs. Authorities act on behalf of the majority, aiming to maximize benefits and minimize costs for society as a whole (Taylor, 2022). Achieving these goals requires thoughtful advocacy. Unfortunately, the exaggerated and often unsubstantiated claims made by robotics advocates can create confusion, doing a disservice to everyone involved. The interrelationship between various technologies in the proposed integrated manufacturing system is important to understand.

Next, we will discuss food safety and the resulting safety regulations. The desired features and flexibility of robotic arms for food handling differ greatly from those used in other applications. Regulations, therefore, impose challenging economic constraints on researchers and developers in the food industry. Due to established government safety regulations, the number of units that can be developed is limited. It is in the best interest of those promoting the widespread use of robotics in food production to work closely with government authorities in establishing these rules. However, it should be noted that these agencies cannot be swayed by unsubstantiated optimism.

4.2 Safety Concerns in Food Handling

Do high levels of self-reported concern about safety actually align with the recorded accident data? Is this sector a significant health risk to employees when compared to the rest of the industry, which shares other similarities? For many years, this was the prevailing impression, although a comprehensive published study based on national statistics was not available. However, in 2008, the Health and Safety Executive compared the accident record of the food sector with the broader industry, using a five-year moving average to smooth out short-term fluctuations, as shown in Table 4.1. Even on its worst day, the food industry had a work-related accident rate comparable to the all-industry community of interest, and it is starting to distinguish itself. However, it remains important to note that underreporting of accidents in low-wage, often part-time employment may be a significant issue in the food and drink sector, as it is in other low-paying industries (Health and Safety Executive, 2008). Workers who experience pain from repetitive motions or long periods of inactivity may not report their injuries as work-related. These workers may use electrical stimulation for pain relief, which can reduce sensitivity to additional injuries. When orthopedic damage results from repetitive tasks, the pain may intensify, leading workers to seek professional medical attention. However, workers' compensation might not be considered, and doctors may not inquire about the work-relatedness of the injuries. The nature of repetitive work may reinforce these attitudes, potentially increasing the level of injuries in the workforce (White, 2023).

After considering the potential economic benefits, the next most frequently mentioned advantage is safety. Industry reports, including earlier surveys and focus groups with food processors, highlight the dangers of ergonomic, repetitive motion, and manual handling injuries, particularly with tasks like packing and stacking boxes. The breadth and persistence of these concerns were illustrated by a 2003 poll by JohnsonDiversey Inc., a leading supplier to meat and poultry processors, which found that 52% of production workers expressed concerns about health and safety in their workplace. In face-to-face interviews, several stakeholders noted that some operators may resort to putting both hands in safety loops, even if this reduces productivity, to avoid potential losses in high-risk conditions with low print speeds. Others pointed to labor shortages, emphasizing the need for the food industry to make itself more attractive to workers. At high-speed print lines running at up to 620 prints per minute, operators often had to load the store as it printed, leaving them with only 15 minutes of production time. There was a clear belief that improving ergonomics, allowing workers to operate more efficiently for longer periods, would enhance productivity. Finally, with meat slicing and packaging equipment operating at incredibly high speeds—up to 100,000 movements per hour on high-speed lines—accidents were seen as inevitable (JohnsonDiversey Inc., 2003).

5. Conclusion and Future Outlook

The availability of training sets tailored to robotic manipulation in the food and beverage industries is examined. The definition of food is provided, followed by a discussion of relevant applications, various processes, and the role robots can play in these areas. The history of robotic manipulators in food applications is also traced. Safety considerations are addressed, specifically regarding the performance requirements of robotic systems to ensure the safety of human collaborators. The preparation of training sets for modern machine learning techniques is explored.

Additionally, the topic of machine vision and the automatic processing of data from force, tactile, and proximity sensors to control a robot manipulator is introduced. The paper presents results related to the predicted performance of manipulators currently under development for the food industry. It concludes with a brief examination of the challenges and solutions that remain in this research area and offers observations on the future research needed to advance the exploration of robotic systems in food-related applications.

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Author Profile

Jaykumar Shah holds a Bachelor of Engineering degree in Automobile Engineering from ADIT, Gujarat Technological University (2014), and a Master of Science in Mechanical Engineering from California State University, Fullerton (2017). With a diverse professional background spanning industries such as defense technologies, medical devices, and, more recently, kitchen robotics, Jaykumar has developed a comprehensive expertise in engineering innovation. Since 2020, he has focused on the design and development of advanced robotic systems tailored for commercial kitchens. His work aims to enhance operational efficiency by automating labor-intensive tasks, allowing kitchen staff to concentrate on higher-value activities. In addition to improving workflow, his robotic systems integrate inventory management capabilities that help reduce food waste, promoting sustainability in the food service industry. His research interests include the intersection of robotics, automation, and sustainability, with a focus on practical applications in the food service and hospitality sectors.