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Dynamic Modeling Analysis of a Three-Stage Batch System: A Case of Madiun Pecel Sauce Production

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Abstract:

Madiun pecel sauce is renowned for its distinctive taste; however, home-based producers face challenges in maintaining consistent supply due to traditional, manual, and batch-based production methods. The production process, which consists of three main sub-processes—roasting, crushing, and mixing—often leads to inefficiencies and bottlenecks, particularly in the roasting stage. This study develops a system dynamics model to analyze the current production process and identify areas for improvement. By connecting three single-batch models, with the third model incorporating an "assembly" process to represent mixing, the model provides a comprehensive framework for enhancing production capacity. Compared to traditional mathematical models based on queuing theory or discrete simulation, the system dynamics approach offers greater simplicity and flexibility. Verification of the model demonstrates that it accurately reflects expected behaviors, serving as a valuable tool for producers to make informed decisions and improve their operations without compromising the traditional taste of Madiun pecel sauce.

Keywords: System Dynamics, Batch Production, Pecel Sauce, Efficiency, Home-Based Producers

1. Introduction:

Madiun is famous for its pecel, a culinary product served in the form of boiled vegetables such as long beans, spinach, turi flowers, and bean sprouts coated with thick pecel sauce made from a mixture of peanuts, chilies, sugar, kaffir lime leaves, and various other natural flavorings. Madiun pecel sauce has a distinctive taste. Many people consider it the best pecel sauce in Indonesia [1]. Although in fact, similar culinary can also be found in other areas, such as Yogyakarta, Blitar, and Surabaya, the unique taste of pecel sauce originating from Madiun makes it a culinary icon of the city.

The city government has made efforts to preserve this culinary heritage by designating the city of Madiun as Pecel Land in 2019. This designation confirms that pecel sauce is a superior product of the region or city. This designation is based on the tradition of making pecel sauce that has been passed down from generation to generation. Currently, there are around 1,000 home-made pecel sauce producers in the area [2]. Although the taste of pecel sauce may differ slightly between producers, the overall taste profile remains unique and different from similar products in other areas.

The process of making pecel sauce begins with roasting 5 to 50 kg of peeled peanuts for approximately two hours. The roasted peanuts are then crushed for approximately two hours. The crushed peanuts are then mixed with other ingredients including chili, sugar, salt, tamarind, and garlic, lime leaves, and others, which amount to approximately 30-35% of the total weight of the mixture [3]. This traditional process is carried out in several sequential stages (roasting, grinding, and blending), but alternately.

Although small-scale companies now rely on batch methods completely, continuous approaches can provide a number of advantages. Continuous methods enable roasting, crushing, and mixing to take place all at once, in contrast to batch operations that finish each step alternately with the next. This has the potential to improve energy integration and production efficiency ([4], [5]). The majority of producers still choose for the more practical batch method since the infrastructure and automation needed for continuous production are still out of their price range.

Given the challenges involved, it is important to model the current batch production process so that we can better understand the system and find optimization opportunities ([6]). This article seeks to deepen this understanding by creating a system dynamics model for the batch production process of pecel sauce. This approach draws inspiration from the concepts of system dynamics modeling in assembly processes ([7]) to explore a three-stage process, with the 'assembly' phase at the end. This is in contrast to previous research ([8]) which focused on a single-stage process.

System dynamics is a modeling tool developed by Jay Forrester and expanded by his successors, such as John Sterman ([9]; [10]). It utilizes stock and flow structures to represent the accumulation and movement of materials or information, making it particularly suitable for modeling production processes. This tool is suitable for understanding complexity in production systems ([11]; [12]). Using differential equations, system dynamics describes how a system evolves. This approach considers the dynamic interactions and feedback between various elements, such as material flows, labor, and information. Its advantages compared to traditional mathematical modeling and discrete simulation are its ability to provide a comprehensive view of system dynamics, display feedback, visualize flows and stocks ([9]; [13]; [14]), and allow testing of various scenarios to support better decisions ([10]; [15]). Figure 1 illustrates the basic concept of system dynamics, highlighting the key components and interactions within the system.

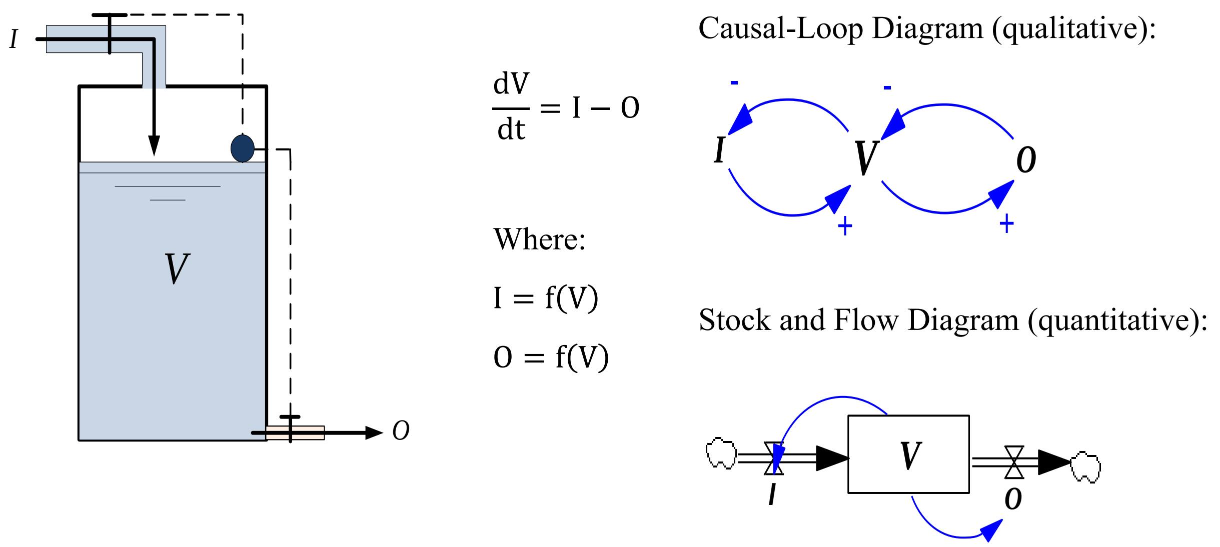

Figure 1: Basic Concept of System Dynamics

By employing system dynamics, this study aims to provide a comprehensive understanding of the Madiun pecel sauce production system, enabling informed decisions for process optimization. We develops a system dynamics model for the three-stage batch production process of pecel sauce, which includes roasting, crushing, and mixing. We analyze the model to find bottlenecks, especially in the roasting stage, and suggest areas for improvement. The paper also offers recommendations to increase production efficiency while keeping the traditional methods and taste of pecel sauce. Overall, all specific objectives have been met, providing a useful analysis and model for further study of the three-stage batch system.

2. Description of the System Under Study

The production of Madiun pecel sauce is a home-based activity carried out in batches once a day during working hours (08:00 to 18:00). The production process involves three main stages: roasting, crushing, and mixing. Each stage is executed sequentially without overlapping, and the batch size typically ranges from 6 kg to 50 kg of peanuts per batch.

The production process of Madiun pecel sauce consists of three main stages. First, peanuts are roasted in one batch for about two hours. Next, the roasted peanuts are crushed in another batch, which also takes around two hours. Finally, the crushed peanuts are mixed with other ingredients to make the pecel sauce, taking approximately one hour. This sequential batch process is currently manual and lacks automation, leading to inconsistencies in production capacity and efficiency [2].

3. Modeling

System dynamics is a simulation technique that models the behavior of complex systems over time, focusing on the interactions and feedback loops between system components. This approach is particularly apt for modeling production systems like the batch process of Madiun pecel sauce, which involves sequential stages with interdependencies.

The methodology consists of several key steps. First, we conceptualized the model by defining the system boundaries and identifying the main components and processes involved in producing pecel sauce. Next, we developed stock and flow diagrams to visually represent how materials accumulate and move through the production stages. We then translated these diagrams into mathematical equations that describe the system's behavior over time. After that, we used Vensim PLE software to build and simulate the model. To ensure accuracy, we verified the model through logical checks and, where possible, empirical validation. Finally, we utilized AI tools to assist in writing and organizing the paper, ensuring that the content is clear and logically structured.

Vensim PLE is a user-friendly system dynamics modeling software that allows for the creation and simulation of complex models. Its graphical interface facilitates the development of stock and flow diagrams, and it supports the implementation of equations and simulations. Although Vensim PLE has limitations in terms of advanced features and model complexity compared to its commercial counterparts, it is sufficient for the purposes of this study, which focuses on a three-stage batch production process.

There are several limitations to consider in this study. First, the complexity of the model is a concern, as Vensim PLE may struggle to handle highly complex models that involve many variables and feedback loops. Second, the accuracy of the model relies heavily on the availability and quality of data, which can be limited in a home-based production setting. Lastly, system dynamics is primarily a continuous modeling approach, which may necessitate approximations when applied to discrete batch processes, potentially affecting the model's precision in representing the actual production process.

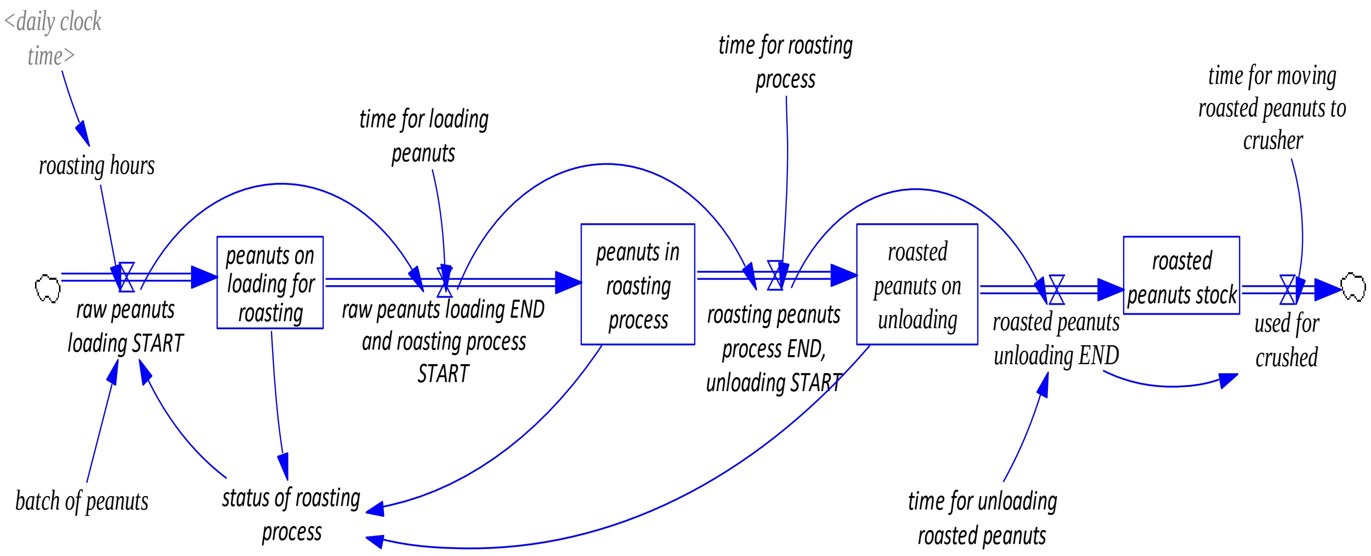

Figure 2: Stock and Flow Diagram for Roasting Stage

Figure 2 presents the stock and flow diagram specifically for the roasting stage, illustrating the accumulation of peanuts as they are loaded, roasted, and unloaded. It highlights the key variables and their interrelationships during this stage of production.

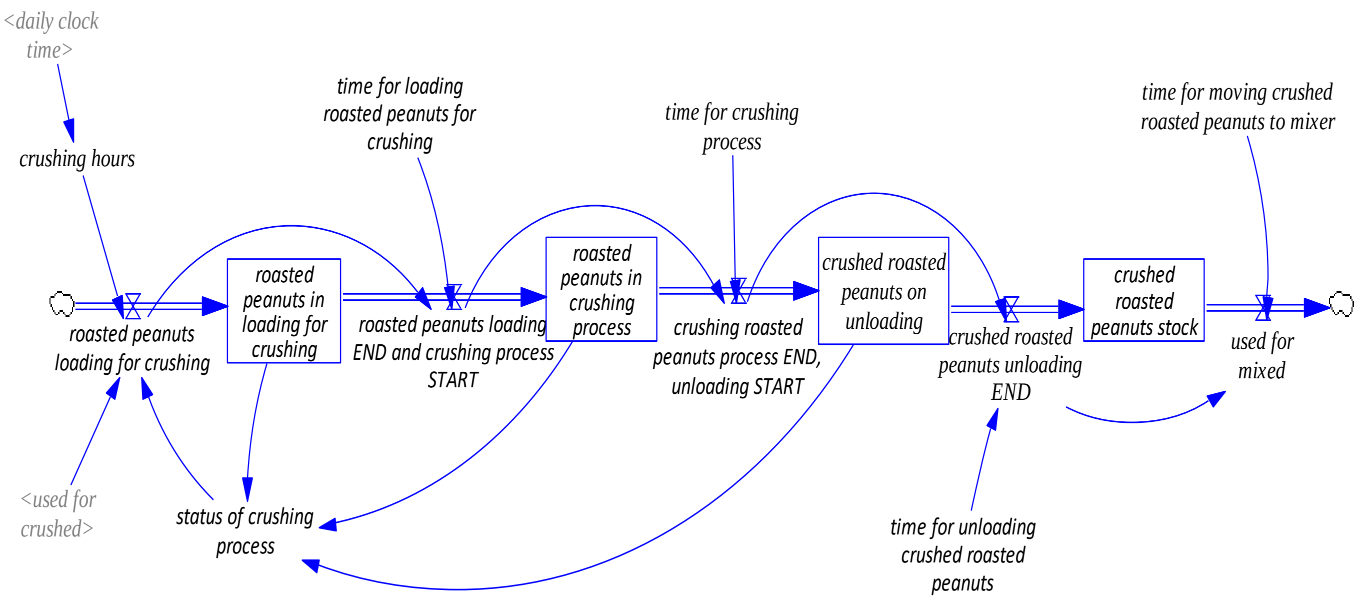

Figure 3: Stock and Flow Diagram for Crushing Stage

Figure 3 depicts the stock and flow diagram for the crushing stage, showing how roasted peanuts are processed into crushed peanuts. It details the flow of materials and the changes in stock levels throughout this stage.

Figure 4 illustrates the stock and flow diagram for the mixing stage, where crushed peanuts are combined with other ingredients to create the final pecel sauce. It captures the dynamics of material flow and stock changes during mixing.

4. Results, Verification, and Discussion

Results: The analysis of the model's behavior was conducted through simulations that examined the dynamics of material flow across the three production stages. The key findings revealed several important aspects. First, the model illustrated the fluctuations in stock levels at each stage over time, underscoring the necessity for synchronized processing times to minimize inventory holding costs and reduce waste. Additionally, the roasting stage was identified as a potential bottleneck, as its longer processing time compared to the crushing and mixing stages could restrict overall production capacity. Lastly, it was found that modifying the batch size has a significant impact on the frequency of loading and unloading activities, which in turn affects the overall efficiency of the production process.

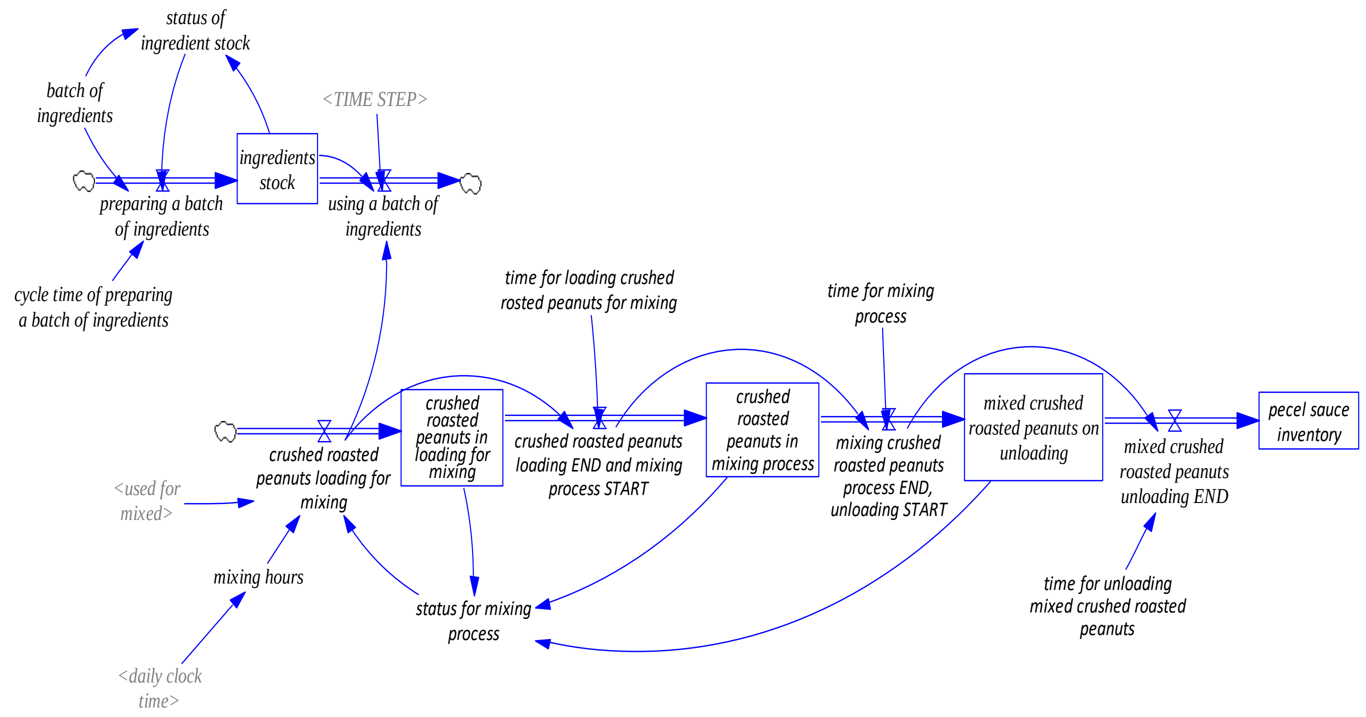

Figure 4: Stock and Flow Diagram for Mixing Stage

Verification: The model was verified through logical checks and chronological analysis of interconnected variables. Several key variables, particularly those related to stock in the stock and flow diagrams, emerged with a chronology and cause-and-effect relationships that align with the underlying conceptual logic.

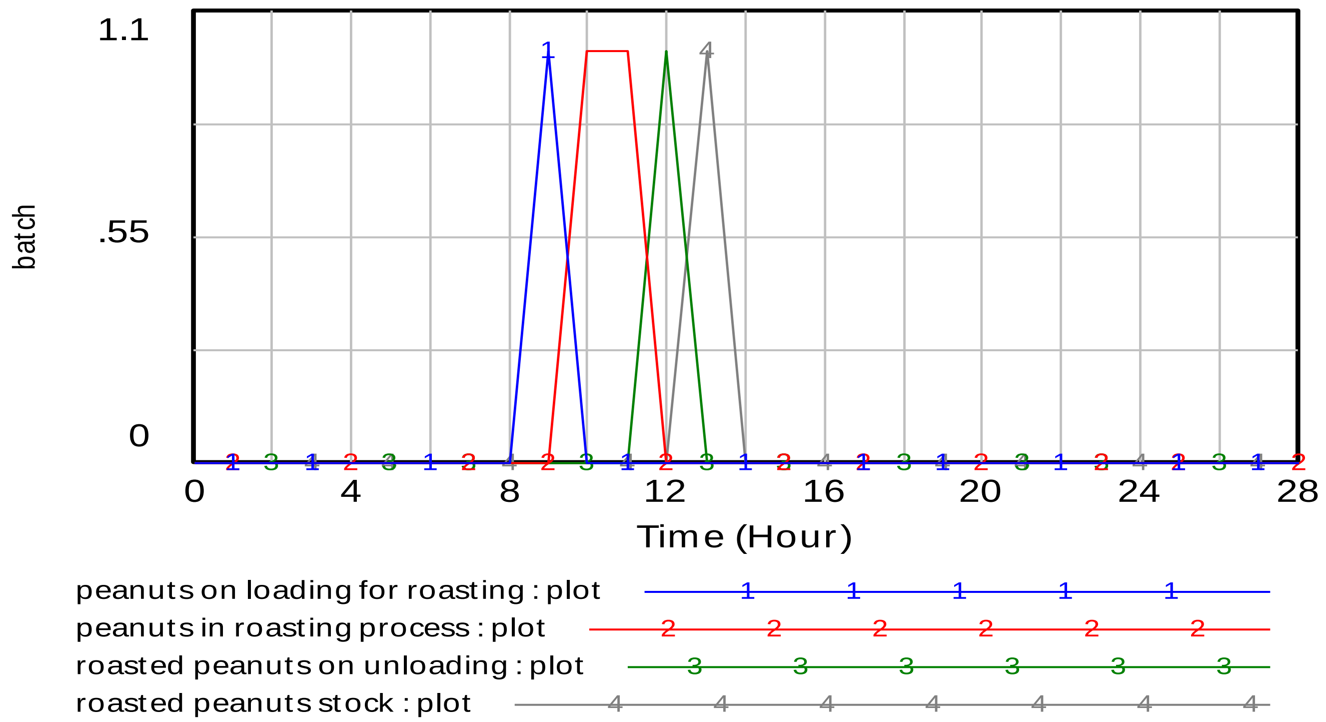

Figure 5: Variable Progression in the Roasting Stage

In Figure 5, we observe a clear progression of variables. Figure 5 illustrates the progression of key variables during the roasting stage, showing how the stock of peanuts changes as they move through the loading, roasting, and unloading processes. The process begins with Peanuts on Loading for Roasting, which increases as peanuts are prepared for roasting. Following this, Peanuts in Roasting Process reflects the active roasting of peanuts, increasing as they are loaded and decreasing as they are moved to the unloading stage. Once roasting is complete, Roasted Peanuts on Unloading rises as the roasted peanuts are unloaded, leading to an increase in Roasted Peanuts Stock, which represents the total amount of roasted peanuts available for the next stage. The timing and quantities of these variables align perfectly, confirming that the model accurately reflects the sequential nature of the production process.

Moving to Figure 6 we can see a different set of variables at play. Figure 6 depicts the progression of key variables during the crushing stage, illustrating how roasted peanuts are processed and the changes in stock levels. The sequence starts with Roasted Peanuts in Loading for Crushing, which builds as roasted peanuts are prepared for the crushing stage. This is followed by Roasted Peanuts in Crushing Process, which increases as peanuts are crushed and decreases as they are unloaded. The next variable, Crushed Roasted Peanuts on Unloading, rises as crushed peanuts are unloaded, leading to an increase in Crushed Roasted Peanuts Stock as they are stored for mixing. The timing and quantities of these variables are consistent with the expected flow of the production process, reinforcing the model's accuracy.

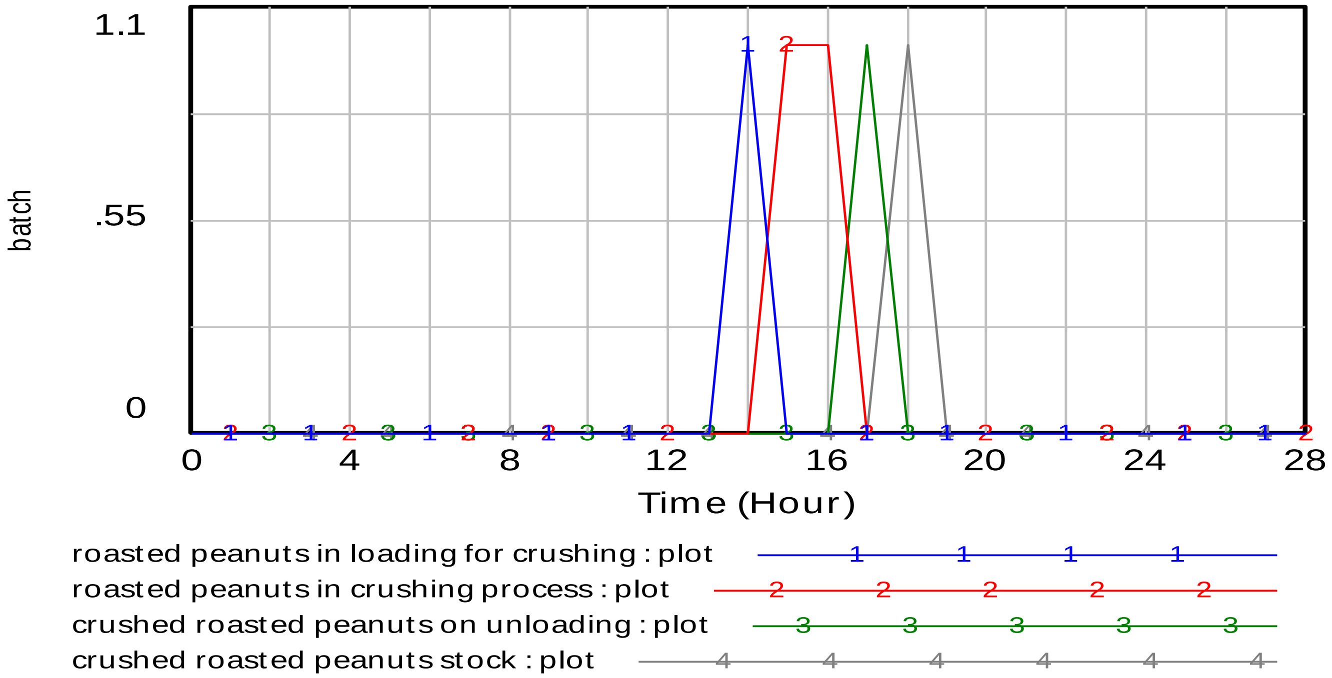

Figure 6: Variable Progression in the Crushing Stage

In Figure 7, we encounter another set of variables. Figure 7 illustrates the progression of key variables during the mixing stage, showing how crushed peanuts are combined with other ingredients to create the final pecel sauce. The process begins with Crushed Roasted Peanuts on Loading for Mixing, which increases as crushed peanuts are prepared for mixing. This is followed by the In Mixing Process, where the stock rises as ingredients are blended. Once mixing is complete, Pecel Sauce on Unloading increases as the finished sauce is unloaded, leading to an increase in Pecel Sauce Inventory, which represents the final product. The timing and quantities of these variables align well, further validating the model's representation of the system.

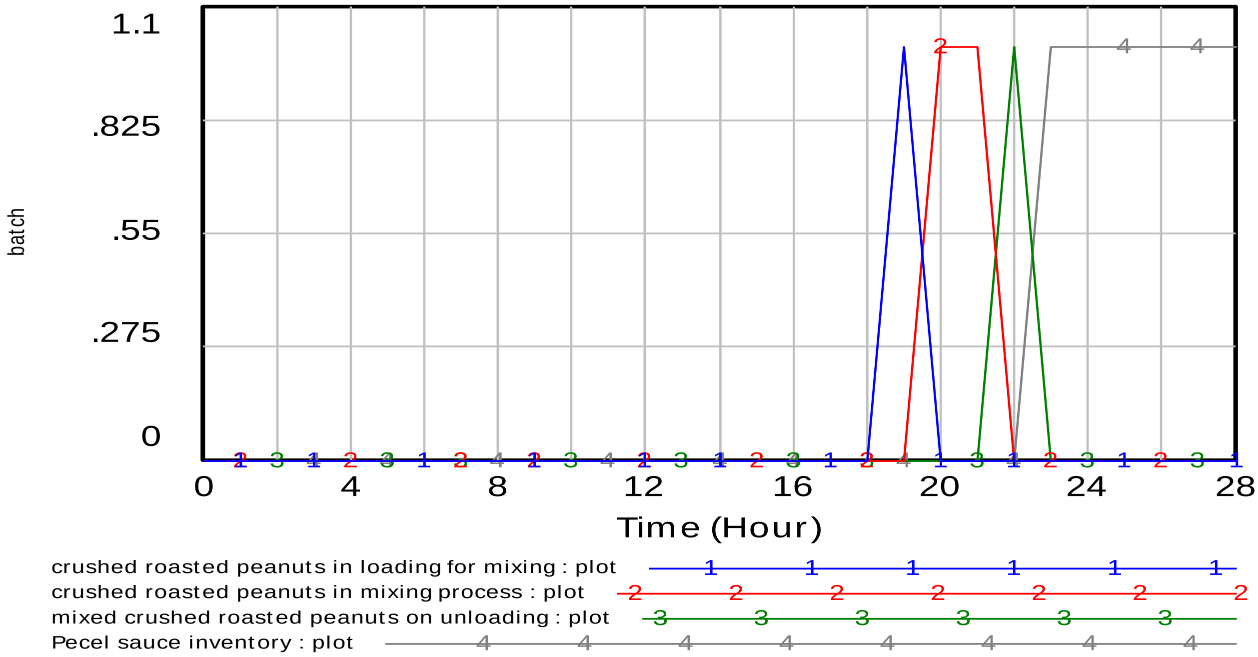

Figure 7: Variable Progression in the Mixing Stage

Finally, in Figure 8, we analyze a comprehensive set of variables. Figure 8 provides a comprehensive view of the progression of key variables throughout the entire production process, illustrating the interdependencies between roasting, crushing, and mixing stages. The sequence starts with Peanuts in Roasting Process, reflecting the active roasting of peanuts. This is followed by Roasted Peanuts Stock, which indicates the inventory of roasted peanuts waiting to be crushed. Next, Roasted Peanuts in Crushing Process shows the peanuts being crushed, leading to an increase in Crushed Roasted Peanuts Stock as they are stored for mixing. The process continues with Crushed Roasted Peanuts in Mixing Process, reflecting the peanuts being mixed, and concludes with Pecel Sauce Inventory, representing the final product ready for sale. The timing and quantities of these variables are consistent with the logical flow of the production process, confirming the model's accuracy in representing the real-world system.

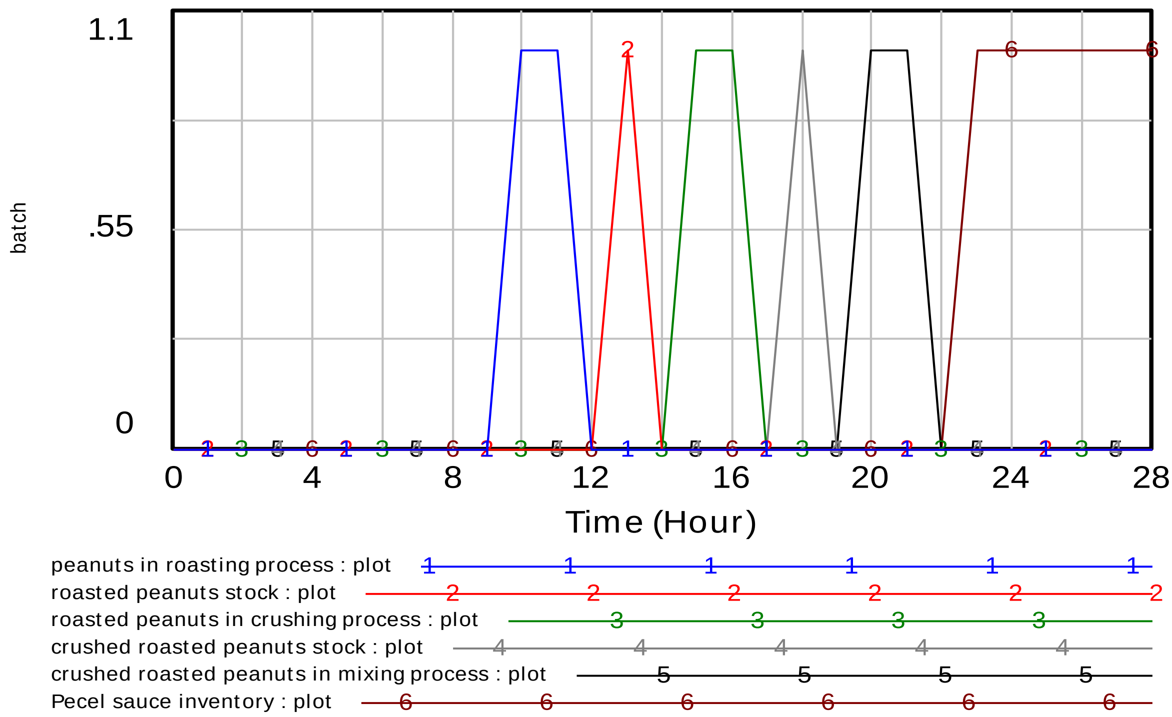

Figure 8: Comprehensive Variable Progression in the Production Process

Overall, the alignment of timing and quantities across all figures demonstrates a logical flow and interdependence that supports the model's accuracy in representing the production process. Figures illustrating the sequential behavior of the system confirm that the model accurately represents the conceptual framework.

Discussion:

The findings suggest that optimizing the roasting process could significantly enhance overall production efficiency. This could be achieved through process improvements, such as enhancing roasting equipment or adjusting roasting times, without compromising the quality of the final product. Moreover, the model highlights the importance of synchronizing the processing times across all stages to prevent bottlenecks and minimize inventory holding costs. Adjusting batch sizes could also help in balancing the workload and improving resource utilization.

The verified model has significant implications as it provides a foundational tool for further analysis and potential enhancement of the three-stage batch production system. This allows producers to explore various scenarios and make informed, data-driven decisions to optimize their production processes. However, there are limitations to consider; the model relies on simplified assumptions and may not fully account for all the complexities present in real-world situations. To improve the model's accuracy and reliability, empirical validation using actual production data is essential.

5. Conclusion:

This study has developed a system dynamics model to represent the three-stage batch production process of Madiun pecel sauce, providing valuable insights into the system's behavior and dynamics. The model successfully captures the interactions between roasting, crushing, and mixing processes, identifying potential bottlenecks and areas for improvement.

Key findings indicate that optimizing the roasting process and synchronizing processing times across stages are crucial for enhancing production efficiency. The model serves as a tool for producers to evaluate different strategies and make informed decisions to improve their operations without altering the traditional taste and methods.

The use of system dynamics in modeling batch production systems offers a flexible and comprehensive approach, enabling a deeper understanding of complex production dynamics. Future research could focus on empirical validation of the model and exploring the economic advantages of continuous versus batch processes in the context of Madiun pecel sauce production.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations:

- AI: Artificial Intelligence
- PLE: Professional Learning Edition
- Vensim: Ventana Systems' Simulation Software

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