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Simulation for sustainable agri-food production: from efficiency optimization to waste reuse

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Abstract

This study analyzes the application of simulation in the agri-food production processes, with a focus on integrating Industry 4.0 technologies to improve efficiency, flexibility, product quality and environmental sustainability. The growing interest in simulation applications, their use in the agri-food sector is still in an initial phase compared to other industries, especially in terms of circular economy practices and waste reuse. This research addresses this gap by focusing on sustainable waste reuse in citrus production processes. Using Siemens Tecnomatix Plant Simulation software, a model was developed to simulate the production of citrus products, such as juices, jams, icings and alcoholic drinks, allowing bottlenecks to be identified and resources to be optimized. Minitab 17 software was used for statistical analysis of the results, confirming the benefits of optimization, including reduced production times and operating costs. The innovative aspect of this study lies in the development of a second model, which emphasizes sustainability through renewable energy generation from production waste. The sustainable model enabled the plant to meet 30% of its energy needs independently, and production time in the juice line was reduced from 4 days to just over 1 day. A second sustainability-oriented model introduces the reuse of production waste to generate renewable energy and by-products, fostering a circular economy. The results highlight how the integration of simulation and statistical tools can promote significant improvements in production performance and energy sustainability, contributing to the evolution of the agri-food sector toward more sustainable and competitive practices.

Keywords: Industry 4.0, Smart Manufacturing, Simulation, Agri-food, Sustainability

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1. Introduction

Implementing changes in an organization, large or small, can be complex and expensive. In this regard, simulation has become a crucial tool for designing and improving systems, significantly reducing development costs and time. In recent years, the adoption of Industry 4.0 technologies has accelerated across various sectors, fostering advancements in simulation and digital twins. These technologies are increasingly applied to optimize processes, reduce resource consumption and achieve sustainability targets, aligning with global trends toward environmental responsibility and circular economy principles. Through simulation models, it is possible to visualize and analyze how a new system might work or how an existing system might behave if modified. Thus, this approach allows to explore and optimize solutions in a virtual environment, avoiding costly mistakes and changes after the new production system is physically built [1]. In this direction, key areas of focus include the challenges in manufacturing that simulation can help address, the available software tools for manufacturing applications, methods for developing reliable models and the associated statistical considerations [2]. The scientific background of this research lies in discrete event simulation (DES) and statistical analysis techniques, such as Design of Experiments (DOE), which have been extensively applied to industrial processes to enhance productivity and quality control. The integration of these techniques with sustainability-focused simulations represents a novel approach to address the dual goals of efficiency and environmental impact reduction. The integration of simulation and modern technologies is becoming a key factor in driving sustainable energy production, allowing industries to optimize resource use, reduce environmental impact and streamline processes by virtually testing solutions before implementation. In this context, simulation is applied across various sectors, including manufacturing, healthcare, and energy, with the agri-food sector gaining significant importance in recent years. One promising approach in this field involves using citrus residues, such as peels and seeds, as a source for sustainable energy. These by- products, mainly generated during juice and jam production, make up about 50% of the original fruit mass and can be turned into valuable resources and energy. Concrete projects show the effectiveness of these technologies: in Spain, a plant has been built to produce bioethanol from citrus peels, and in Florida, a plant dedicated to producing ethanol from citrus residues, has been completed [3]. In Brazil, orange juice production generates a substantial amount of waste, representing 50-60% of the fruit's weight. These residues, traditionally sent to landfills or used as animal feed, contain valuable compounds that could be transformed into higher-value products. A recent study proposed a conceptual biorefinery model integrated into the orange juice production chain, aiming to convert this waste into chemicals, fuels and energy [4].

This study, based on an illustrative example of a company in the agri-food sector, highlights how simulation can be applied to enhance manufacturing processes. In the detail of the conducted study, the company consists of citrus production lines of which the results of the simulation are analyzed, enabling improvements in key areas such as production efficiency, flexibility, product quality and environmental sustainability. Considering the waste reuse, a second more sustainable version of the model is proposed with promising results.

The remainder of this paper is organized as follows. A brief review of relevant literature is provided in Section 2. In Section 3, the illustrative example model and its sustainable version are outlined and the simulation-based methodology is described. Section 4 shows the simulation results, while in Section 5 the conclusions and possible future developments are presented.

2. State of the art

Simulation is becoming increasingly vital in manufacturing industries for optimizing production and managing operational complexity. Discrete event simulation (DES) is crucial for identifying and managing bottlenecks in batch production processes. An examination conducted on tire production revealed, through simulation, how bottlenecks affect production flow and how strategic changes could enhance efficiency [5]. Process optimization can be achieved through various techniques, including Design of Experiments (DOE), ANOVA, numerical simulations and quality tools. As a matter of fact, designing and analyzing experiments using tools like Minitab, enables to reduce waste percentages [6]. The integration of DES with the DOE is crucial in optimizing productivity. By combining these two techniques, the researchers were able to accurately model the system dynamics and systematically evaluate the impact of key variables such as cycle times and station reliability with reference to the automotive sector [7]. In this perspective, DES can significantly enhance production performance management through the use of key performance indicators (KPIs), offering several advantages: real-time performance monitoring and management, identification and optimization of bottlenecks, improvement of process efficiency [8].

The evolution of simulation techniques has progressed from modeling individual processes to full integration with Industry 4.0, with a growing focus on digital twins and predictive simulation tools, enabling dynamism and real-time control of industrial operations [9]. Over the years it has been useful to implement re-engineering processes in sectors such as the food industry. In a previous study, it is shown how simulation can be worthy for modeling automated wheat storage and how advanced information systems, based on Industry 4.0 technologies, can promote adaptive quality control [10]. In the food industry context, the application of process models enables the optimization of production operations, taking into account specific variables such as raw material quality and processing conditions. Furthermore, the integration of digital twins allows dynamic adjustments to production processes, ensuring rapid responses to changes in operational conditions, enhancing the quality of the final product [11]. Nowadays, it is important to involve sustainability factors of the processes in the simulation, to avoid the risk of partial optimization. To effectively measure and evaluate productivity and environmental parameters, it is essential to consider them simultaneously rather than separately. An effective approach involves integrating productivity factors, such as batch size and resource management, with environmental parameters, such as emissions and energy consumption. A practical example, like juice production, demonstrates how certain system changes can simultaneously improve both environmental and productivity outcomes, while others might enhance one aspect at the expense of the other [12]. Manufacturing simulation and digital engineering tools have enhanced the industry over the years addressing environmental constraints during the design phase. Key factors include lean manufacturing, waste reduction and environmental impacts, with methods for assessing energy efficiency and CO2 emissions integrated into factory simulation software [13]. In a circular economy optic, it is important to take into account the production waste to be reused as raw material in other processes, and, for that purpose, the food waste is the most suitable. In this field, different simulation software, such as Aspen Plus, are used to mathematically model chemical processes. The use of Aspen Plus provides a powerful means for optimizing biogas production from food waste. By modeling the anaerobic digestion process, it is possible to analyze and adjust operational parameters such as temperature, pH and retention time to identify optimal conditions. The results show that these optimizations can significantly increase biogas yield, enhancing energy efficiency and reducing undigested residues [14]. The adoption of circular economy practices by small and medium-sized enterprises (SMEs) across various sectors and its integration with sustainability requires further exploration of conceptual boundaries, highlighting the importance of innovation and tailored tools in enabling the implementation of circular economy practices effectively [15].

The research study reveals that, while simulation is increasingly implemented across various sectors, the agri-food sector presents unique challenges compared to others due to critical factors such as safety, quality, and perishability. These complexities underscore the need for models capable of jointly addressing multiple aspects with a sustainability-focused approach, making it an area worthy of further study and specialized model development. In this context, our study contributes to filling this gap by proposing a dual approach: a simulation model focused on optimizing production efficiency, coupled with an innovative sustainability-oriented model that reuses production waste to generate renewable energy. This dual model not only enhances traditional production metrics, such as reducing bottlenecks and improving resource utilization, but also aligns with circular economy principles by transforming waste into valuable subproducts [16]. Such an approach is novel in the agri-food sector, setting the groundwork for future applications in sustainable production.

3. Agri-food production line simulation model

The study described in this paper is based on an illustrative example of a company operating in the agri-food sector. Due to its adherence to reality and its generality, the research could be considered by the companies of this sector in order to improve their manufacturing processes. The study conducted aims to achieve some objectives that characterize Industry 4.0, through the use of simulation. The main ones concern: production efficiency, using simulation it is possible to identify bottlenecks, inefficiencies, downtime, waste by analyzing where to intervene to optimize the process; production flexibility, using simulation it is possible to identify the optimal number of active production lines to respond to market demand changes; product quality, by simulating the use of sensors it is possible to monitor the time the products pass through the phases in which they are still at risk of deterioration; environmental sustainability, through simulation it is possible to test the feasibility of a more sustainable process by implementing a form of circular economy which consists of creating products from production waste. The production system described in this paper deals with processing of citrus fruits (oranges, lemons and bergamots) to produce juices, icings and jams. Furthermore, the company recovers waste resulting from production by realizing two additional products: alcoholic drinks, using the peels resulting from cutting and peeling phases; organic material, using the fruits discarded during the selection and washing phase. To meet the growing consumers' needs for healthier products, a production line for sweet oranges-based juices without added sugar is also considered.

In light of the above, the finished products belong to five different categories: juices (orange juice, sweet orange juice, lemon juice and bergamot juice); jams (orange jam and bergamot jam); icings (lemon icing, orange icing and bergamot icing); alcoholic drinks (Limoncello and Arancello); organic material. The raw materials for feeding the production chain are divided into: raw materials for production (lemons, oranges, sweet oranges, bergamots, water, sugar, alcohol) and raw materials for packaging (cardboard bricks for juices, glass jars for jams, glass bottles for alcoholic drinks, PET bottles for icings, plastic bags for waste). Finally, to reuse the production waste in a better way, a more sustainable version of the model was suggested.

3.1 Data Collection Methods

The data included in this study were collected from research on real companies operating in the agri-food industry in order to be adherent to reality and to ensure a detailed comprehension for of each phase involved in the process.

In order to accurately reflect the variability of various operations, two types of time distributions were considered for machinery: constant and uniform. Constant distributions are used when operating times are actually invariable, regardless of operating conditions or variations in the production process. This type of distribution is typical for highly standardized stages, where times are predetermined and follow a fixed pattern. Uniform distributions, on the other hand, are used to model processes where times may vary within a specific range, but with equal probability for each value within that range. This type of distribution is applied in cases where operations may be influenced by a number of variable factors, but where no predominant trend toward a particular time value could be identified. The costs of machinery and operators came out of a market analysis, comparing price lists of specialized suppliers that operate in this field. In addition, the cost of energy was estimated by referring to average market prices and updated energy tariffs. The energy consumed was calculated using the technical specifications of the major manufacturers' machineries derived from the research. This approach enabled to obtain an accurate and reliable estimate of the times, costs and energy consumption associated with machineries used in the sector. The core simulation study employed the software Siemens Tecnomatix Plant Simulation for analysis and modelling purposes. Siemens Tecnomatix Plant Simulation is an advanced simulation technology platform from Siemens Digital Industries that helps industrial organizations create digital models of their plants and warehouses, explore system characteristics and optimize their operational and business performance. Finally, to conduct comprehensive analyses and validate the precision of the collected data, the statistical software Minitab 17 was employed.

This advanced tool facilitates the application of essential analytical techniques, thereby enhancing the reliability and relevance of the data used in the simulation study.

3.2 Simulation Model

For the development of the simulation model, the following steps were followed. After problem formulation and data collection, as previously described, the conceptual model was built. The definition of the conceptual model was helpful in defining an abstract and simplified representation of the simulation model then implemented through Siemens Tecnomatix Plant Simulation, as shown in Fig. 1.

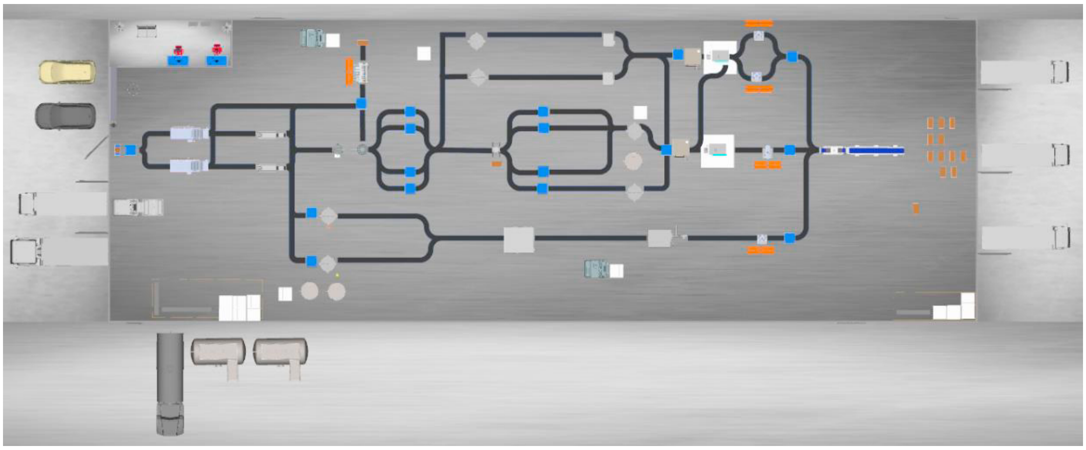


Fig. 1. Simulation model view from above.

At the beginning of the simulation, a quantity of fruit, set within an external Excel file connected to the simulation model, fills the Source at 6:00 am on a three-day cadence. The incoming fruit goes through the next stages of Selection&Washing, Peeling&Cutting and Juicing&Filtering. The process then branches into three different lines.

- The first ones are the Juices. The fruits are squeezed, filtered and placed in barrels. Then the water inside them is removed through the concentration phase. The concentrated juices are then left to rest to allow the product to reach a certain stability, improving its consistency and uniformity before being mixed with water for the Orange sweet juices and with water and sugar for the others in order to create a homogeneous mixture. Subsequently, there is the sterilization phase to guarantee the food safety of the products and extend their shelf life. They are then cooled in special ColdRooms before being packaged.
- The second products are the Juices Icings and Jams. The fruits are squeezed, filtered and placed in barrels. They are then mixed with sugar before being cooked in special ovens (CookingRoom). Then, there is the sterilization phase, in common with the juice line, before being cooled packaged.
- The last ones are the Alcoholic Drinks. The orange and lemon peels resulting from the peeling phase are mixed with alcohol, water and sugar in special barrels and then left to stand for 30 days to allow the infusion phase. At the end of 30 days, the skins are extracted from the barrels and the alcohol is bottled.

Each product, at the end of its production line, is subjected to quality control. In order to follow the objective of circular economy, the production waste is recovered in two ways: the peels resulting from cutting and peeling oranges and lemons are used for the production of alcoholic drinks; the fruits discarded.

The EnergyAnalyzer tool of Siemens Tecnomatix Plant Simulation provides the energy consumption of each machinery in the simulation environment. In the case under consideration, as the Fig. 2 shows, the cooling stages for juices, jams and icings require the greatest energy consumption. In particular, due to the fact that juices are the products produced in larger quantities than other ones, their line turns out to be the most energy wasteful.

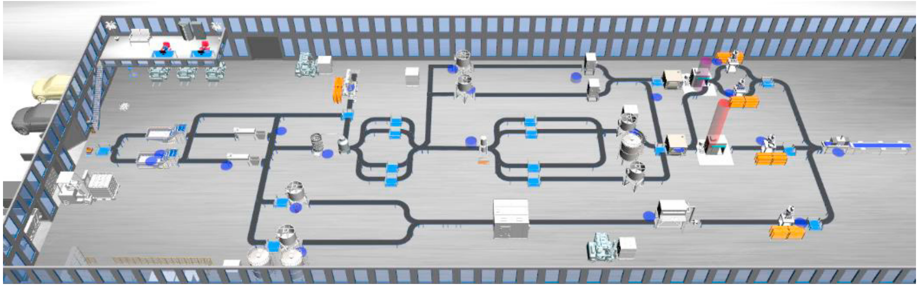


Fig. 2. EnergyAnalyzer tool visualization in the simulation model.

3.3 KPI Analysis

In the production system, 5 different KPIs are monitored in relation to the objectives set at the beginning of the simulation. In particular, for each objective there is a corresponding performance measure.

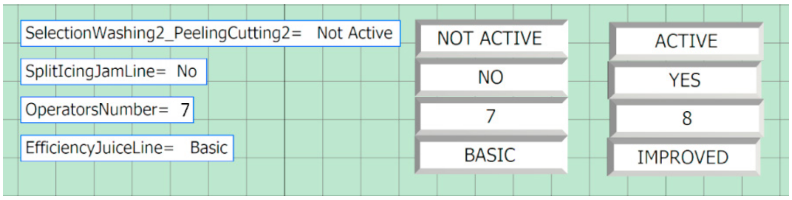
Table 1. KPIs monitored in the simulation model.

Objective	KPI
Reduce flow time	Flow Time Juices
	Flow Time Icings and Jams
Optimize resource utilization	Utilization level of machineries
	Utilization level of operators
Costs monitoring	Total Cost = Machinery Cost + Energy Cost + Operators Cost

As shown in the Table 1, the Flow Time relating to the production of alcoholic beverages is not monitored as there are no investments along this line for its reduction in the simulation. The machinery cost refers to the annual depreciation expense for each machine.

3.4 Input Parameter

The primary function of the input section is to allow users to modify specified parameters in accordance with a provided set of guidelines. Before starting the simulation, users can adjust various parameters through Button objects, which offer a simple and user-friendly way to change values. These buttons are commonly used to manage numerical variables and parameters within the simulation model. The parameters available for modification in the input section are displayed in Fig. 3. The selection of these parameters and their allowable ranges resulted from a comprehensive analysis of the plant. This in-depth study identified critical aspects of production where adjustments could have the most impact. Through the simulation of various scenarios, these parameters were fine-tuned to maximize the model's flexibility and responsiveness. As a result, it reflects realistic improvements and supports informed decision-making, effectively enhancing production efficiency.



SelectionWashing2_PeelingCutting2= Not Active
SplitIcingJamLine= No
OperatorsNumber= 7
EfficiencyJuiceLine= Basic

Fig. 3. Input parameters commands in the simulation model.

- Selection&Washing2 and Peeling&Cutting2: since these are perishable products, to reduce their waiting time before being processed, the duplication of the first two machines of the process (Selection&Washing and Peeling&Cutting) is considered.
- SplitIcingJamLine: the possibility of creating Icing and Jams in two separate lines rather than in a single common one is being evaluated, involving the addition of three machines (MixingLine2, CookingLine2 and Sterilization2).
- Operators Number: the hiring of an additional operator is considered.
- EfficiencyJuicesLine: the efficiency improvement involves the use of higher performing machineries exclusively along the juice production line (Concentration, ConcentratedJuices, MixingJuices, MixingSweetOrangeJuice and CoolRoom Juices).

3.5 New simulation sustainable model

The system described, starting from fruits processing, enables the production of differentiated products through three main production lines, from which some waste is also generated. In order to introduce a more sustainable and eco-friendly approach in the production system simulation model, two lines dedicated to waste recovery are added expanding the current system, as shown in Fig. 4.

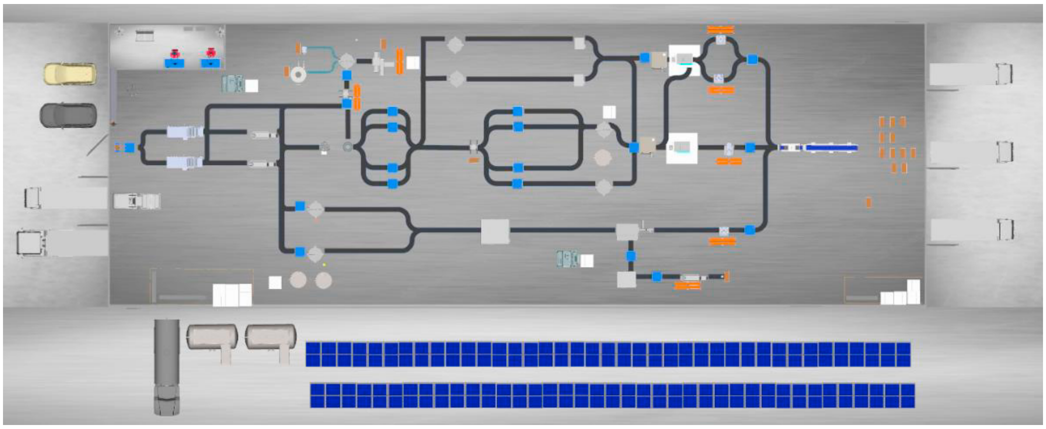


Fig. 4. Simulation sustainable model view from above.

More specifically, this modification allows for the alignment of the system with environmental sustainability and renewable energy objectives, as well as fostering the pursuit of a stronger circular economy. The interventions involve production lines in which the waste, represented by the organic material, could still be reused to produce energy and additional marketable products.

- In the prior version of the model, the waste resulting from the Selection&Washing, Peeling&Cutting, Juicing&Filtering stages is collected as organic material. With the implemented modification, the organic material (biomass), still rich in exploitable properties, is instead used for renewable energy production through the implementation of an anaerobic biomass digestion process. In this process, anaerobic bacteria decompose organic material in an oxygen-free environment, producing biogas, which is primarily composed of methane and carbon dioxide. In particular, citrus fruits are rich in organic material and are well-suited as a feedstock for this process. The biogas produced can be used to generate electricity or heat, while digestate, a subproduct of the process, can be utilized as fertilizer. This approach promotes renewable energy production, reduces organic waste and supports a more sustainable industry.
- In the previous model, orange and lemon peels are used exclusively for the production of alcoholic drinks and, at the end of their use, they are discarded permanently. The new process introduced enables the transformation of the discarded peels from that production line into fragrant products, such as potpourri. After being separated from the alcoholic drinks production cycle, a crucial drying phase follows, by which the color and aroma of the peels are preserved and their shelf life is improved. The final product, rich in natural and fresh fragrances, can be used to scent rooms or as decoration, adding value to production waste.

Therefore, the new simulation sustainable model allows alternatives to be offered for the use of production waste that would otherwise go unused. Suggested uses include: generating electricity from biomass to partially power the plant, using alternative fuels that can be burned instead of the fossil ones; producing digestate, which can be sold to fruit suppliers, to obtain discounts and allow the use of natural fertilizers that guarantee the good quality of the raw material; waste recovery of peels from the alcoholic infusion process to produce fragrant products to be introduced into a new market. Regarding electricity generation, a new “SelfPowered” KPI was introduced, which measures the percentage of how much the plant meets its energy needs on its own.

4. Results and discussion

This section discusses the main results that emerged from the study. In particular, for the first version of the simulation model presented, 80 experiments were carried out using Siemens Tecnomatix Plant Simulation and Minitab 17 software. As for the sustainable version of the model, the second one examined, preliminary results are presented regarding the quantities of products that can be obtained from production waste, along with the outcome related to the newly introduced KPI, called "SelfPowered".

4.1 First model results

In this study, the input parameters of the model are referred to as "factors", while the key output values from the simulation model, used for trend analysis, are designated as "key performance measures". The initial determination of the total number of simulation model runs was based on the potential combinations of the different factor levels, identifying 16 possible combinations. An experimental approach ensured distinct outcomes for each replication, even with identical input parameters.

The experiment was replicated 5 times. This choice of 5 replications was made to ensure statistical robustness in the results, allowing for the assessment of variability and enhancing the reliability of the findings. By conducting multiple replications, the study captures a broader range of potential outcomes under identical input conditions, which is crucial for a realistic and comprehensive analysis in simulation-based research. Additionally, this number or replications provided a balanced approach between computational efficiency and result accuracy. These replications enable a more accurate evaluation of performance metrics, such as flow times and resource utilization, reducing the likelihood of anomalies or outliers skewing the overall conclusions. Following this, a statistical analysis of the experimental results was performed, which is presented through a series of graphs generated using Minitab 17 software. The simulation represents a year of work.

An ANOVA analysis, executed using Minitab, was employed to evaluate the main effect plot, aiming to understand which modification of the plant, represented by the factors, have a greater impact on the plant itself.

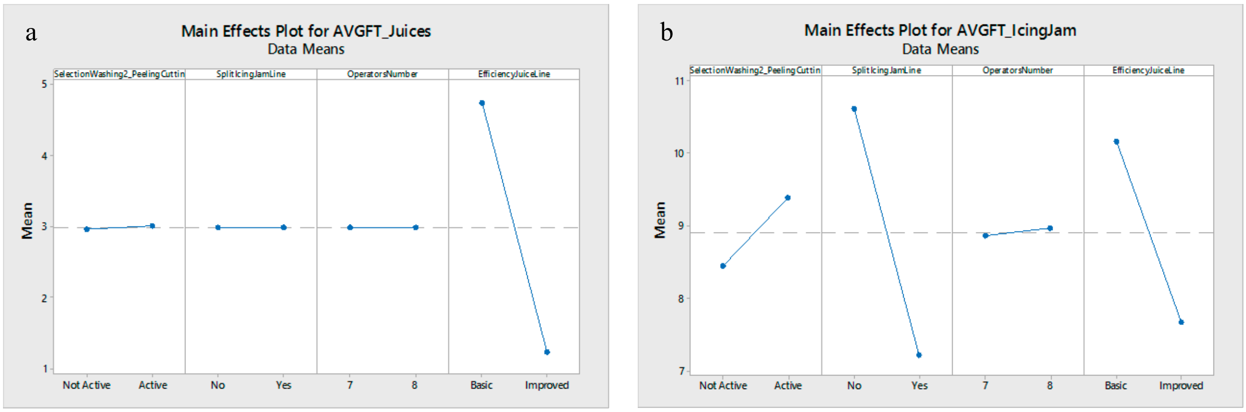


Fig. 5. (a) Main Effects on Average Flow Time Juices; (b) Main Effects on Average Flow Time Icing&Jam.

Fig. 5 (a) shows how efficiency on the juice production line results in a radical reduction in their average flow time, from about 4 days to just over 1 day. Instead of using the same production line for icing and jam production but splitting it into two lines, enables a reduction of their average flow time, by about 3 hours, as shown in Fig. 5 (b).

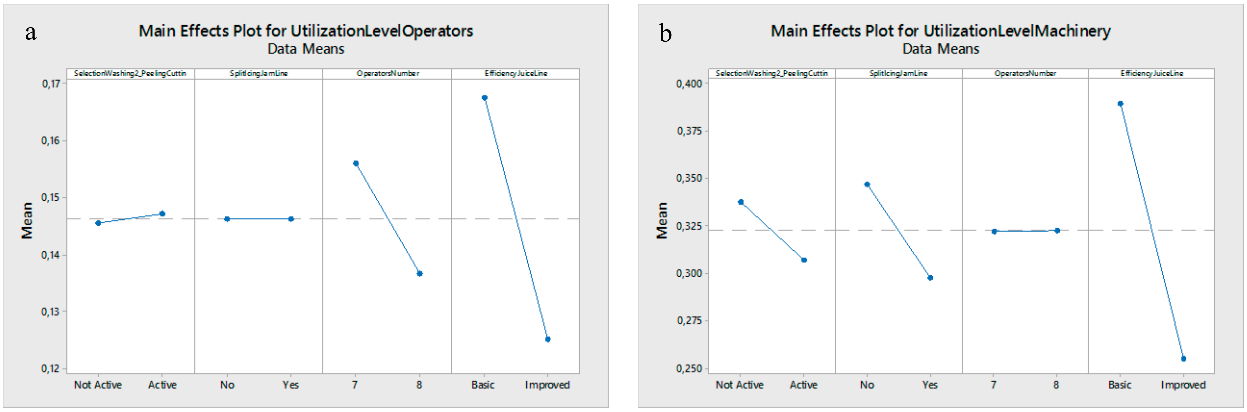
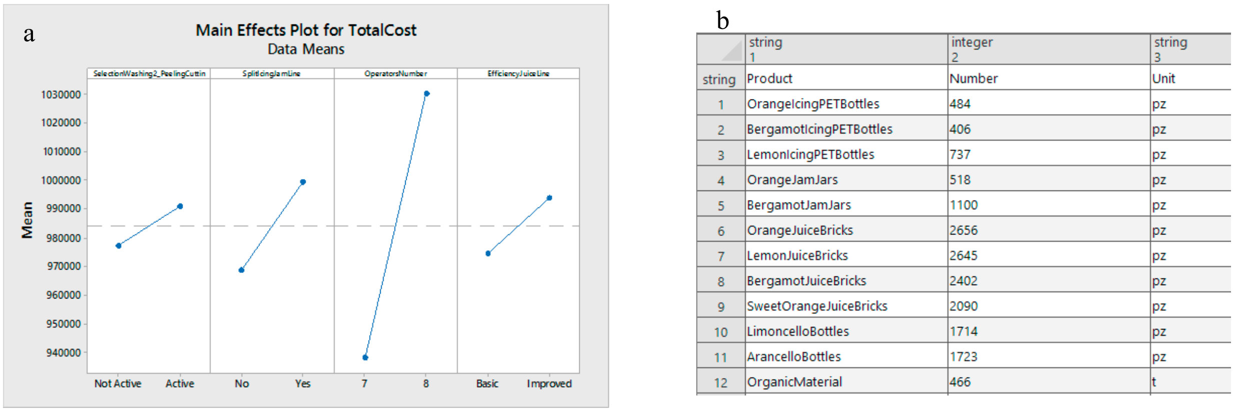


Fig. 6. (a) Main Effects on Utilization Level Operators; (b) Main Effects on Utilization Level Machinery.

Switching from the basic to the improved juice production line, represented by the efficiency juice line factor, results in a clear reduction in both the level of operator utilization, depicted in Fig. 6 (a), and the level of machinery utilization, shown in Fig. 6 (b).



	string 1	integer 2	string 3
string	Product	Number	Unit
1	OrangeIcingPETBottles	484	pz
2	BergamotIcingPETBottles	406	pz
3	LemonIcingPETBottles	737	pz
4	OrangeJamJars	518	pz
5	BergamotJamJars	1100	pz
6	OrangeJuiceBricks	2656	pz
7	LemonJuiceBricks	2645	pz
8	BergamotJuiceBricks	2402	pz
9	SweetOrangeJuiceBricks	2090	pz
10	LimoncelloBottles	1714	pz
11	ArancelloBottles	1723	pz
12	OrganicMaterial	466	t

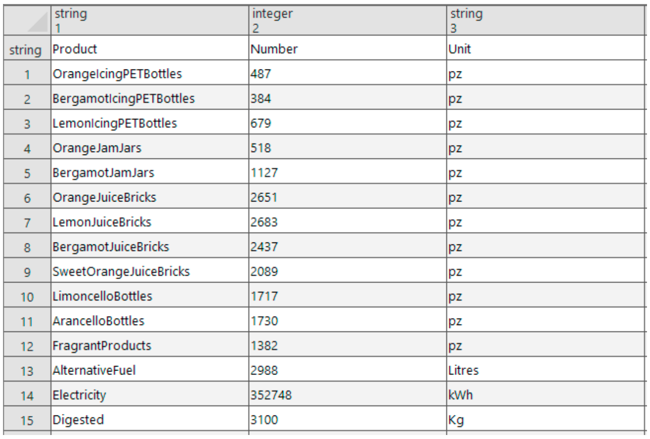
Fig. 7. (a) Main Effects on Total Cost; (b) Product quantities obtained.

Fig. 7 (a) shows that the main effect on total costs is due to the increase of one operator per work shift (each day there are 2 work shifts lasting 8 hours each, from 6:00 am to 10:00 pm). Fig. 7 (b), on the other side, shows the quantities of products that can be produced over the course of a year.

4.2 Sustainable model preliminary results

Comparing Fig. 7 (b) with Fig. 8 shows that the quantities of the plant's main products remain about the same, but in addition, with the sustainable line it is possible to make numerous other products from the production waste.

Specifically, considering the amount of electricity that it is possible to produce in this sustainable version of the model, the “SelfPowered” KPI gives as a result that it is possible to self-power the plant for a percentage equal to 30 percent of the plant's energy needs over the simulation period.



	string 1	integer 2	string 3
string	Product	Number	Unit
1	OrangeIcingPETBottles	487	pz
2	BergamotIcingPETBottles	384	pz
3	LemonIcingPETBottles	679	pz
4	OrangeJamJars	518	pz
5	BergamotJamJars	1127	pz
6	OrangeJuiceBricks	2651	pz
7	LemonJuiceBricks	2683	pz
8	BergamotJuiceBricks	2437	pz
9	SweetOrangeJuiceBricks	2089	pz
10	LimoncelloBottles	1717	pz
11	ArancelloBottles	1730	pz
12	FragrantProducts	1382	pz
13	AlternativeFuel	2988	Litres
14	Electricity	352748	kWh
15	Digested	3100	Kg

Fig. 8. Product quantities obtained in the simulation sustainable model.

5. Conclusions

Simulation represents a powerful tool for analyzing complex scenarios, allowing for hypothesis testing without real-world risks. It enhances decision-making by predicting the impact of critical variables and optimizes processes in a safe and efficient environment while exploring innovative solutions. This study applies these principles to an illustrative example of a company in the agri-food sector to enhance manufacturing processes. Specifically, the company consists of citrus production lines and the simulation results are analyzed in order to improve its performance. Building on these findings, a second more sustainable version of the model is proposed, incorporating waste reuse as a key factor, thus demonstrating the potential of simulation to drive sustainability in industrial operations. This study clearly illustrates the power of simulation in optimizing industrial processes, showing how adjustments to production models can lead to substantial improvements. It enabled an in-depth exploration of how various factors influence production processes, providing a robust basis for data-driven decision-making. For the initial version of the simulation model, 80 experiments were conducted using Siemens Tecnomatix Plant Simulation and Minitab 17 software. The findings revealed that altering certain key factors resulted in significant gains in the efficiency of the juice production line, including a radical reduction in average flow time. Furthermore, these changes led to a decrease in the use of both operators and machinery. The ANOVA analysis confirmed that these modifications positively affected overall costs and annual production. In addition, the results from the sustainable model demonstrate the feasibility of integrating eco-friendly practices without sacrificing productivity. The model's ability to convert production waste into new products and achieve partial energy self-sufficiency highlights the simulation’s role in enhancing both operational efficiency and environmental sustainability. This integrated approach addresses the increasing demand for sustainability in the agri-food sector and provides a framework for future improvements and innovations. The limitations of this model lie in the fact that the proposed simulation models are not based on data from a real company, but rather on an illustrative example. However, companies operating in the agri-food sector can draw valuable inspiration from these models to implement improvements in their production processes and adopt sustainable practices. For future research, it is recommended to explore the integration of simulation with virtual reality (VR). Combining VR with simulation models used for optimizing production processes and sustainability, could offer an immersive experience, allowing for more detailed and realistic visualization and interaction with simulated data and processes. Additionally, VR could serve as a training tool for operators, facilitating learning and preparation without the risks associated with real world environments. Another avenue for research suggests further investigating the preliminary results obtained from the second version of the model by examining how sustainability strategies can be optimized. This includes improving not only energy efficiency and waste management but also addressing other critical aspects such as productivity and operational costs. In conclusion, the study demonstrates the power of simulation in improving industrial processes and promoting sustainability by increasing production efficiency and reducing operational costs. The sustainable model illustrates how advanced ecological practices, such as waste reuse and energy self-sufficiency, can be adopted without compromising productivity. This approach not only provides a concrete alternative for integrating ecological solutions but also serves as a virtuous example of how sustainability can be effectively achieved in the industrial sector. However, it is important to note certain limitations of this study: the proposed simulation models are based on an illustrative example rather than data from a real company, which may impact the generalizability of the results. Additionally, while the study presents preliminary findings on sustainability integration, further research with real-world data is necessary to validate and refine these outcomes. These limitations suggest that future studies could benefit from collaborations with industry partners to enhance the accuracy and applicability of the models.

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