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Design of a Supply Chain and Manufacturing Process for Synthetic Lumber

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Abstract: Synthetic lumber can be produced from recycled materials and exhibits impermeability, anti-bacterial resistance, and low weight. It offers a low-maintenance alternative for disaster response structures like hexayurts. Previously made in Italy, production is proposed to start in Manassas, VA. A five-stage manufacturing process includes collection, cleaning, grinding, extrusion, and packing of pallets, which weigh 1000 kg each. A stochastic simulation models factory layouts, costs, and resource allocation while minimizing expenses. The simulation shows that the lowest-cost configuration to produce 983 pallets in 30 days with a 95% probability for delivery of 2078 hexayurts is a factory with ten cleaning machines, ten grinding machines, and thirty extrusion machines. At this rate of production, the cost per pallet is $757. The projected five-year revenue is $228.2M, with a $174.3M profit, 323% ROI, and a 0.99-year break-even period, providing a cost-effective, sustainable building material solution.

Keywords: Simulation, Synthetic Lumber, Manufacturing Process, Disaster Response, Business Plan

1. Introduction and Context Analysis

NOVAFoam is a lightweight, durable synthetic lumber made from 100% recycled EPS with water-resistant and anti-bacterial properties, offering significant savings in maintenance and transportation. In 2024, there were 27 individual weather and climate disasters causing at least $1 billion in damages, second only to the record-setting 28 events in 2023 (National Oceanic and Atmospheric Administration, 2024). Disaster relief shelters benefit from NOVAFoam's durability, low maintenance, and ability to insulate in harsh environments. The market benefits from impermeability and anti-bacterial properties, which reduce mold growth and provide temperature insulation. The low weight of the synthetic lumber also reduces transportation costs to remote or temporarily inaccessible areas.

The preferred structure for disaster response is a hexayurt, an easy-to-build, resilient, and widely used structure. (Hexayurt Project, 2025). It consists of six 4' x 8' sides and a 2' angled roof. A typical disaster response order would require 2,000 hexayurts to be delivered within 30 days. To support such demand, a supply chain and manufacturing process for the synthetic lumber must be implemented.

1. The process begins by collecting a combination of industrial and consumer expanded polystyrene waste.
2. The material is then cleaned to remove 95% of contaminants that could affect structural integrity.
3. The cleaned material is then ground into small pellets no larger than 1mm.
4. The ground expanded polystyrene is then melted in an extrusion machine and filtered for purity. A proprietary chemical powder is mixed in to adjust the material's properties, along with dye if a specific color is needed. An antibacterial additive may also be included, depending on the intended use.
5. The NOVAFoam boards are then cooled into a solid form and cut to the desired length as it exits the extrusion machine. The cut pieces are then packaged to be sent out of the manufacturing floor.

2. Stakeholder Analysis

NOVAFoam was previously manufactured in Italy, but production ceased when the inventor and owner retired. Now, a U.S. investor aims to restart production domestically with an EPS extrusion machine already in possession. With a provided business model, the created simulation serves as a digital twin to analyze the costs and product throughput of a NOVAFoam factory based on user inputs.

Stakeholders emphasized the need for durable, lightweight, and hygienic materials to reduce transport costs and improve response efficiency. Disaster response customers, including government agencies and NGOs, prioritize speed, cost-efficiency, and durability in shelter solutions. The lower weight of the NOVAFoam also reduces transportation costs to remote regions, or regions that have lost access.

Other key stakeholders include industrial EPS providers for material sourcing, with the most consistent supply coming from local industrial waste, while consumer waste introduces greater variability. Environmental agencies ensure compliance with regulations and sustainability standards, while local communities benefit from recycling initiatives and job creation. The primary stakeholders in the NOVAFoam supply chain include material suppliers, manufacturers, disaster relief agencies, regulatory bodies, and investors. Suppliers ensure a steady stream of EPS waste, while disaster relief organizations seek affordable and reliable shelter materials. Regulatory agencies oversee compliance with recycling and safety standards. Investors monitor financial viability, and factory operators prioritize efficient, sustainable production to meet demand and control costs.

3. Disaster Response and AS-IS Process

Current disaster response materials like timber are heavy, require upkeep, and degrade quickly under harsh conditions. Manufacturers then transform these materials into construction components designed for rapid deployment. Government agencies, non-profit organizations, and disaster relief organizations purchase these materials to build emergency shelters and infrastructure in affected areas. Regulatory bodies ensure compliance with safety and environmental standards.

Disaster response teams play a role in planning and constructing disaster structures when needed, ensuring shelters are quickly and effectively deployed. End users, including displaced individuals and relief workers, benefit from shelters that are quick to assemble, cost-effective, and resistant to harsh environmental conditions.

A key challenge in disaster relief construction is the need for durable yet affordable materials that minimize long-term maintenance costs while maximizing resilience in extreme conditions.

4. Problem and Need Statement

The performance gap is identified in the maintenance phase of a product's lifecycle, stemming from the lack of durability in materials used in the as-is process. Comparable materials require high maintenance, costing between $0.51 and $0.76 per board foot annually (Yalamanchili, 2024). For reference, this could be between $729 and $1,086 every 5 years per hexayurt. This highlights the significant cost burden of maintenance services for these materials, emphasizing the need for a more durable and cost-effective solution.

4.1 Problem Statement

Disaster response efforts face challenges in providing safe, durable, and hygienic infrastructure. Traditional materials like wood are expensive to transport, prone to damage, and create health risks in shelters, food storage, and healthcare facilities.

4.2 Need Statement

There is a need for a strong, low-maintenance, and naturally hygienic building material that can withstand harsh conditions while being inexpensive to transport. NOVAFoam addresses this need by recycling EPS into a moisture-resistant, long-lasting, and lightweight material that offers a cost-effective alternative for disaster relief shelters, food storage, and improving emergency response efficiency and sustainability. The cost to ship NOVAFoam is up to 30% lower than treated hardwood lumber.

5. Literature Review

Expanded polystyrene (EPS) is most commonly used as an insulator, helping buildings retain heat and improve energy efficiency (Ramli Sulong et al., 2019). NOVAFoam shares these insulation benefits, but its rigid structure allows it to serve as an external building material with compression strength similar to red oak (Kretschmann, 2010). This makes it suitable for applications where both strength and environmental resistance are required.

Unlike traditional materials like wood, which cost between $0.51 and $0.76 per board foot annually to maintain (Yalamanchili, 2024), NOVAFoam is resistant to moisture and bacteria, reducing the long-term cost of upkeep. While recycled EPS introduces more variability into the supply chain than lumber, this challenge is addressed through stochastic modeling, which helps evaluate how delivery inconsistencies can affect throughput and cost (Yao & Chen, 2018).

These combined properties position NOVAFoam as a strong candidate for disaster response shelters like the hexayurt, which require fast, lightweight, and reliable materials (Hexayurt Project, n.d.).

6. Concept of Operation and To-Be Process for the Supply Chain and Manufacturing Process for Synthetic Lumber

The TO-BE process transforms recycled EPS into durable boards through five stages: collection, cleaning, grinding, extrusion, and packaging. The material has a perpendicular compression factor of 7 MPa, similar to oak wood (Kretschmann, 2010), NOVAFoam's density (701 kg/m³) and low water absorption (0.5%) also contribute to lower transport costs and material durability.

7. Requirements for the Supply Chain and Manufacturing Process for Synthetic Lumber

The system must collect at least 3,500 kg of recycled EPS daily, clean and grind the material to remove at least 95% of contaminants, maintain additive precision within ±5% during extrusion, and package the boards into 1,000 kg pallets for shipment. These constraints guide the throughput and quality assurance across the five-step manufacturing process.

8. Design Analysis of the Supply Chain and Manufacturing Process for Synthetic Lumber Using a Stochastic Simulation Model

8.1 Objectives of Simulation

Model the supply chain and manufacturing process of NOVAFoam using Python to simulate throughput and daily costs, enabling a clear visualization of operational efficiency and cost dynamics. This Python-based model gives potential investors data-driven insights into NOVAFoam's scalability, resource allocation, and economic viability.

8.2 Simulation Requirements

The stochastic simulation model replicates five key processes within the supply chain and manufacturing system: EPS Collection, Cleaning, Grinding, Extrusion, and Packaging. Each phase operates under a set of overarching requirements that serve as constraints throughout the process. The system shall simulate EPS collection using a triangular distribution to model the intake of waste EPS from both industrial and consumer sources. The cleaning process shall determine batch sizes, cleaning speed and efficiency, and weight loss due to contaminant removal. The grinding process simulation shall evaluate the grinding speed and its effect on overall throughput. The extrusion process shall assess spool-up time, extrusion speed, filter cleanings, and mold changes to model production efficiency. Lastly, the packaging and palletizing simulation shall analyze the throughput and storage requirements for finished products.

To ensure the system meets all specified performance criteria, five verification test plans have been developed. These tests validate each process's compliance with efficiency, throughput, and operational constraints, ensuring the model accurately represents real-world manufacturing conditions.

8.3 Simulation Functional Architecture

The simulation's functional architecture defines the five key components of the system, aligning with the additional process introduced earlier. It also outlines the sub-functions within each component, offering a clear framework for how the simulation models and supports the overall manufacturing process.

8.4 Input, Output, and Parameters Diagram

The inputs to the simulation include the number of each type of machine and the delivery size (Figure 1). Costs are represented as parameters as they are beyond the control of the factory operator. The primary outputs consist of the cost per pallet and the total number of pallets produced, along with machine utilization data to offer insights into operational performance during the simulation.

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The simulation operates for 16 hours per day across two 8-hour shifts. EPS deliveries are sourced at the start of each day with no lead time, and palletized storage is exported daily to model storage constraints.

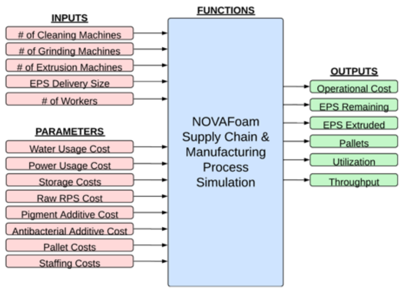

Figure 1. Input, Output, and Parameters Diagram

8.5 Simulation Results

Empirical operational data for parameters such as water/electricity costs, machine throughput, and set-up and breakdown times were collected. Raw EPS, clean EPS, ground EPS, extruded boards, and pallets are tracked throughout the simulation. The five metrics plotted over a five-day simulation with one cleaning machine, one grinding machine, and three extrusion machines are shown in Figure 2. This configuration ensures balanced throughput, preventing material stockpiles over time. Raw EPS is delivered to the factory at the start of each day, creating an initial spike. The cleaning machine processes the raw EPS in batches, converting it into clean EPS while incurring some material loss. The grinding machine then processes the clean EPS continuously, a step simulated with small time intervals for accuracy. The extrusion machines take the ground EPS and transforms it into extruded boards, branded as NOVAFoam. Finally, the boards are packaged into pallets, each weighing one thousand kilograms, which serve as the simulation's final output.

The daily operational costs, categorized by type, are shown in Figure 3. The most significant expense is the raw material delivered at the start of each day, followed by staff costs as the next largest expense. This chart provides a clear breakdown of cost distribution, offering valuable insights to guide decision-making when prioritizing cost reductions and optimizing factory operations.

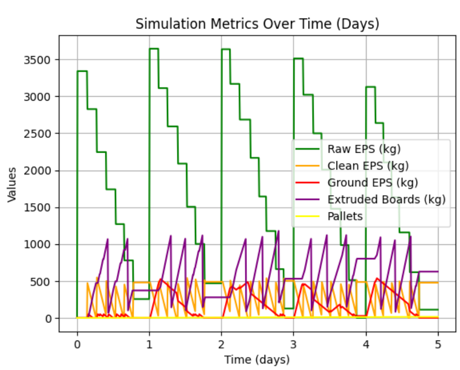

Figure 2. Throughput Results

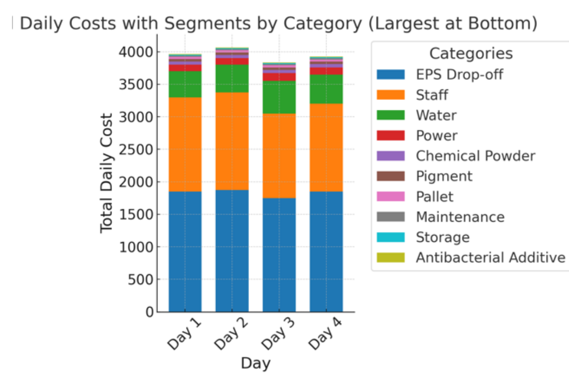

Figure 3. Daily Operational Costs

Figures 2 and 3 display throughput and cost data over a 100-day simulation using a configuration of 1 cleaning machine, 1 grinding machine, and 3 extrusion machines. Adjustments to the inputs include delivery size and the standard deviation of those deliveries. This variation in delivery standard deviation reflects the inconsistent availability of raw materials from different sources. The 5th percentile throughput is 308.8, which is 11.7 units below the mean, highlighting the system's sensitivity to delivery variability and its potential impact on minimum production levels.

The graphs in Figure 4 and Figure 5 represent a scenario with 2 cleaning machines, 2 grinding machines, and 5 extrusion machines simulated over 100 days. The key difference is the increased standard deviation in delivery size in figure 5, which leads to a $3.56 higher cost per pallet and a 50% increase in the standard deviation in the cost per pallet. This increase is primarily attributed to storage costs incurred from the backlog of material caused by inconsistent deliveries.

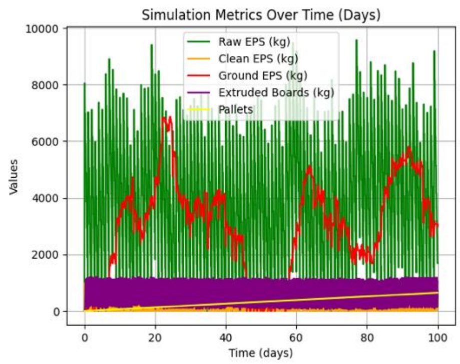

Figure 4. Potential Operational Scenario (1)

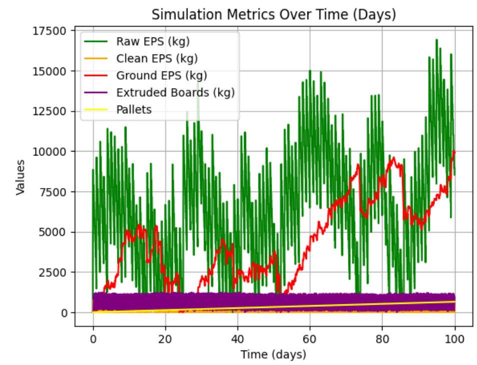

Figure 5. Potential Operational Scenario (2)

The cost per pallet versus the ratio of cleaning and grinding machines to extrusion machines reaches a minimum at 3/1 cleaning-grinding/extrusion ratio (Figure 6). Cleaning and grinding machines are grouped due to having the same throughput. The red line represents the mean, while the grey lines indicate one standard deviation from the mean. A ratio of 15 extrusion machines to 4 cleaning and grinding machines results in an average cost per pallet similar to a 3:1 ratio, but with a larger standard deviation, making 3:1 the best choice. The cost per pallet versus the number of workers for a setup with three extrusion machines and one cleaning and grinding machine is shown in Figure 6. Figure 7 indicates that the optimal number of workers for this setup is two, as adding more increases salary costs without a proportional production increase. Fewer workers significantly slow down production, reducing output and increasing the cost per pallet.

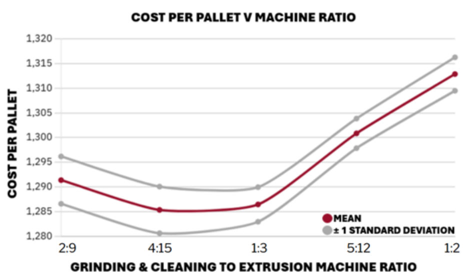

Figure 6. Cost per Pallet v Machine Ratio

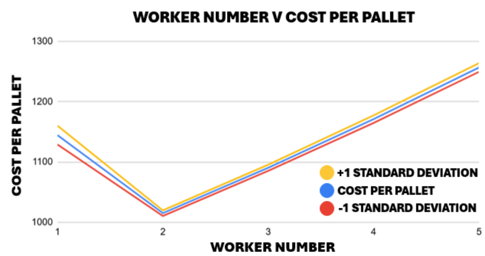

Figure 7. Worker Number v Cost per Pallet

Using a design of experiments (DOE) table, different factory setups were modeled to analyze production efficiency, cost per pallet, and machine utilization (Figure 8). The table evaluates varying numbers of cleaning, grinding, and extrusion machines, along with staff levels and EPS delivery sizes, to determine optimal configurations. Each input was simulated over 100 days for 100 trials. A trend observed is that an increase in the standard deviation of raw EPS delivery size corresponds to an increase in the standard deviation of pallets produced and the cost per pallet. These findings align with the insights from the previous two graphs. The lowest cost per throughput configuration consists of 1 cleaning machine, 1 grinding machine, and 3 extrusion machines, balancing pallet production at 322 and cost per pallet at $1256. This table serves as a foundation for further model optimization and can support the introduction of additional variables, such as demand fluctuations, delivery dynamics, and other operational constraints to enhance the simulation.

Inputs						Outputs						
						Pallet Produced		Cost Per Pallet		Machine Utilization (μ)		
Cleaning Machine (#)	Grinding Machine (#)	Extrusion Machine (#)	Staff (#)	EPS Delivery Size (Mode)	EPS MIN/MAX	μ	σ	μ	σ	Cleaning	Grinding	Extrusion
1	1	1	5	3500	2500 | 4500	129.36	1.40	2910.64	34.15	0.87	0.82	0.81
1	1	3	5	3500	2500 | 4500	322.73	3.65	1256.82	6.90	0.87	0.82	0.69
1	1	3	5	3500	1500 | 5500	320.55	7.14	1262.72	13.13	0.87	0.82	0.69
1	1	6	5	7000	5000 | 9000	345.22	2.50	1755.31	17.89	0.93	0.88	0.39
1	1	6	5	7000	3000 | 11000	345.09	2.29	1754.63	28.64	0.93	0.88	0.39
2	2	6	10	7000	5000 | 9000	645.33	6.13	1191.27	5.58	0.89	0.82	0.67
2	2	6	10	7000	3000 | 11000	645.02	15.78	1192.37	13.06	0.88	0.82	0.67
2	2	5	10	7000	5000 | 9000	641.72	5.48	1197.20	10.95	0.89	0.82	0.80
2	2	5	10	7000	3000 | 11000	636.03	9.61	1200.76	14.39	0.88	0.81	0.80

Figure 8. Design of Experimentation

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8.6 Two Thousand Hexayurt Case Study

A baseline manufacturing setup consists of one cleaning machine, one grinding machine, three extrusion machines, and two staff members. This setup produces 838,162 kg of NOVAFoam annually, with a standard deviation of 6,976 kg. This would be enough to build 1,774 hexayurts per year. The maximum throughput configuration for 12-foot-long 2x4 boards yields 244 boards per day with a cost per board of $16.41, with a standard deviation of $0.14.

A typical disaster response order would require 2,000 hexayurts to be delivered within 30 days. To meet this baseline, a machine manufacturing setup of 10 cleaning machines, 10 grinding machines, 30 extrusion machines, and 30 staff members would be needed. This configuration yields at least 2,078 hexayurts within 30 days in 95% of simulated cases, indicating a high reliability level. The median output is 2,181 hexayurts, meaning that in half of all simulations, production exceeds this number.

With each machine costing ~$200,000 and an initial investment of $10M for a factory location, there is a total initial investment of ~$20M. Annual variable costs remain below $6.773 million in 95% of simulations, reflecting the upper limit of expected yearly operating expenses under typical variability, bringing total costs to ~$53.867M over the first 5 years.

9. Business Plan and Conclusion

NOVAFoam presents a sustainable and innovative solution to the growing problem of expanded polystyrene (EPS) waste by transforming 100% recycled EPS into durable, high-quality synthetic lumber. With an initial investment of $20,000,000, the production facility is designed to operate efficiently, maintaining low material costs while ensuring high performance and longevity. The estimated annual variable costs of $6.773M enable cost-effective manufacturing, with financial projections indicating a strong return on investment (ROI) of 323% and a break-even period of just 0.99 years.

By targeting disaster relief agencies and nonprofit organizations, NOVAFoam is positioned as a practical and affordable alternative to traditional building materials, particularly for emergency shelter construction. Its combination of low water absorption, built-in antibacterial properties, and insulation comparable to softwoods makes it a resilient and reliable choice for sustainable construction. Furthermore, by diverting EPS waste from landfills and promoting a circular economy, NOVAFoam reduces environmental harm and contributes to a more sustainable future in the building materials industry.

One of the main limitations of the simulation is that it does not simulate demand for the product. If more time was available to work on this project, adding a demand simulation would greatly benefit the project by being able to estimate profit instead of cost for a given factory setup. Another limitation is that product delivery from warehouses to the final customer is not simulated. Adding this feature would allow for a better understanding of the cost of direct-to-customer sales.

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