Transdisciplinarity and the Future of Engineering B.R. Moser et al. (Eds.) © 2022 The authors and IOS Press. This article is published online with Open Access by IOS Press and distributed under the terms of the Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC 4.0). doi:10.3233/ATDE220680

An Investigation into Additively Manufacturable Latticed Packaging for Fresh Produce

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Abstract. Fresh produce is most commonly stored in corrugated fibreboard containers (CFCs) post-harvest. However, CFCs and packaging fillers like foams that serve as a cushion for fresh produce are a single-use product that is costly and not environmentally friendly. Reusable plastic containers (RPCs) are an alternative to CFCs, but due to its high transmissibility of forces that lead to damage of the content as well as its high upfront cost to manufacture and implement, the adoption of RPCs is low. With the advancement in additive manufacturing, this study aims to structurally innovate RPCs by incorporating lattice configurations in them. The proposed lattice structures will translate the characteristics of cushioning materials into the container's feature. Via direct frequency response simulation, the preliminary results demonstrated that proposed designs can sufficiently protect the fresh produce by reducing the maximum displacement experienced when subjected to loads within a common frequency range. This study hopes to inspire more efforts in reducing the consumption of CFCs and developing a more sustainable practice in the food packaging industry by adopting reusable packaging.

Keywords. packaging, additive manufacturing, lattice structures, sustainability

Introduction

Packaging is a significant component of the food industry as it protects products from various external influences and damages, thereby keeping them in optimal condition throughout the logistics chain, from the producer to the end-user. This is especially so for fragile products like horticultural and perishable products that are highly sensitive to environmental changes. Specifically, the packaging used in the storage and transportation process plays a key role in keeping fresh produce clean, free from mechanical damage, significant moisture loss and microbial decay.

According to the European Federation of Corrugated Board Manufacturers, a large proportion of the total corrugated fibreboard containers (CFCs) consumed were used for the storage of fresh produce like fruits and vegetables [1] as it offers high compression strength, bending resistance, impact resistance and low grammage [2]. These mechanical properties are highly valued given that the value of fresh produce is dependent on their

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quality when it reaches consumers. Although there are ongoing attempts to optimize the design of CFCs by consuming less material, generating less waste and retaining strength [3, 4], CFCs are essentially a single-use product that may be considered wasteful and resource-intensive to manufacture. In fact, paper and cardboard were the second largest contributor of waste generated worldwide in 2016 [5].

An alternative to CFCs is recyclable plastic containers (RPCs), which have greater durability and strength. RPCs are reusable, with several studies demonstrating that it is a more economical and environmentally friendly option with each reuse [6-8]. However, fresh produce is more prone to bruising due to a lack of damping within the rigid walls of an RPC. While foams and boards can be inserted along the walls and in between the layers to cushion the fresh produce, they require extra labour to implement and are not reusable, hence incurring additional costs and contributing to the existing wastage problem. Furthermore, current RPCs are generally heavier, not as collapsible, more costly to manufacture and transport. As such, the adoption of RPCs for the storage and transportation of fresh produce remains relatively low. Despite its potential as a more sustainable option compared to CFCs, there has been little focus on the optimization of RPCs for use in storing fresh produce. Moreover, the current designs of RPCs are limited by conventional manufacturing processes. Therefore, the purpose of this project is to investigate how an RPC can integrate the advantages of CFCs through additive manufacturing and attenuate its undesirable features, while keeping the cost and material used to a minimum. This marks the start of a critical effort to reduce the consumption of CFCs through the adoption of RPCs, and ultimately developing a more sustainable practice in the food packaging industry. On a macro scale, the potential and realization of proposed designs will require expertise from multiple disciplines - essentially a problem that can only be addressed with transiciplinary engineering efforts from the storage, logistics, transport and supply chain sectors.

1. Literature review

1.1. External influences and damages experienced during transportation

Fresh produces are subjected to free-fall, abrasion against each other or the walls of the packaging, vibration, and compressive load. K. Vursavus and F. Ozguven investigated the mechanical damage caused by vibration and difference in packing methods on apples using two different packaging materials and three arrangement patterns subjected to the same vibrational load [9]. The transmissibility of the packaging was deemed a key parameter since most of the packaging methods recorded were sensitive to a vibration frequency of 9Hz - an average vibration frequency measured on a truck-bed. It was found that the CFC with a triangular pattern arrangement performed the best while the wooden crate with random volume packaging was the worst due to its high transmissibility ratio across the frequency range of 3 - 24Hz. Additionally, it was noted that apples at the top of the container had the highest degree of freedom and can achieve intermittent weightlessness when subjected to a vibrational load. As a result of the continuous intermittent weightlessness, the knocking and rubbing of the apples against the second layer or the top of the packaging caused the apples on the top layer to record the most damage. Cushioning materials may be placed at the top of the packaging can help in reducing damages, however, the cost and inconvenience of using them were deemed prohibitive [9]. In contrary, T. Acıcan et al. reported that apples stored at the bottom of

a wooden crate is subjected to larger free-fall force, horizontal impact force, vibrational force, and mechanical force during transit [10]. The apples were subjected to a vibrational load and random points from each layer were selected for measurements. Except horizontal impact force where the differences were marginal, the three other forces recorded had a greater distinction between the layers, with the bottom layer recording the largest magnitude consistently. It can be inferred that impact-absorbing materials that can dampen these forces should be placed at the base of the packaging to minimize the mechanical damage experienced [10]. Complementary with previous studies, T. Fadiji et al. also reported that, CFCs recorded the highest level of transmissibility between the range of 9 - 15Hz [11].

1.2. Desired properties and features of a container

The ability of a container to provide adequate protection to its contents depends on several different mechanical and structural properties of the material used, which includes its transmissibility, compression strength, bending resistance and impact resistance. Even though the studies mentioned previously with regards to the mechanical damage induced on fresh produce were contradictory in the area where the most damage occurs, both studies suggested the use of cushions for damping purposes. According to N. Dubey and V. Mishra, the major functions of cushioning materials for perishable produce are protection from mechanical, vibration, compression, and abrasion damage. It should also protect against transfer of infection and moisture, while filling up the void space within the container. The ideal cushioning material should also be flexible, corrosion-resistant, physiologically inactive, able to dissipate heat due to the respiration of the fresh produce, able to preserve the inherent properties of the fresh produce like taste, while being environmentally friendly and cost-effective [12]. As the implementation of additional cushioning material is inconvenient, uneconomical, and may not be environmentally friendly, the aim of this study is to propose a new container design such that an environmentally friendlier approach to translate the properties of a cushioning material can be implemented.

It is crucial that the proposed container continues to provide sound mechanical protection for the fresh produce. To achieve effective damping and reduce the damage induced on fresh produce during storage and transportation, the transmissibility of the container should be minimized. This means that the container should be capable of isolating the content from vibration. Vibration can be attenuated through two types of damping systems, either passively through the likes of foams or rubber pads or actively through a control of viscous friction like a car's suspension. Typically, when a product requires a passive approach to damping, it involves the implementation of cushioning materials. However, this reveals an additional process in assembly, which can be avoided. An alternative to achieve passive damping is through the integration of lattice structures within the product, where additive manufacturing can be leveraged. Past studies reported that lattice structures can help to reduce a product's mass without compromising its strength and have also shown to be capable of isolating vibration as well [13, 14]. With additive manufacturing, the production of lattice structures becomes much easier, with increased degrees of geometrical and hierarchical design freedom and complexity.

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2. Initial set-up and loading conditions

2.1. Benchmark model

The design modelling and simulation were conducted on Autodesk Inventor Professional 2022. A simple top-open box with an external dimension of 200.8 by 116.5 by 240mm and a wall thickness of 3.5mm made up of high-density polyethylene (HDPE) was modelled as shown in Figure 1. Ventilation holes along the walls of the container are standardized across the experiments at 140mm from end to end with rounded ends of 40mm diameter. This model is meant to resemble a simple RPC. Each apple is modelled as a sphere of 57.15mm in diameter is also used within this study. The model of the box is scaled down to hold 4 layers of 6 apples in a 3 by 2 arrangement. It can be rescaled into a full-scale container by extending the geometry while maintaining symmetry. The apples were then placed into the box layer-by-layer, allowing it to rest in a triangular pattern as shown in Figure 2. The model containing 24 apples was subjected to a static stress analysis between the frequency range of 3 - 25 Hz and a force of 200N is applied at the top of the container. This result will serve as the benchmark to compare against for all subsequent container designs and iterations in this study. The general set-up and loading conditions for the simulation can be found in Table 1.



Figure 1. 3D model of a simple top-open box.



Table 1. Loading conditions for	or all	simulations.
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Mode of simulation	Direct Frequency Response (3 – 25Hz)	
Load	200N on the top of the container	
Gravity	$-9810 mm/s^2$ in the Y-direction	

2.2. Design alternatives

To investigate other design alternatives, the container set up for simulation is decomposed into its individual design features, based on the packing method, damping method (types of lattice structures depending on the shape and size of unit cells), number of layers and the strut diameter, as seen in Table 2. To integrate lattice structures and accomodate its variations in dimensions, a base extending further downwards by a

maximum of 50mm was included. The lattice structures are constructed by extruding and cutting a base shape along the XY and ZY plane, forming an array of unit cells along the two planes.

Multi Jet Fusion was selected as the additive manufacturing method to produce the proposed containers as the lattice structures can be directly printed within the container with minimal post-manufacturing steps required. Additively manufacturable materials such as the common HDPE, HP 3D Reusability PA11 from HP Inc. [15] and Ultrasint® TPU01 from BASF [16] were also selected for this study. In particular, HDPE is hypothesized as the primary material of choice as it is strong, food-safe, physiologically inactive, recyclable, does not promote corrosion nor act as a source for transfer of infection.

Strut diameter	Number of layers	Damping method (Types of lattice structures)	Packing method	Material	Design Features
2mm		Lattice structure (Diamond)	Pattern pack	High-Density Polyethylene (HDPE)	
4mm		Lattice structure (Hexagonal #1)	Ing	Polyamide-11 (PA11)	Plausible Solutions
6mm	3	Lattice structure (Hexagonal #2)	Volume packing	Thermoplastic Urethane (TPU)	

Table 2. Morphological chart.

3. Basis for evaluation

To examine and evaluate the transmissibility of the container, a comparison between the benchmark model (model A) and the container with lattice structures (model B) is performed. For a container behaving like a simple undamped spring-mass system and driven by a periodic displacement like a vibration, the transmissibility of the container is given by:

$$T = \left| \frac{x}{u} \right| = \frac{1}{1 - \frac{\omega^2}{\omega_0^2}}$$
(1)

where *T* represents the transmissibility, *x* is the distance moved by the container, *u* is the forced displacement which represents the peak amplitude of the vibrational load at a frequency of ω and ω_0 is the natural frequency of the container. By performing a similar direct frequency response simulation over a wider frequency range, the natural frequency of the containers can be determined. As seen in Figure 3, it was found that model A has a natural frequency at 149Hz while model B has a natural frequency at approximately 109Hz. Assuming that the system behaves like a simple undamped spring-mass system, model B would result in a higher transmissibility ratio and cause a larger displacement value due to the lower natural frequency. Instead, preliminary results of the study showed that model B had lower displacement values overall. Therefore, by contradiction and first principles, the system should be treated as a damped system instead and the transmissibility of the container is given by:

$$T = \left| \frac{x}{u} \right| = \sqrt{\frac{1 + [2\zeta\left(\frac{\omega}{\omega_0}\right)]^2}{[1 - \left(\frac{\omega}{\omega_0}\right)^2]^2 + [2\zeta\left(\frac{\omega}{\omega_0}\right)]^2}}$$
(2)

where ζ represents the damping ratio.

There are difficulties in measuring, simulating, and evaluating the damping ratio due to the dynamics involved and the software limitations. The load frequency experienced by the container will vary over a wide range under the actual dynamic conditions experienced during transportation, and thus the transmissibility values of the containers will vary. To better compare and discuss the alternative designs within this study, the maximum displacement experienced by the container filled with apples when subjected to the simulated load will be used and compared against the benchmark to identify a plausible solution instead.







Figure 3. Log of maximum displacement versus frequency of (A) the benchmark and (B) the latticestructured container.

4. Results and discussion

By varying the different parameters that determine the container's ability to protect its content, specifically the parameters of lattice structures integrated, multiple design alternatives can be tested. The morphological chart as shown in Table 2 visually captures the necessary product functionalities while exploring plausible solutions such that the model analysis were kept computationally feasible during the simulation. These solutions were modelled and simulated based on the same set-up and loading conditions as the benchmark and compared against one another. Table 3, 4, 5 and 6 display the results of the total displacement experienced, the percentage improvement in terms of a decrease in the displacement, the Von Mises strain experienced and the mass of each alternative, based on the direct frequency response simulations at 9Hz.

As seen in Table 3, TPU containers performed the best out of the three materials tested as it improved the displacement results for most of the containers. The influence of TPU on the containers remain consistent regardless of the design, reducing displacement by 2.7% on the benchmark model and 16.1% on the diamond lattice model. Across the designs, the strain experienced were small, indicating that plastic deformation is unlikely. Despite the vastly different mechanical properties of the materials tested, the results were only affected by a relatively small amount. Although a stiffer material with a higher Young's Modulus like PA11 recorded a lower strain, it did not lead to a lower maximum displacement compared to the same design with TPU. With reference to Table 4, out of the three different lattice structures tested on a TPU container, the diamond lattice structure that resembles a body-centred cubic system performed the best, demonstrating a 16.1% reduction in displacement.

For ease of comparison with the benchmark model, subsequent experiments were conducted and standardized based on the HDPE material. From Table 5, it can be deduced that more layers of lattice structures within the container results in a larger decrease in the maximum displacement experienced. For the same given thickness of 50mm where the lattice structures are modelled within, the container with smaller unit cells can allow for more layers of lattice structures, which proves to perform better than

one with larger unit cells and less layers. The container with 3 layers of diamond lattice saw a 12.4% improvement over the 7.8% improvement for that with 2 layers. With reference to Table 6, the container with 2.5 layers of lattice structures and 6mm strut diameter showed the greatest reduction in displacement by up to 17.7%. The variation in strut diameters showed the greatest difference in results for the same material and number of layers with an improvement of 4.2% for the one with 2mm strut diameter to 17.7% for the one with 6mm strut diameter.

Though the 3-layered diamond lattice container is heavier than the benchmark model, it can be noted that the mass percentage difference for the total mass of the container, inclusive of the fresh produce, is projected to be significantly lower. It is reasonable to suggest that the recommendation shown in Figure 4 - a densely packed container of smaller unit cells and more layers with a larger strut diameter in a given volume - as a better performing and plausible solution for additively manufacturable latticed RPCs.

Model	Mass (kg)	Total displacement (mm)	Improvement for displacement (%)	Max Von Mises Strain
Benchmark (HDPE)	0.567	27.554	-	2.938×10^{-3}
Benchmark (TPU)	0.655	26.832	2.7	3.547×10^{-3}
Benchmark (PA11)	0.625	27.117	1.6	1.856×10^{-3}
Diamond Lattice (HDPE)	1.024	24.146	12.4	1.297×10^{-3}
Diamond Lattice (TPU)	1.413	23.127	16.1	2.482×10^{-3}
Diamond Lattice (PA11)	1.129	23.407	15.1	1.017×10^{-3}

Table 3. Comparison of benchmark model and Diamond Lattice model with different materials.

Table 4.	Comparison	of damping	methods based	on 3-lavered.	. TPU	models with	4mm strut diameter

Model	Mass (kg)	Total displacement (mm)	Improvement for displacement (%)	Max Von Mises Strain
Hexagonal Lattice #1	1.076	23.989	12.9	2.740×10^{-3}
Hexagonal Lattice #2	1.019	24.382	11.5	1.331×10^{-3}
Diamond Lattice	1.413	23.127	16.1	2.482×10^{-3}

Table 5. Comparison of HDPE Diamond	Lattice models with	h 4mm strut diamet	er and different	number of
	layers.			

Model	Mass (kg)	Total displacement (mm)	Improvement for displacement (%)	Max Von Mises Strain
2 layers	0.855	25.393	7.8	1.782×10^{-3}
2.5 layers	0.954	24.625	10.6	1.526×10^{-3}
3 layers	1.024	24.146	12.4	1.297×10^{-3}

Table 6. Comparison of 2.5-layered, HDPE Diamond Lattice models with various strut diame	eters.
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Model	Mass (kg)	Total displacement (mm)	Improvement for displacement (%)	Max Von Mises Strain
2mm strut diameter	0.743	26.405	4.2	1.938×10^{-3}
4mm strut diameter	0.954	24.625	10.6	1.526×10^{-3}
6mm strut diameter	1.222	22.690	17.7	1.338×10^{-3}

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5. Conclusion

This study explored the design of additively manufacturable RPCs by incorporating lattice configurations at the base of the containers to reduce damage to fresh produce during transportation. Based on the preliminary investigation, the container with the 3 layers diamond lattice structures had the greatest decrease in the maximum displacement experienced when subjected under a direct load frequency. An increase in the number of unit cells, layers and the strut diameters of the lattice structures can increase the mass of the container, which may lead to more energy expensed during transportation. Further transdisciplinary studies considering factors such as the measurement of environmental metrics in additive manufacturing and the feasibility evaluation of logistics movement, supply chain management and operations versus current practices are required to realize these recommendations. The mechanical performance of the container can be also further enhanced by gathering more insights on the correlation between each parameter and the container's mass, and considering the design of ventilation holes to identify the possible trade-offs and limitations to the current design while reducing the overall material consumed. This can help to realize the vision of additive manufacturing, to enable higher degrees of design freedom to produce innovative solutions that were previously impossible to manufacture. Through this study, the authors hope to inspire more environmentally sustainable and effective ways to contain, transport, and protect fresh produce over the existing CFCs, which are produced via conventional manufacturing methods, by introducing additively manufacturable latticed packaging.



Figure 4. Recommended container design (scaled-down version) based on this study.

6. Acknowledgement

This paper is supported by HP-NTU Digital Manufacturing Corporate Lab (School of Mechanical & Aerospace Engineering, Nanyang Technological University), National Research Foundation (NRF) Singapore and the Singapore Government through the Industry Alignment Fund – Industry Collaboration Projects Grant (I1801E0028).

7. References

- T. E. F. o. C. B. Manufacturers, Annual Statistics 2020, Online 2020. [Online]. Available: https://www.fefco.org/about-fefco/industry-statistics-home.
- [2] J. Park, S. Chang, and H. Jung, Numerical Prediction of Equivalent Mechanical Properties of Corrugated Paperboard by 3D Finite Element Analysis, *Applied Sciences*, vol. 10, p. 7973, 11/10 2020, doi: 10.3390/app10227973.
- [3] J. H. Patterson, *Material Reduction in Corrugated Containers for the Fresh Produce Industry*, Orfalea College of Business, 2011, https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1024&co ntext=itsp, accessed June 20, 2022.
- [4] J. J. Singh, R. N. Kisch, J. Chhun, and E. Olsen, Design-An Opportunity in Reducing Corrugated Fiberboard Carbon Footprint, *Journal of Applied Packaging Research*, 2009, Vol. 3, pp. 105-118.
- [5] S. Kaza, L. C. Yao, P. Bhada-Tata, and F. Van Woerden, *What a Waste 2.0*. The World Bank Group, 2018.
- [6] S. Singh, V. Chonhenchob, and J. Singh, Life Cycle Inventory and Analysis of Re-usable Plastic Containers and Display-ready Corrugated Containers Used for Packaging Fresh Fruits and Vegetables, *Packaging Technology and Science*, 2006, vol. 19, pp. 279-293, doi: 10.1002/pts.731.
- [7] M. Levi, S. Cortesi, C. Vezzoli, and G. Salvia, A Comparative Life Cycle Assessment of Disposable and Reusable Packaging for the Distribution of Italian Fruit and Vegetables, *Packaging Technology* and Science, 2011, vol. 24, doi: 10.1002/pts.946.
- [8] D. Mollenkopf, D. Closs, D. Twede, S. Lee and G. Burgess, Assessing the Viability of Reusable Packaging: A Relative Cost Approach, *Journal of Business Logistics*, 2005, vol. 26, pp. 169-197, doi: 10.1002/j.2158-1592.2005.tb00198.x.
- [9] K. Vursavuş and F. Ozguven, Determining the Effects of Vibration Parameters and Packaging Method on Mechanical Damage in Golden Delicious Apples, *Turkish Journal of Agriculture and Forestry*, 2004, vol. 28, pp. 311-320.
- [10] T. Acıcan, K. Alibaş, and İ. S. Özelkök, Mechanical Damage to Apples during Transport in Wooden Crates, *Biosystems Engineering*, 2007, vol. 96, no. 2, pp. 239-248, doi: https://doi.org/10.1016/j.biosystemseng.2006.11.002.
- [11] T. Fadiji, C. Coetzee, L. Chen, O. Chukwu, and U. L. Opara, Susceptibility of apples to bruising inside ventilated corrugated paperboard packages during simulated transport damage, *Postharvest Biology and Technology*, 2016,vol. 118, pp. 111-119, doi: https://doi.org/10.1016/j.postharvbio.2016.04.001.
- [12] N. Dubey and V. Mishra, Cushioning materials for fruits, vegetables and flowers, in M. W. Siddiqui et al. (ed.) *Innovative Packaging of Fruits and Vegetables*, Apple Press, Oakville, 2018, pp. 275-314.
- [13] W. P. Syam, W. Jianwei, B. Zhao, I. Maskery, W. Elmadih, and R. Leach, Design and analysis of strut-based lattice structures for vibration isolation, *Precision Engineering*, 2018, Vol. 52, pp. 494-506, doi: https://doi.org/10.1016/j.precisioneng.2017.09.010.
- [14] K. Monkova, M. Vašina, M. Zaludek, P. Monka, and J. Tkac, Mechanical Vibration Damping and Compression Properties of a Lattice Structure, *Materials*, vol. 14, p. 1502, 03/18 2021, doi: 10.3390/ma14061502.
- [15] L. P. Hewlett-Packard Development Company. HP 3D High Reusability PA11. [Online]. Available: https://cimquest-inc.com/resource-center/HP/Materials/HP-PA11-Datasheet.pdf
- [16] BASF. Technical Data Sheet for Ultrasint® TPU01. [Online]. Available: https://forwardam.com/wp-content/uploads/2021/04/BASF_3DPS_TDS_Ultrasint-TPU-01.pdf