Reducing postharvest losses of apples : optimal transport routing (while minimizing total costs)

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Abstract:

Fresh products may suffer considerable damage during postharvest transportation caused by vibrations and shocks (i.e. transient vibrations that damp out over time). The Belgian apple industry is yearly worth 125-140 M euro (EBITDA to apple growers) and experiences losses between 10 and 25% corresponding to 10-25 M euro. Apple losses can be attributed to fungal diseases that enter the apple through bruised or punctured tissue and contaminate the fruit. Vibrations occurring during transports are a major contributor to bruises or punctures on apples, and, as a consequence, need to be avoided.

An effective method to reduce the apple loss rate is by minimizing the number and intensity of vibrations that occur during the transport route. In this paper, we suggest planning transport routes based on transportation costs as well as costs related to the loss rate of apples. As a consequence, the transport vehicle is able to avoid road segments with poorly maintained road segments or road segments that are more susceptible to induce higher vibration amplitudes. The results of transport simulations illustrate that the Belgian apple growers can gain industry profits of 250 to 1,500 thousand euros. Both from an economical as well as an ecological perspective our findings are substantial and relevant. The methods used in this research can be adopted by other fruit varieties by transforming the input parameters.

Graphical abstract

[Figure]

Key words: Postharvest losses, Transport costs, Path optimization, Apple damage

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1. Introduction

Transport is a crucial phase in the distribution of fresh food products, from the harvesting operation to the consumer. However, during transport and handling, fresh products may suffer considerable damage. A myriad of research papers has been published on this topic for diverse food products like pears[1], strawberries[2], bananas[3], kiwis[4], watermelons[5], etc. The problem of damage to apples is most extensively researched due to the high loss rates of apples[6–9]. The loss rate can be attributed to the appearance of bruises, the most common type of post-harvest mechanical injury. However, the likeliness that the presence of minor mechanical injuries, which later on lead to fungal diseases, is often overlooked by the market inspectors[7]. Postharvest pathogens, such as gray mold (*Botrytis*) or blue mold (*Penicillium*), are able to enter the fruit by the dead or wounded tissue and contaminate the fruit. As a consequence, total product loss levels, depending on customer awareness, between 10 and 25% are typically found[7,9–12]. Even peak values with a loss rate up to 50% are observed[7]. The economic and ecological costs emphasize the importance of reducing mechanical damage to fresh products[13].

Multiple stages can be distinguished for the distribution of Belgian apples beginning with the harvest in the orchard and ending with being sold on the Belgian market[7]. After picking the apples in the orchard, the apples are transferred from the picking baskets into the wooden bulk bins (Figure 1). Afterwards, the apples are transported from the orchard to the storage rooms with a forklift tractor or possibly bulk transport. Then the apples are transported to the auction. At the auction, they are unloaded off the bulk bins, graded, sorted and transferred to other packaging types. Finally, the apples are transported to the seller and in the last step transported by the customer. At the auction apples are sorted over diverse categories, presented in Table 1 – Appendix. Apples not used for direct consumption by the user are processed in other food products (e.g. juices and compote)[8]. However, the price for degraded apples (not suitable for direct consumption) is 1/3 of the normal auction price[14].

Figure 1: Transport of apples in wooden bulk bins & bruise damage of apples

Source: [9,35]

In the literature on apple losses during postharvest processing, four categories of research papers were distinguished by Van Zeebroeck (2007)[7]: (1) on the source, magnitude, and nature of the impact and vibration input (e.g. single fruit impacting on single fruit[15–17], a fruit container subjected to vibrations[9]) (2) on the packaging material and the container itself (e.g. damping and cushioning properties[18]) (3) on the influence of individual fruit with neighboring fruit in modifying the vibration input[19] (4) on the susceptibility of fruit to damage as a function of maturity, temperature, size and cultivar[8]. While this is important research, a research gap is left to reducing fruit loss rates by minimizing the number of vibrations that occur during the transportation of fruit. On the one hand, the duration or the exposure to vibrations could be diminished by taking the shortest path from origin to destination. On the other hand, the amplitude of the vibrations can be reduced by avoiding roads with potholes or roads that are not properly maintained. Furthermore, the importance of this was already highlighted by the Department of Transport of the State of Michigan (USA). In the 1990s, the State of Michigan filed a project in which a road map was prepared indicating road segments with poor road quality for three regions with the largest apple production[8].

In this study, we held on to a novel approach to reduce the loss rate of apples during transport. The objective was to develop a shortest path algorithm minimizing transportation costs, as well as costs related to apple losses. By avoiding poorly maintained road segments or road segments that are more susceptible to induce higher vibration amplitudes, the apple loss rate can be reduced. Multiple simulations give estimations on the cost reductions the apple industry could face when implementing the algorithm and its input parameters. The model presented in this paper can be used by Belgian apple growers when planning transport routes from the storage facilities (orchard) to the auction market. Since Belgian vibration data is used in this research, the scope of this work is limited to the transport of apples on the Belgian road network. However, the fruit sector, in general, could use the concepts addressed in this paper when adjustments are implemented for the fruit species. Furthermore, this paper is considered a proof of concept: utilizing different vibration data with regards to road typology enables studies on a wider (geographical) scale.

2. Methodology

In order to quantify the vibration response on container load during truck transport, vibration measurements were performed (Specifications on vibration measurements – Appendix). Vibrations were measured with the use of a laptop connected to a data acquisition board (National Instruments USB-6361), which was linked to an accelerometer (Sparkfun ADXL 335). The experimental set-up was charged with an external battery and transformed to the necessary voltage using a transformer. The accelerometer was mounted on the container floor and performed measurements in three directions with a sample rate of 10k samples per second. The truck, with pneumatic spring, drove during three separate days (in total 15 hours) on Belgian roads of varying type and quality. During the experiment, a GoPro video camera (Hero 4, mounted on the shoulder of the truck driver) was used to visually capture the road characteristics and the driving speed. This simultaneous two-fold measuring approach enables to relate vibration data to specific road typologies. The data, analyzed in Matlab 2015a, gave insights on the Belgian road typology, the number of transient vibrations and the RMS-values (root mean square of time-domain accelerations) of road segments (Table 2 - Appendix).

It is difficult to characterize a clear-cut relation between vibrations during transport and loss rates of apples[8]. For instance, O'Brien et al. (1965)[20] indicated that the upper bins in the container can be subjected to accelerations up to four times the vibrations measured on the lowest bins. The literature also does not provide conclusive evidence of the effect of the bin size and depth on the damage rate of apples[8]. Only by assessing loss rates as a percentage of the damaged fruits in relation to the total mass of the fruits transported, the researcher can eliminate the effect of the position of the fruit on the fruit damage caused by transport vibrations[8]. In Figure 2, the influence of acceleration on the damage rate of apples in a wooden crate is presented.

Figure 2: Relation acceleration – apple bruises
(Duration transformed to 1 second on frequency of 4 Hz)

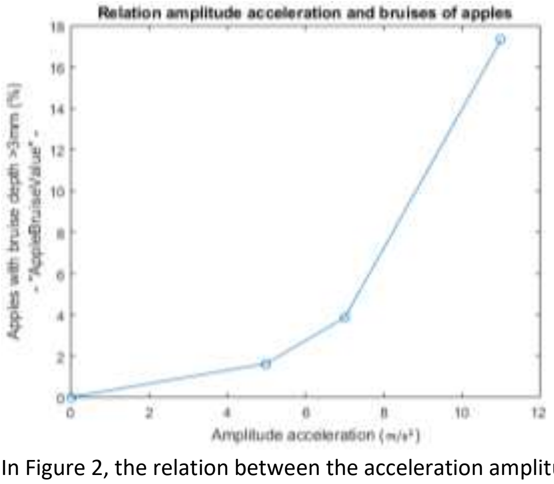
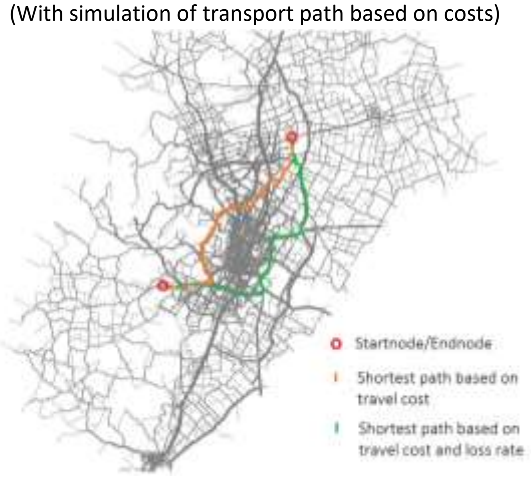


Figure 3: Austin, Texas network
(With simulation of transport path based on costs)



In Figure 2, the relation between the acceleration amplitude of the imposed vibrations and the percentage bruises of apples is depicted, performed by Van Zeebroeck et al. (2006)[24]. The graph is convex, which indicates that vibrations of high acceleration (and transient vibrations of high amplitude that damp out over time) are more harmful for apples than vibrations of lower acceleration. The current relation with respect to vibrations and bruises of apples is incorporated in the constructed model to simulate damage to apples during transport (variable name "AppleBruiseValue"). Source Figure 2: [24]

In Figure 3, a graphical representation of the freely accessible network of Austin, Texas is presented. The figure indicates two possible simulations of apple transport in which the shortest path is calculated based on the travel cost (a) and based on both the travel cost and the loss rate of apples (b). Source Figure 3: [21]

In order to simulate the multiple means of apple transports a freely accessible network of Austin, Texas was used (a freely accessible Belgian transport network is not available). The network contains 7,388 nodes and 18,961 links or arcs that connect the nodes[21] (Figure 3). Information on distances and free flowtime (i.e. the time required to cover the distance between two nodes) was available for every arc. Vibration data of Belgium roads (Table 2 - Appendix) was linked to the network, matching a specific type of road surface to every arc based on the driving speed between arcs. In order to perform a transport simulation the Dijkstra shortest path algorithm[22] was used, also known as the Global Positioning System (GPS) navigation algorithm. With the current network, multiple transport simulations were conducted taking into consideration transportation costs and costs related to damaged apples. However, since a direct relation between vibrations and apple loss rate is difficult to quantify, it is required to circumvent the problem and work in different steps (Table 3).

Table 3: Stepwise implementation of the algorithm

Step 1: Preprocessing - Calculate 'Travel Cost' for every arc - Calculate 'VibrationValueARC' for every arc
Step 2: Do 1,000 transport simulations (with random origin and terminus node) - Calculate Dijkstra shortest path based on 'Travel Cost' - Calculate corresponding 'AppleDamageValue' (=sum('VibrationValueARC' over shortest path arcs)
Step 3: Scenario-building - Building the relation 'AppleDamageValue' and apple loss rate
Step 4: Search for paths with lower cost - Calculate Dijkstra shortest path based on 'Total cost' = 'Travel Cost' + 'Cost Apple losses'
Step 5: Pay-off when using the algorithm - Calculate $'Profit' = 'TOTAL\ COST'_{SP:TRAVEL\ COST} - 'TOTAL\ COST'_{SP:TRAVEL\ COST+COST\ LOSS\ RATE}$

In *step 1*, the transportation cost and an artificially created variable 'VibrationValueARC' was calculated for every link (formulae in Table 4). Transportation costs over arcs are build up based on total vehicle cost per mile (i.e. fuel, maintenance/repair, tires, depreciation) and driver cost. Driver cost and vehicle cost were linked with arcs based on distances and free flowtime. The values of the costs were based on the report of Barnes (2003)[23] and converted to kilometers and euros (exchange rate 24-02-2017: 1 USD = 0.9442 EUR). The variable 'VibrationValueARC' was more complex to build. In previous preprocessing steps, a specific type of road surface (with corresponding vibration characteristics: Table 2 - Appendix) was assigned to every arc. The road surface was randomly assigned to arcs based on the speed segmentation in Table 2, which was possible since the network included information on driving speed (free flowtime) over all arcs. We then made a distinction between vibrations and shocks (i.e. vibrations of high amplitude that are transient and damp out over time). A random RMS-value of the time-domain vibrations (of the distribution presented in Table 2 - Appendix) was attributed to every road section or arc. Furthermore, a histogram of transient vibrations (per minute) was allocated to each road segment (randomly selected from Table 2 – Appendix). If the random generator selected above (below) average counts of peaks for the first acceleration bin of the histogram (e.g. 5-7 m/s^2), then also random above (below) average counts of peaks were selected for the other acceleration bins.

Subsequently, the randomly generated RMS-value of time-domain vibrations and the distribution of transient vibrations occurring when traveling over each road segment are linked with the damage to apples. From literature (Figure 2) can be derived that the relation acceleration vs. damage to apples is a convex curve[24]. Figure 2 also suggests that transient vibrations are more damaging than vibrations, although the time of exposure is shorter. Vibrations during road transport generally have an acceleration amplitude smaller than 5 m/s^2 while most transient vibrations are higher of amplitude (Table 2 – Appendix). Therefore, Figure 2 illustrates that the relation between bruises to apples due to vibrations is presented on the left hand side of the function below 5 m/s^2. The influence of transport shocks on the bruises of apples is displayed on the right-hand side of the graph with acceleration amplitude higher than 5 m/s^2. As a consequence, for every RMS-value of the vibrations and acceleration bin of the transient vibrations (e.g. 5-7 m/s^2), the artificially created 'AppleBruiseValue' is calculated from Figure 2. Consecutively, the new and artificial variable 'VibrationValueARC' is created, i.e. the sum of the 'AppleBruiseValue' (calculated from Figure 2) multiplied with the time of exposure[**]. In conclusion, for every road segment the acceleration amplitude of the vibrations and shocks is related to the bruises of apples, which is then multiplied by the time the road section is traversed.

Table 4: Arc costs (Calculations of step 1)

$`Travel\ Cost' = ('Total\ Vehicle\ Cost'\ x\ 'Distance\ of\ arc') + ('Driver\ Cost'\ x\ 'Free\ flow\ time')$
$`VibrationValueARC' = \sum ('AppleBruiseValue'\ x\ 'Time\ of\ exposure')$
With $'Driver\ Cost'$ = 27.45 euros/hrs. & $'Total\ Vehicle\ Cost'$ = 1.91 euros/km

In *step 2,* the shortest path (Dijkstra's algorithm[22]) was calculated with only 'Travel Cost' as an input parameter. A total of 1000 simulations were generated; for every new simulation the origin and terminus node of the network was randomly chosen. However, apple orchards are located on the edge of the city and, therefore, the adaptation was made that the origin node is required to have less than three arcs and an average travel cost per arc lower than 15 euros. Therefore, only 15% of the nodes were considered a possible origin node or location of an apple orchard in the network. Once the shortest paths were known, it was possible to determine the 'TotalAppleDamage'-value, i.e. the sum of all 'VibrationValueARC'-numbers over the corresponding arcs of the shortest path.

In the following *step 3,* the 'TotalAppleDamage'-values of all transport simulations are matched with apple loss rates. Moreover, previous research reported loss rates between 10 and 25%, which mainly occur in the first stages of apple distribution[7]. With the use of different scenarios, we were able to quantify loss rates of apple transports taking into consideration loss rates before transport and the

[**] Vibrations: the random RMS-value of time-domain vibrations and its 'AppleBruiseValue' is extrapolated over the time the road section is traversed // Transient vibrations: the distribution of shock samples is displayed per minute and is extrapolated over the time the road section is traversed. Every sample has a duration of 1e-5 seconds (due to the sample rate of the transport vibration and shock measurements).

influence of duration of the transport (exposure to vibrations) on the loss rate. The different scenarios included within the paper will be elaborated in detail in section 3 (Results).

Subsequently in *step 4*, new shortest paths (Dijkstra's algorithm[22]) are calculated based on the total costs that occur during transport. Moreover, the 'Travel Cost' is included as well as the cost related to the losses of apples. For every node that has the ability to be part of the shortest path the algorithm investigates the impact of adding the extra 'VibrationValueARC' of the arc that results in a higher 'TotalAppleDamage' and hence a higher apple loss rate. Furthermore, the loss rate of apples is afterwards quantified based on the following two assumptions: (1) the load capacity of a truck transport was fixed to 10 ton[25] and (2) the price of degraded apples is 1/3 of the regular price[14]. The regular price was fixed to 0.50 euros per kg (i.e. the average apple price in Belgium in recent years)[26].

In a final *step 5*, the profit of implementing the algorithm is calculated. After determining profit values of transport iterations performed in this simulation (Table 5), the results are extrapolated to the Belgium apple market. In recent years, the growers sold 300 million (M) kg apples on the Belgian auction market (fresh and degraded apples)[14,26].

Table 5: Profit value (Calculations of step 5)

$'Profit' = \ 'TOTAL\ COST'_{SP:TRAVEL\ COST} - {'TOTAL\ COST'}_{SP:TRAVEL\ COST+COST\ LOSS\ RATE}$
With $'TOTAL\ COST'_{SP:TRAVEL\ COST} \ = \ 'TRAVEL\ COST'_{SP:TRAVEL\ COST} + {'COST\ LOSSES'}_{SP:TRAVEL\ COST}$

3. Results

Different scenarios were generated in order to estimate the effect of vibrations on the damage rate of apples, as suggested in step 3 of section 2 (Methodology). The main assumption introduced in the scenarios is that the postharvest loss rates of apples have values between 10 and 25%. As a consequence, four scenarios were built where 50%, 75%, 90% and 100% of all truck transport simulations have a loss rate between 10 and 25%. In Figure 4-7, four different scenarios are presented. It is important to keep in mind that the begin loss rate or loss rate before transport varies. Furthermore, the unknown relation between duration of transport and the mechanical damage rate of apples was also incorporated. Wilkus (1989)[27] revealed that most of the apple damage occurs during the initial stages of the truck transport. As a consequence, the relation between 'AppleDamageValue' and 'Loss Rate' should be a concave curve (presented in Figure 4-7). The exact slope of the curve can be approximated by estimating parameter 'λ'. The relation 'Loss rate' – 'AppleDamageValue' that was introduced, can be presented as:

$$'LOSS\ RATE'_i = ('LOSS\ RATE'_{end} - 'LOSS\ RATE'_{start})\ x \left(\frac{'AppleDamageValue'_i}{'AppleDamageValue'_{loss\ rate\ end}}\right)^{\lambda} + 'LOSS\ RATE'_{start}$$

With
i : number of iteration
λ: input parameter with $\lambda \in]0, 1]$ (to determine the degree of concavity)
'LOSS RATE'$_{start}$: loss rate where 'AppleDamageValue' is equal to zero (loss rate before transport)
'AppleDamageValue'$_{loss\ rate\ end}$: 'AppleDamageValue' attached to 'LOSS RATE'$_{end}$. In this formula 'LOSS RATE'$_{end}$ is maintained at 25%.

In Figure 4-7 the four different scenarios can be found where 'AppleDamageValue' is linked with apple loss rate. In the three scenarios different values of 'λ', which relates to the unknown influence of time (while having vibrations and shocks) on the damage of apples, are introduced to build different curves. The constraint on the value 'λ' that can be chosen is that with changing 'λ' the 'LOSS RATE'$_{start}$ cannot be below zero. When the curve of the loss rate is known, the loss rate can be included in the shortest path calculation of step 4.

With minimizing 'Travel Cost' and costs coming from apple losses when choosing the shortest path, the apple growers are supposed to save money they would otherwise lose when taking the path with the minimum 'Travel Cost'. The total value of apples being transported is 5000 euros (10 ton of apples with a value of 0.50 euro/kg). For the new optimal path calculated with the algorithm, the apple growers have higher travel costs that are compensated by extra profit coming from lower apple loss rates. In Figure 8, a histogram of the profit per transport over 1000 iterations (in scenario 3 [75%] with 'λ'=0.8) is presented. By performing a transport over the optimal path on average 27.39 euros was saved in the particular scenario of Figure 8. An overview of the reduction in loss rate per transport (in scenario 3 [75%] with 'λ'=0.8) can be found in Figure 9. In Figure 9, on average the transports had a loss rate that was 10.66% lower.

Figure 4: 'Loss rate' – 'AppleDamageValue'
SCENARIO 1 (100%)

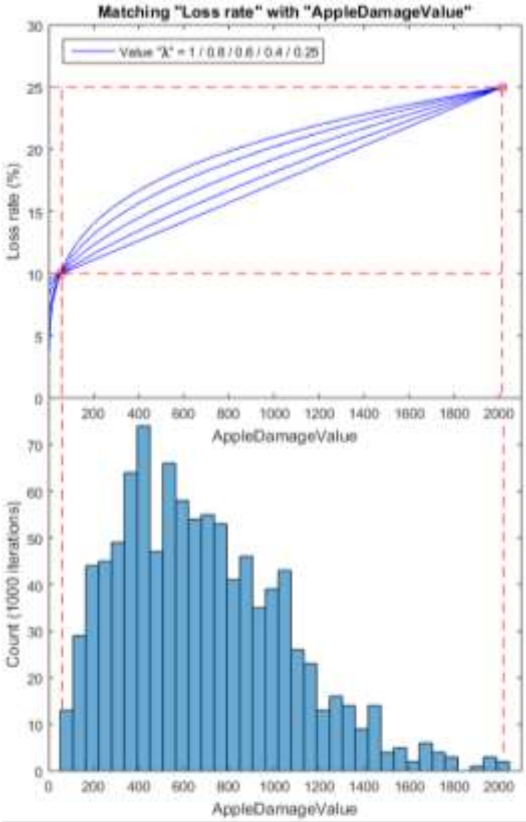


Figure 5: 'Loss rate' – 'AppleDamageValue'
SCENARIO 2 (90%)

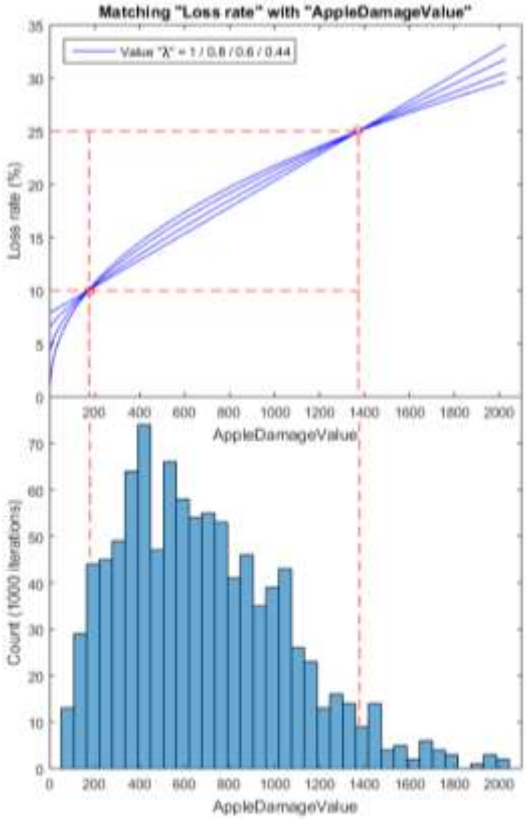


Figure 6: 'Loss rate' – 'AppleDamageValue'
SCENARIO 3 (75%)

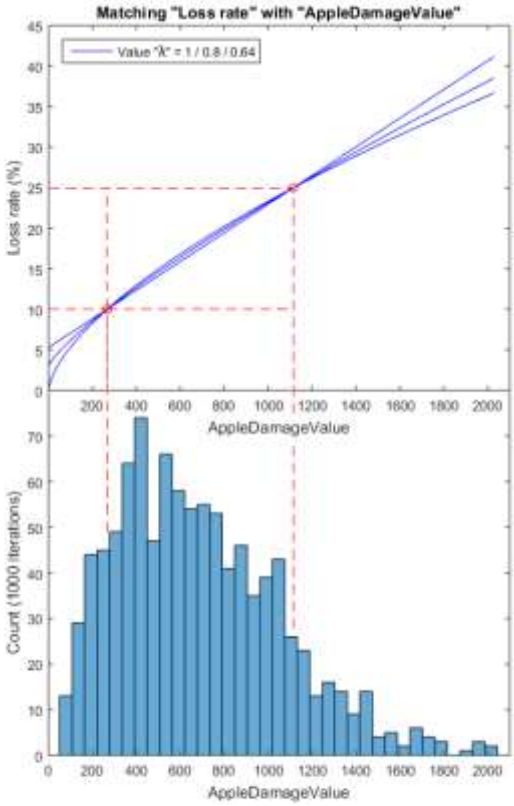


Figure 7: 'Loss rate' – 'AppleDamageValue'
SCENARIO 4 (50%)

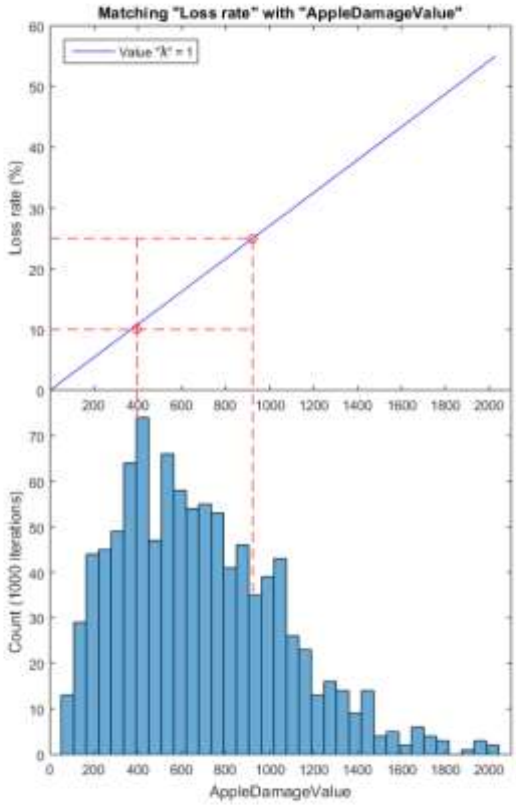


Figure 8: Histogram profit per transport
(Scenario 3 with parameter 'λ' = 0.8)

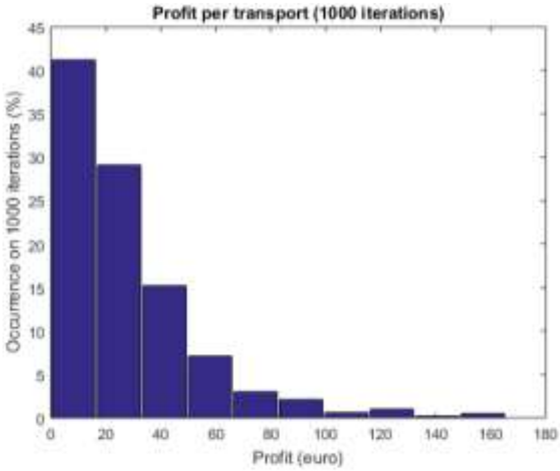
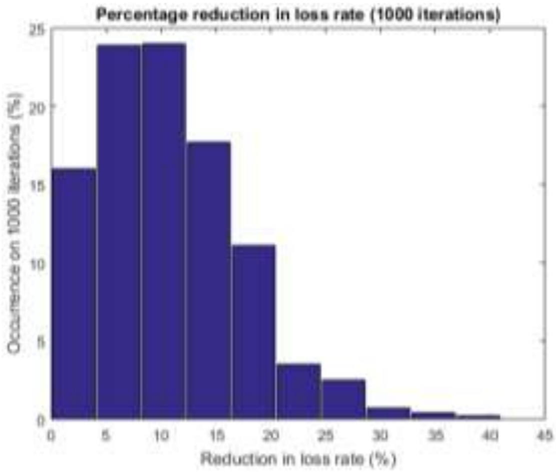


Figure 9: Histogram reduction in loss rate
(Scenario 3 with parameter 'λ' = 0.8)



For all different scenarios, the profit for the apple growers was calculated (Table 6). Since the size of the Belgian apple industry is identified between 125-140 M euro, the profits of implementing the model are extrapolated to the industry level by using confidence intervals. Note that if the value of 'λ' becomes smaller 'LOSS RATE'$_{start}$ has to decrease as well in order to comply with the fact that 50%, 75%, 90% or 100% of 'AppleDamageValues' have to be between 10 and 25% loss rate. Also, the industry profit decreases with lower 'λ' and increases from scenario 1 to 4. From Table 6 can be inferred that between 250 and 1,500 thousand euros can be saved when planning apple transport routes.

Table 6: Industry profit for different scenarios when implementing the model

Type scenario	λ	$'LOSS\ RATE'_{start}$	$'LOSS\ RATE'_{end}$	Industry Profit (euro)
Scenario 1 (100%)	1	9.6	25	274,000 – 303,000
Scenario 1 (100%)	0.8	9.1	25	275,000 – 304,000
Scenario 1 (100%)	0.6	8.1	25	266,000 – 294,000
Scenario 1 (100%)	0.4	5.4	25	251,000 – 277,000
Scenario 1 (100%)	0.25	0	25	230,000 – 255,000
Scenario 2 (90%)	1	7.9	25	524,000 – 579,000
Scenario 2 (90%)	0.8	6.5	25	508,000 – 561,000
Scenario 2 (90%)	0.6	4.0	25	487,000 – 539,000
Scenario 2 (90%)	0.44	0	25	470,000 – 520,000
Scenario 3 (75%)	1	5.3	25	812,000 – 898,000
Scenario 3 (75%)	0.8	3.0	25	781,000 – 863,000
Scenario 3 (75%)	0.64	0	25	757,000 – 836,000
Scenario 4 (50%)	1	0	25	1,353,000 – 1,496,000

With only saving a couple of euros per transport, the value of implementing the model could be perceived rather modest. However, from an industry perspective, the profit in absolute value is substantial (definitely since Belgian fruit growers cope with low profit margins[26]). Between 1% and 15% of the euro value of all lost apples is recuperated by incorporating the algorithm. However, by incorporating the model not all losses of apples that are attributed to vibrations and shocks during transport can be reduced. The latter can be explained in a logical manner. In multiple simulations, the path calculated on 'Travel Cost' alone is similar to the optimal path calculated on 'Travel Cost' and costs related to apple losses. When planning transport routes based on 'Travel costs' alone, the truck is likely to drive on highway roads. Driving on highway roads will save time for the truck driver since the driver is allowed to maintain high speeds. In other words, the more highway roads are incorporated in the path, the faster the truck can traverse distance and the lower 'driver cost' comes into play. At the same time, driving over highway roads is also beneficial from the point of view of avoiding or minimizing vibrations. Most damage is caused by driving over cobblestone roads or roads with concrete pavement (Table 2 - Appendix). As a consequence, the optimal path calculated on both costs related to traveling and loss rates will also incorporate highways roads. This will result in the optimal path being similar to the 'Travel Cost'-path.

4. Conclusions

Postharvest damage to apples can lead to significant economic costs to apple growers. The apple industry, which is worth (EBITDA) 125-140 M euro per year to apple growers (calculated from the total amount of apples harvested), suffers from loss rates typically between 10 and 25%[7]. These apple loss rates lead to yearly industry costs of 10 – 25 M euros due to the fact that in Belgium the auction price for second-hand apples is 1/3 of the normal auction price[14]. In this paper, we held on to an innovative approach to reducing the loss rate of apples. By planning transport routes on which normal transportation costs are incorporated, as well as costs related to the loss rate of apples due to transport vibrations. Transport vibrations could be quantified by characterizing road types with respect to vibrations and shocks (transient vibrations). The results suggest that a significant amount of 250 – 1,500 thousand euros per year can be saved yearly when planning apple transport routes. Additionally, the latter profit can be interpreted by apple orchards as an external cost related to outsourcing apple transports. Both from an economical perspective (increased profits for apple growers), as well as from an ecological perspective (more effective use of natural resources) this result is substantial. On a global scale, roughly one out of three global fresh fruits and vegetables (FFVs) are thrown away due to quality-issues[28]. With an ever-increasing world population, all efforts to reduce the millions of tons of avoidable perishable food waste along the food supply chain are helpful. More intelligent transport planning can be a new step in limiting food losses, more specifically by directly lowering loss rates and further reducing invisible or latent losses in product quality. The use of limited information on quality reduction of apples during transport, as well as the narrow focus on the Belgian road network are limitations of the study. Taking into consideration the outcome of this research, the fruit sector could use the concepts addressed in this paper when adjustments are implemented for the fruit species.

In future research, it is required to fine-tune the input parameters of the model. Better input values will produce an improved model and more accurate estimations of the reduced costs that can be expected when implementing the model. In order to be more specific, the relation between the duration of transport and the mechanical damage rates of fruit needs be researched. Furthermore, a better characterization of fruit losses due to transport needs to be examined more accurately. The model itself could also be more developed when introducing the likeliness of traffic jams (stochastic parameters). This will have a significant influence on driver cost per road segment and, as a consequence, also on the total travel cost.

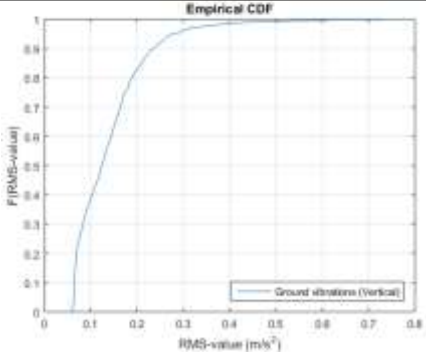
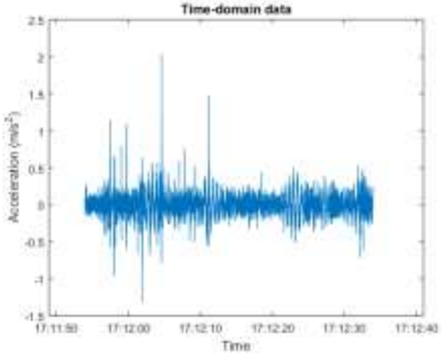
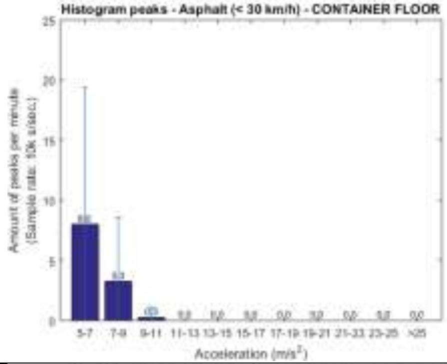
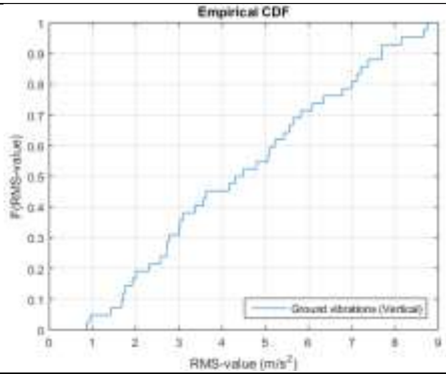
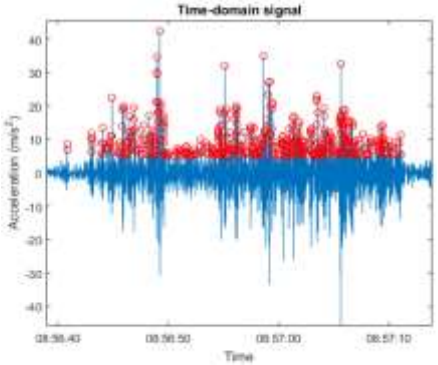
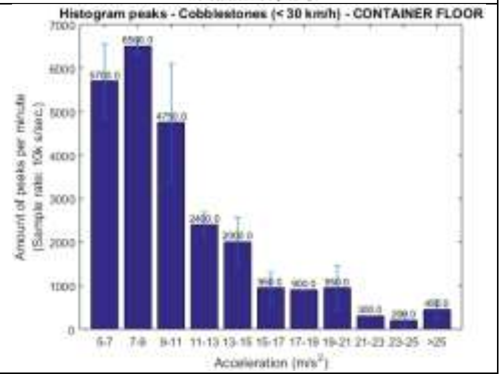
APPENDIX

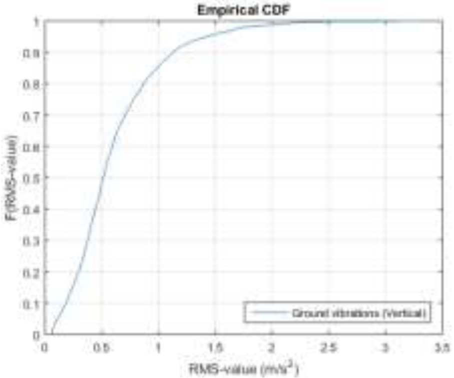
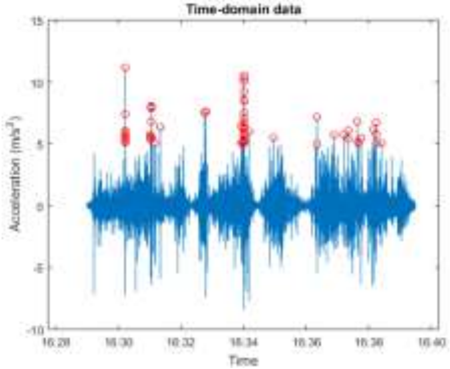
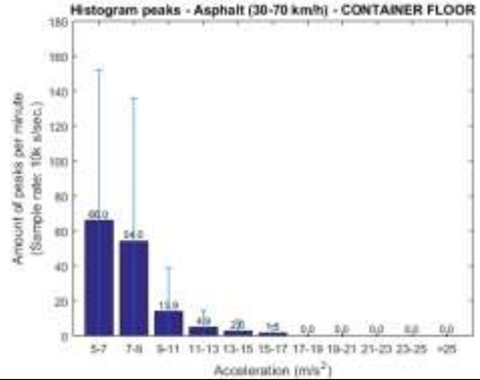
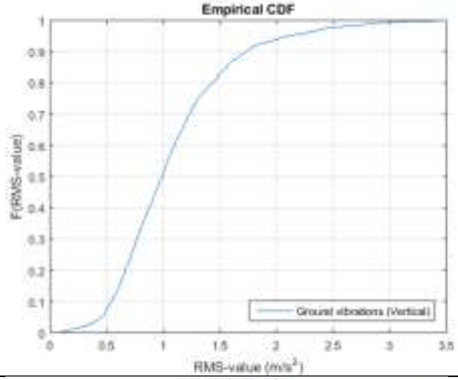
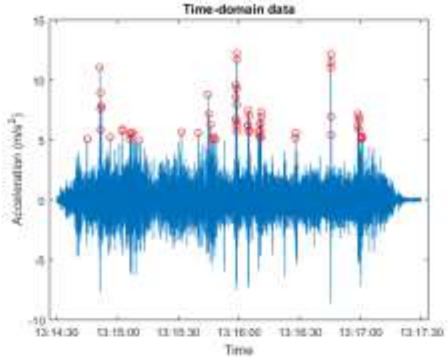
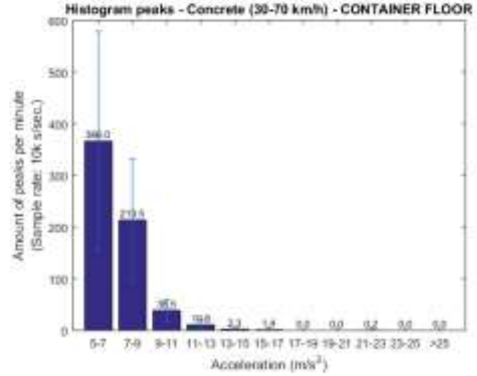
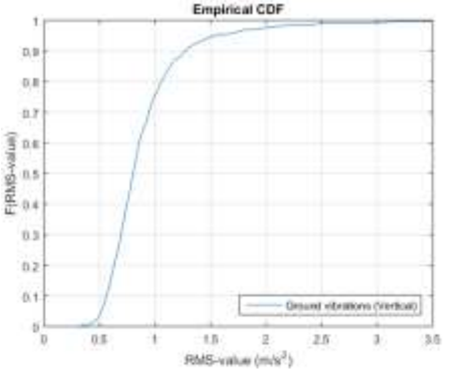
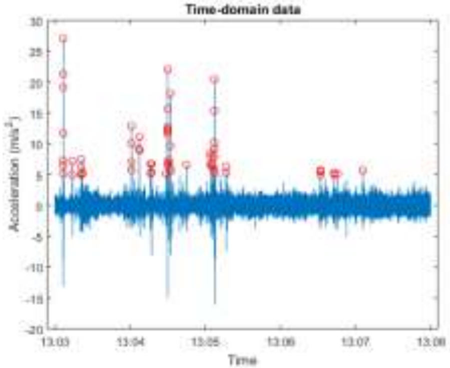
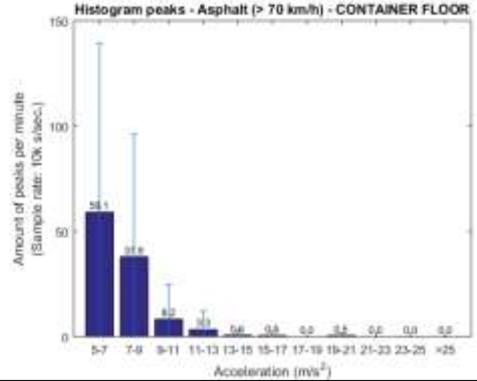
Table 1: Damage classes of apples according to USDA scale

Damage class	[Extra information in the attached reference]
I U.S. Extra Fancy	Grade Standard Reference: Title 7 CFR 51.300 This category includes apples of the highest quality. Different tolerances and quality requirements (e.g. color, bruise depth) are used for different apple varieties. A combination grade (U.S. Extra Fancy – U.S. Fancy) may be used.
II U.S. Fancy	Grade Standard Reference: Title 7 CFR 51.301 Apples of higher medium quality can be classified in class II. Different tolerances and quality requirements (e.g. color, bruise depth) are used for different apple varieties. A combination grade (U.S. Extra Fancy – U.S. Fancy and U.S. Fancy – U.S. No.1) may be used.
III U.S. No. 1	Grade Standard Reference: Title 7 CFR 51.302 Apples of lower medium quality can be classified in class III. Different tolerances and quality requirements (e.g. color, bruise depth) are used for different apple varieties. A combination grade (U.S. Fancy – U.S. No.1 and U.S. No.1 – U.S. Utility) may be used.
IV U.S. Utility	Grade Standard Reference: Title 7 CFR 51.303 U.S. Utility-apples have the lowest quality. Different tolerances and quality requirements (e.g. color, bruise depth) are used for different apple varieties. A combination grade (U.S. No.1 – U.S. Utility) may be used.

Source: [29]

Table 2: Characterization of Belgian roads (vibration response)

Road surface (speed segmentation)	Roads at speed limit	Cumulative distribution function (CDF) of RMS-value – acceleration of time-domain vibrations [Vertical; intervals of 1s]	Peaks in acceleration (> 5 m/s^2) – Time-domain – [**Example** – not related to the histograms on the right]	Transient vibrations: Histogram of time-domain vibration samples (> 5 m/s^2) – Peak –
Asphalt pavement (< 30 km/hrs.)  Source: [30]	89.3 %			
Cobblestones (< 30 km/hrs.)  Source: [31]	10.7 %			

Asphalt pavement (30-70 km/hrs.)  Source: [32]	78.1 %			
Concrete pavement (30-70 km/hrs.)  Source: [33]	21.9 %			
Asphalt pavement (> 70 km/hrs.)  Source: [34]	100%			

Specifications of vibration measurements on trucks / trailers: Transport 1: truck + trailer 3 axles (1+2) [MAN TGA SH265 FNLC] (length trailer 7.5 meters – weight full capacity 26 tons – end of transport 15 tons) – extra trailer 2 axles [Renders RMAC 9.9N] (length trailer 7.5 meters – weight full capacity 18 tons – end of transport 13.5 tons) // Transport 2: truck + trailer 3 axles (1+2) [MAN TGA SH265 FNLC] (length trailer 7.5 meters – weight full capacity 26 tons – end of transport 15 tons) // Transport 3: truck + trailer 5 axles (2+3) [Volvo FH440 + Renders Liftachse ROC 12.27N] (length trailer 13.5 meters – weight full capacity 39 tons – end of transport 16 tons) // Transport 4: truck + trailer 5 axles (2+3) [VOLVO FH440 + Renders Liftachse ROC 12.27N] (length trailer 13.5 meters – weight full capacity 39 tons – end of transport 16 tons)

Close to all food products are transported in their (secondary) packaging and stacked on pallets. Therefore, vibrations were measured on top of the wooden pallet itself (exactly the same spot for all case studies) in current study. The objective was to identify the vibrations packages are subjected to and to incorporate the resultant of the (possible) interaction between the pallet and the container floor. The vibration measurements performed in current research are used to simulate transport and, therefore, it is worthwhile to incorporate the (possible) effect of the pallet. The pallet with the measuring devices was located between one forth and one third of the rear end of the (extra) trailer length (respectively 1.8m - 2.5m [transport 1], 1.8m - 2.5m [transport 2], 3m – 4.5m [transport 3 and 4]).

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