Faculty of Applied Economics

Dissertation

The impact of vibrations, shocks, and temperature during distribution on the flavor quality of bottled beer

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of
Doctor in applied economics

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Advances are made by answering questions.

Discoveries are made by questioning answers.

– Bernard Haisch –

Publications

The following publications are included in parts or in extended version in this thesis:

- Paternoster A, Van Camp J, Vanlanduit S, Weeren A, Springael J, Braet J. The performance of beer packaging: Vibration damping and thermal insulation. *Food Packaging and Shelf Life* 2017;11:91-97. doi:10.1016/j.fpsl.2017.01.004.

- Paternoster A, Vanlanduit S, Springael J, Braet J. Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit. *Food Packaging and Shelf Life* 2018;15:134-143. doi:10.1016/j.fpsl.2017.12.007.

- Paternoster A, Vanlanduit S, Springael J, Braet J. Vibration and shock analysis of specific events during truck and train transport of food products. *Food Packaging and Shelf Life* 2018;15:95-104.

Furthermore, the following papers are in the publication process, not yet submitted, or outside the scope of this thesis:

- Springael J, Paternoster A, Braet J. Reducing postharvest losses of apples: Optimal transport routing (while minimizing total costs). *Computers and Electronics in Agriculture* 2018;146:136-144. doi:10.1016/j.compag.2018.02.007.

- Paternoster A, Jaskula-Goiris B, De Causmaecker B, Springael J, Braet J, De Rouck G, De Cooman L, Vanlanduit S. The Influence of the Interaction between Vibrations and Temperature, Simulating Transport, on the Flavor Quality of Beer. *Journal of the Science of Food and Agriculture* (paper under review) ; 2018.

- Paternoster, A., Jaskula-Goiris, B., Perkisas, T., Springael, J., De Rouck, G., De Cooman, L., Braet, J. The influence of temperature and time on the sensorial quality of lager beer – simulating the Overall Aging Score (OAS). *Journal of Food Quality and Preference* (paper not yet submitted) ; 2018.

- Paternoster A, Jaskula-Goiris B, Buyse J, Perkisas T, Springael J, Braet J, De Rouck G, De Cooman L. The relation between beer flavor instability, the preference & the drinkability of fresh over aged beer. *Journal of Food Quality and Preference* (paper not yet submitted) ; 2018.

- Jaskula-Goiris B, De Causmaecker B, De Rouck G, Aerts., G., Paternoster, A., Braet, J., De Cooman L. Influence of transport and storage conditions on beer quality and flavour stability. *Journal of Institute of Brewing* (paper accepted); 2018

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Preface

Belgian beer is renowned for its large variety in flavors and aromas, and excellent quality. Not only AB Inbev, the largest brewer in the world, but also the multiple small and authentic breweries that make these beers, are the symbol of the cultural heritage that represents Belgium. The increasing globalization and internationalization induce that these beers are not only available within, but also progressively outside the borders of Belgium. The export of Belgian beer has been rising by double digit numbers, year after year, starting from 2000. Nevertheless, there have been issues related to the exported beer: the flavor quality and stability of the beer is considerably lower when controlled in the last part of the supply chain. In other words, the beer that is exported, experiences flavor changes that are destructive and irreversible of nature.

This doctoral thesis is dedicated to research the flavor stability and quality of the Belgian beers in the foreign markets. More specifically, the impact of the exposure to vibrations, shocks and temperature during the distribution of beer is studied. Since the study of the dissertation involved vibrations and shocks (physics), beer quality (chemistry) and economic feasibility studies (economics), the research combined multiple domains. This study is unique since the effect of transport vibrations on the quality of a fluid is investigated, in contrast to the literature of the mechanical damage of (food) products and product packaging.

First, the vibrations, shocks and temperature patterns are studied to which bottled beer is exposed during transport to foreign countries and storage. The impact of different parameters was investigated: the type of transport, the packaging and the stacking of the crates on the pallet. Based on the previously generated information, experiments were designed in order to estimate the influence of the latter parameters on the flavor quality of bottled beer. In the previously formulated experiments, the beer quality was predominantly characterized by means of the concentrations of the chemical beer quality compounds. Also, taste experiments were designed and executed in order to investigate if the general consumer is able to distinguish fresh from aged beer, and to identify differences in the consumption behavior when consuming fresh related to aged beer. The objective of this study was to frame the problem of the beer flavor stability, and to offer a framework that provides information and insights for breweries that would like to invest in the quality of their beer. Additionally, the feasibility of refrigerated transports and collaboration in logistics was assessed. By means of surveys, models, and simulations, the research objectives were tested. Finally, a study was developed in which the feasibility of providing the breweries transport and storage simulations was researched. This service might be offered to breweries in order to help the industry providing the (foreign) markets beer of higher quality.

In this Ph.D. dissertation, I hope to contribute to literature by providing research results and research methods. Additionally, I would aspire that breweries progress in improving the beer flavor quality and, further, ameliorate the image of Belgian beer of excellent quality.

From this study can be concluded (abstract conclusions underneath text) that both elevated temperature and transport vibrations contribute to the beer flavor instability. Furthermore, the impact of temperature on the beer flavor quality is larger compared to transport vibrations and shocks. Nevertheless, a possible interaction effect between temperature and vibrations was observed during our experiments. The experiments give rise to developing the foundations of a promising and revolutionary accelerated aging test that can reduce the aging time from 2 months to respectively 4 days. The taste experiments in which the general consumer was surveyed indicated (within the limitations of the studies) that a difference was tasted between fresh and aged beer (4 months at 30°C). However, there was no clear preference for fresh over aged beer. The drinkability of fresh beer was identified to be higher than aged beer, which is predominantly attributed to Belgians older than +/- 27 years. Additionally, contextual parameters (e.g. group psychology, marketing) indicate to be a major influence in our experiments as well as during normal day-to-day consumption.

In the economics part of this study, the feasibility was assessed of refrigerated transports, horizontal collaboration in logistics and transport & storage simulations. Refrigerated transports indicated to be complex to organize, due to the ex-works distribution, although feasible when an increase in price (together with an increase in sales volume) is achieved. Horizontal collaboration in logistics can be beneficial for small breweries / small order quantities (annual demand < 150 pallets - although complex to organize). In this research, only a theoretical simulation of bundling cargo in the supply chain was conducted. Finally, transport & storage simulations (i.e. a software model and a physical test environment) can be offered to the breweries with the aim to generate insights on the beer flavor quality in the foreign markets.

When examining this work, the reader should take into consideration the limitations of the study. The first limitation relates to the measurement equipment. When considered by a vibration specialist the measurement equipment is primitive. Nevertheless, the equipment meets the expectations when considering the scope of this research project. Secondly, the sample sizes of the vibration experiments and the taste experiments are relevant from a statistics point of view, however should be enlarged to accomplish more in-depth conclusions. Thirdly, the beer flavor and aroma are characterized by means of a sensorial parameter (i.e. Overall Aging Score) or chemical parameters (e.g. aldehydes, iso-α-acids). The two types of parameters are independently analyzed and interpreted. When being aware that the Overall Aging Score is a (subjective) Likert Scale measure with significant variation, the sensorial characteristics are inadequately quantified. Additionally, only a theoretical estimation of the feasibility of implementing refrigerated transports was provided in this work with limited brewery-specific data.

Based on the conclusions and limitations of this study, recommendations for future research can be provided. In future work, the reproducibility of vibration and shock experiments on different beer types should be pursued. Furthermore, the role of oxygen in beer when being exposed to vibrations, the impact of exposing a vibration of a single or multiple frequencies, and a single or multiple vibration dimensions should be researched. Since the sample size of the taste experiments should be expanded as well as the respondents groups, more research on consumer perceptions, trends and behavior (especially in the export markets) is recommended. Finally, it is suggested to work on the reproducibility of the taste qualification.

When creating a database, the chemical concentrations can be linked with the flavor acceptance and preference of the consumer by using data mining techniques. This measure will be more objective and informative than the currently used Overall Aging Score.

General conclusions

- Elevated temperature and vibrations contribute to flavor instability
- Temperature is more important with respect to flavor stability compared to vibrations and shocks
- New and promising beer aging test technique
- Taste experiments:
  - A difference was tasted between fresh and aged beer
  - Preference for fresh over aged beer was not clear
  - Drinkability of fresh beer is higher than aged beer (Belgians older than +/- 27 years)
  - Influenced by contextual parameters (marketing, location, etc.)
- Refrigerated transport and storage is recommended but is complex to organize
- Opportunity in organizing transport & storage simulations

Limitations of the study

- Measurement equipment
- Sample sizes
- Quantifying beer flavor and aroma
- Theoretical estimation of economic feasibility

Recommendations for future research

- Reproducibility of vibration and shock experiments on different beer types
- Vibrations and the role of oxygen, exposing a single frequency vs. multiple frequencies, vibration dimension (vertical, lateral, longitudinal)
- Consumer perceptions, trends and behavior (in the export markets)
- Reproducibility of taste qualification
  - Linking chemical concentrations with flavor acceptance and preference vs. OAS/GAS

Dutch preface

Belgisch bier is wereldwijd gekend om zijn grote variëteit in smaken en aroma's, en zijn uitstekende kwaliteit. Niet alleen AB Inbev, 's werelds grootste brouwer, maar ook de talrijke kleine en authentieke brouwerijen die deze bieren maken, staan symbool voor het culturele erfgoed van België. De toenemende globalisering en internationalisering maken dat onze bieren niet alleen in België maar eveneens in toenemende mate in het buitenland kunnen worden genoten. De export van onze bieren stijgt reeds vanaf 2000, jaar na jaar, om en bij de 10%. Desalniettemin zijn er problemen opgetreden met de geëxporteerde bieren: de smaakkwaliteit van het bier, bij de kwaliteitscontrole in het laatste deel van de supply chain, is sterk verminderd. Met andere woorden, het bier dat geëxporteerd wordt, ondergaat een smaakverandering die destructief en onomkeerbaar is.

Deze doctoraatsstudie werd opgezet ter onderzoek van de smaakstabiliteit van de Belgische bieren die geëxporteerd worden naar het buitenland. Meer bepaald werd de impact van trillingen, schokken en temperatuur tijdens de distributie van bier onderzocht. Dit multidisciplinair onderzoek bevat invloeden van fysica (vibratieanalyse), chemie (kwaliteitsanalyse van bier), en economie (haalbaarheidsstudies). Nieuw aan deze studie is dat de invloed van transportvibraties op de kwaliteit van een vloeistof wordt onderzocht, in tegenstelling tot de gekende literatuur van de mechanische schade van (voedsel)producten en verpakkingen.

In eerste instantie werd gekeken naar de vibratie- , schok- en temperatuurpatronen die zich voordoen tijdens de buitenlandse transporten en opslag. Hierbij werd gekeken naar de invloed van het type transport, de verpakking, en de hoogte van de stapeling op een pallet. Daarna werden op basis van deze informatie experimenten opgesteld om de invloed van deze parameters op de smaakkwaliteit van bier te achterhalen. In de voorgaande experimenten werd de bierkwaliteit voornamelijk chemisch en kwantitatief benaderd. Naast deze experimenten werden eveneens smaakproeven opgesteld en uitgevoerd. Zo werd onderzocht of de gewone consument bekwaam is om vers van verouderd bier te onderscheiden en in welke mate de consumptie van vers en verouderd bier verschilt. Met deze analyse was het de bedoeling het probleem van de smaakstabiliteit van bier te onderbouwen, en tevens een draagvlak te bieden voor brouwerijen die willen investeren in de bierkwaliteit. Additioneel werd er een economisch luik uitgewerkt aan deze doctoraatsstudie. Er werd gekozen om de haalbaarheid van gekoelde transporten en horizontale samenwerking in de logistiek te onderzoeken. Op basis van enquêtes, modellen, en simulaties werd een kader gecreëerd die deze onderzoeksdoelstellingen kon testen. Tenslotte werd er een eerste studie uitgevoerd naar de mogelijkheid van het samenstellen van een omgeving waarin transport en opslag gesimuleerd kan worden. Deze dienst zou aan de brouwerijen aangeboden worden teneinde de sector te helpen in hoger kwalitatief bier op de markt te brengen.

Met dit doctoraat werd getracht een bijdrage te leveren aan de literatuur op basis van de onderzoeksresultaten en de aangebrachte onderzoeksmethodiek. Daarnaast hoop ik dat de Belgische brouwerijen een stap vooruit zijn in het verbeteren van de bierkwaliteit en het internationaal op de kaart zetten van Belgisch bier van uitmuntende kwaliteit.

Uit deze studie kan geconcludeerd worden (samengevatte conclusies onder de tekst) dat zowel blootstelling aan een verhoging van temperatuur als transport vibraties bijdragen aan de smaakinstabiliteit van bier. Daarenboven, de impact van temperatuur op de bierkwaliteit wordt hoger ingeschat wanneer vergeleken met transport vibraties en schokken. Niettegenstaande werd er tijdens onze experimenten een mogelijk interactie effect blootgelegd tussen temperatuur en vibraties. Dit laatste geeft aanleiding tot het ontwikkelen van een nieuwe veelbelovende en revolutionaire versnelde verouderingstest die de verouderingstijd van 2 maanden kan reduceren tot 4 dagen. De smaakproeven waarbij de algemene consument werd bevraagd gaven aan (rekening houdende met de beperkingen van de studie) dat er een verschil werd geproefd tussen vers en verouderd bier (4 maanden op 30°C). Toch was er geen uitgesproken voorkeur voor vers boven verouderd bier. De drinkbaarheid van vers bier is hoger dan die van verouderd bier, hoewel deze bevinding voornamelijk werd toegeschreven aan de categorie van Belgen ouden dan +/- 27 jaar. Daarenboven, contextuele parameters (zoals o.a. groepspsychologie en marketing) blijken een grote invloed te hebben binnen de context van onze experimenten alsook bij de normale dagelijkse consumptie van bier.

In het economische deel van deze studie werd de haalbaarheid onderzocht van gekoelde transporten, horizontale samenwerking in de logistiek en transport & opslag simulaties. Gekoelde transporten reduceren de blootstelling aan temperatuur maar zijn complex te organiseren, mede door de ex-works distributie. Toch zijn gekoelde transporten haalbaar wanneer de verkoopprijs kan worden verhoogd (in combinatie met een verhoging van de verkoopvolumes). Uit de uitgevoerde theoretische simulaties blijkt een horizontale samenwerking in de logistiek voordelig te zijn voor kleine brouwerijen / kleine orderhoeveelheden (jaarlijks volume < 150 paletten – toch complex te organiseren). Tenslotte kunnen transport & opslagsimulaties (op basis van een software model en een fysische testomgeving) aangeboden worden aan de brouwerijen met als doel inzicht te verschaffen in de smaakstabiliteit van hun bier in de buitenlandse markt.

Bij het interpreteren van de resultaten en conclusies van dit werk is het belangrijk eveneens te wijzen op de beperkingen van de studie. In eerste instantie kan erop gewezen worden dat de gebruikte vibratie meetapparatuur primitief wordt geacht door de ogen van een vibratiespecialist. Niettegenstaande voldoet de apparatuur aan de eisen ten einde aan onze onderzoeksdoelstellingen te voldoen. Betreffende de steekproefgroottes van de vibratie en smaakexperimenten kan geduid worden dat deze vanuit statistisch oogpunt relevant zijn maar verder uitgebreid zouden moeten worden om meer diepgaande conclusies te bekomen. Ten derde, tot op heden werd de biersmaak en aroma gekwantificeerd door een sensorische parameter (de 'Overall Aging Score') of enkele chemische parameters (vb. aldehyden, iso-α-zuren). De twee parameters worden onafhankelijk van elkaar geanalyseerd en geïnterpreteerd. Aangezien de 'Overall Aging Score' een (subjectieve) Likertschaal meeteenheid met grote variantie is, worden de sensorische karakteristieken van bier samples onvoldoende accuraat beoordeeld. Daarenboven werden uitsluitend theoretische schattingen gemaakt van de haalbaarheid studies van het implementeren van gekoelde transporten met beperkte brouwerij-specifieke data.

Gebaseerd op de conclusies en beperkingen van dit werk kunnen aanbevelingen voor verder onderzoek gedaan worden. De reproduceerbaarheid van de vibratie en schokexperimenten op verschillende biertypes zou moeten nagestreefd worden. Vervolgens, de rol van zuurstof in bier bij blootstelling aan vibraties, de impact van het opleggen van vibraties van een enkele of meerdere frequenties, en een enkele of meerdere vibratiedimensies zouden moeten onderzocht worden. Aangezien het aanbevolen is de steekproefgrootte en de respondentgroepen van de smaakproeven uit te breiden, is eveneens extra onderzoek naar de consumenten ervaringen, perceptie en gedrag in de exportmarkten sterk aangewezen. Tenslotte, het is aanbevolen te werken aan de reproduceerbaarheid van het kwantificeren van de biersmaak. Wanneer een database wordt gecreëerd kunnen de chemische concentraties gelinkt worden aan de smaakacceptatie en preferentie van de consument door middel van 'data mining technieken'. Deze maatstaf zal objectiever en meer informatief zijn dan het gebruik van de huidige 'Overall Aging Score'.

Algemene conclusies

- Blootstelling aan verhoogde temperatuur en vibraties dragen bij tot een instabiele biersmaak
- Controle van temperatuur is belangrijker dan vibraties en schokken met betrekking tot de smaakkwaliteit van bier
- De basis werd gelegd voor een nieuwe en veelbelovende verouderingstechniek
- Smaakproeven:
    - Een verschil tussen verse en verouderd bier werd geproefd
    - De preferentie van vers boven verouderd bier was niet evident
    - De drinkbaarheid van vers bier is hoger dan verouderd bier (te wijten aan Belgen ouder dan +/- 27 jaar)
    - Sterk beïnvloed door contextuele parameters (marketing, locatie, etc.)
- Gekoeld transport en opslag is aanbevolen maar is complex te organiseren
- Opportuniteit in het organiseren van transport & opslag simulaties

Beperkingen van de studie

- Meetapparatuur
- Sample sizes
- Kwantificeren van de biersmaak en aroma
- Theoretische schattingen van de economische haalbaarheid

Aanbevelingen voor verder onderzoek

- Reproduceerbaarheid van vibratie- en schokexperimenten op verschillende biertypes
- Vibraties en rol van zuurstof in bier, blootstelling aan een enkele frequentie vs. meerdere frequenties, vibratie dimensie (verticale, laterale, longitudinale)
- Consumenten perceptie, trends en gedrag (in de exportmarketen)
- Reproduceerbaarheid kwantificeren van smaak
    - Linken chemische concentraties met smaak acceptatie en preferentie vs. OAS/GAS

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List of abbreviations

ADF	Apparent degree of fermentation
BSWith	Blond specialty beer with refermentation after bottling
BSWIthout	Blond specialty beer without refermentation after bottling
Cal.	Caloric content
DO	Dissolved oxygen
DSWith	Dark specialty beer with refermentation after bottling
Ea	Apparent extract
ECDF	Empirical Cumulative Distribution Function
Eorg	Original extract
Er	Real extract
ft.	foot (e.g. 40ft. containers)
FFT	Fast Fourier Transform
GAS	General Aging Score (=OAS)
HSO	Headspace oxygen
LB	Lager beer
LSP	Logistics Service Provider
MAD	Median absolute deviation
nHi	Nominal homogeneity index
OAS	Overall Aging Score (=GAS)
Pal.	Pallets of beer
PSD	Power Spectral Density Function
RDF	Real degree of fermentation
Reefer	Refrigerated transport container
RMS	Root Mean Square (amplitude)
T/C ratio	*Trans-/Cis-* iso-α-acids ratio
TEU	Twenty Foot Equivalent Unit
TPO	Total package oxygen
Trans.	Transports of beer

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Part 1: Introduction

1.1 Beer quality during distribution and storage as a research topic

Research on the flavor stability (of exported beer) is a research gap that needs to be explored. The topic is extremely relevant and important to the industry, government and consumer. In the current section, a first introduction on the subject of the dissertation will be elaborated.

Relevance of research on the beer flavor stability problem

Due to market globalization, Belgian beer, known for its excellent quality, is available worldwide. In recent years, Belgian beer exports have significantly been increasing from 5 million hl in 2000 up to 13 million hl in 2015[1]. However, breweries indicated a problem during the export of beer: the beer is often severely degraded in flavor quality upon arrival[2]. Moreover, the exposure of beer to long transportation times and variable storage conditions causes the chemical composition of beer to irreversibly degrade[3,4]. The result is an aged or degraded beer flavor that differs in both taste and aroma from fresh beer. Flavor stability problems of beer could result in a rejection of the beer brand and decreasing sales[4]. Therefore, the exact parameters, that induce lower beer quality and correspond to the conditions beer is exposed to during transport and storage, were investigated in the research presented in this dissertation.

Research on flavor stability of beer is relevant and important for the Belgian economy since the export of Belgium beer contributes to revenues of 1.7 billion Euro (2015) and corresponds to 66% of the beer produced by the Belgian breweries[1]. In 2000, the export of Belgium beer contributed to revenues of 0.7 billion Euro and corresponded to 37% of the beer produced by the Belgian breweries[1]. Furthermore, since the volume of Belgian beer destined for export has increased considerably in the last decade, the Belgian breweries are more dependent on the performance of exported beer. The latter can be attributed to consumer trends, i.e. increasingly, (foreign) consumer groups are searching for new and unknown beer flavors, for which they are willing to pay a premium price, and which are different from the domestic bulk produced beer[5]. As a consequence, premium priced Belgian imported beer experienced increasing sales, especially in the extra-European markets[1]. The consumer trend of searching for new beer flavors also caused the rapid rise of craft- and micro-breweries in Belgium and abroad[1,5]. The small breweries offer the consumer a large variety of beer with high-quality flavors and aromas, positioned in the premium segments and prepared with local artisanal brewing processes[5]. In order to compete with other breweries in the premium segment and to meet the expectations of the customer, Belgian breweries are believed to increase the focus on distributing fresh and (improved) high-quality beer with a uniform flavor.

As a consequence, in order to safeguard the future of the quality label of Belgian beer and to support Belgian breweries exporting beer abroad, further research is performed on beer flavor stability. More specifically, the current study examines the impact of vibrations and shocks[I] in combination with temperature on the flavor stability of beer and the economic influence of an improved beer quality.

[I] Shocks are defined as transient vibrations that damp out over time[35]. In this dissertation, both the word 'shocks' as well as 'transient vibrations' are used to name the category.

Flemish government funded project [IWT-VIS/Brewers-120786]

This Ph.D. research was part of a Flemish government funded project (IWT-VIS/Brewers-120786). The research project (2014-2019) was initiated to investigate the beer flavor instability problem of exported beer by the Flemish breweries. Both strategic (basic) research and the implementation of process and product improvements in order to improve beer flavor quality were incorporated in the research project. The project has 54 project partners including all major Flemish breweries and some maltsters (i.e. the problem of beer flavor instability was also researched with respect to the malt that is employed to brew beer). Furthermore, the IWT-VIS project is managed by the KU Leuven Technology campus Ghent that operates a preeminent lab working on beer flavor chemistry. In the context of this research project a partnership between KU Leuven Ghent and UAntwerpen was set up in which UAntwerpen was responsible for conducting transport vibration analysis, setting up experimental designs and performing statistical tests. The current Ph.D. dissertation is one of the exponents of this fruitful partnership.

1.2 Structure of the dissertation

The current work is structured as follows. In Part 2, an extensive overview of the research framework is presented. The Part identifies the structure of the Belgian brewery landscape, the industry and consumer trends (section 2.1), provides information on how to assess beer quality (section 2.2) and mentions the research gaps (section 2.3). The research goals and scope are presented in Part 3. In the following Part 4, the research design and methodology of the doctoral research are introduced. In the subsequent Part 5, the findings of the research are presented. Moreover, the transport and storage conditions (vibrations, shocks, and temperature) beer is exposed to, are studied in detail. Afterwards, the relation between the latter conditions and the chemical and sensorial quality of beer will be explored. Furthermore, the economic impact of the flavor instability of beer is assessed and the economic feasibility of investments to improve beer quality is investigated. In Part 6, the relevance and the implications of the findings are discussed, the strengths and the limitations of the recommendations are assessed and possibilities for future research are identified.

Part 2: Research framework

2.1 The brewery landscape and consumer trends

In order to be able to frame the research that is executed in this dissertation, an introductory section on the market structure of breweries and on consumer trends is presented. First, a historical perspective on Belgian beer and Belgian breweries is described in section 2.1.1. Consecutively, the market structure of the brewing industry on an international and Belgian level is explored in section 2.1.2 and 2.1.3. Consumer trends that shape the brewing industry, i.e. the rise and growth in craft and imported beer and the 'premiumization' of beer brands, are described in section 2.1.4.

2.1.1 Historical perspective – Belgian breweries

Brewing beer is believed to be a known practice in Europe from 5000 BC, i.e. Celtic tribes (5000-500 BC), Egypt (1500-1000 BC), and the Roman Empire (500 BC – 1000 AD)[6,7]. However, in the Middle Ages brewing beer became a commercial activity often performed in the monasteries. Beer was served as a supplement for water, which was regularly polluted. Also, Belgium experienced the rise of multiple monasteries that brewed beer and started the rich tradition of the different styles of Belgian beer. In the 18th-19th century, multiple private companies began brewing beer led by a diffusion of innovations (e.g. thermometer, hydrometer, yeast strains, etc.). Apart from today's largest brewing companies that entered the scene in this time period as the Artois brewery (- the predecessor of AB Inbev - in Belgium), Heineken (the Netherlands) and Carlsberg (in Denmark), every municipality established to have its own brewery. Furthermore, breweries were supported by national governments since taxes coming from beer sales have always been a major source of the financing of governmental activities[7,8].

In the 20th century, after the Second World War, the breweries developed from a local scope (up to the 1960s), to a national scope due to technical innovations, and a global scope in recent years. The more effective control of the brewing process, the automatization in brewing and packaging, and the improved road infrastructure have led to an enhanced shelf life of beer, economics of scale, and the possibility to export beer. The process of internationalization also caused an acquisition movement that resulted in a severe reduction in the global number of breweries[6]. AB InBev, which in 2016 announced the merger with SABMiller, is one of the companies that showed enormous growth due to this trend. Up to today, the image of Belgium is linked to the monasteries that brew traditional Belgian beer, the dominance of AB Inbev on the world scene, and the high variety of quality beers[6,7].

2.1.2 The international beer industry

Due to globalization and the acquisition movement, a large share of the global beer production comes from a small number of large multinationals, as is indicated in Table 1. The beer industry is considered a 'global' industry and is concentrated due to the multinationals capitalizing on synergies across borders[6,7]. However, in recent times a new phenomenon is shaping the brewing industry: the rise of craft breweries. The consumer demand for new beers and the availability of the technology (i.e. equipment) brewing small batches of beer causes the rise of these small breweries. The category only produces 7 percent of the global beer market production, although the number of breweries rises with roughly 10% per year[5,9]. In the United States, the growth rate of 16.2% per year is even larger, as stated in Table 2. The craft beer trend originated and is most prominent in the United States but is also present in Europe[10].

Table 1: Multinational brewing companies (2016)

Brewery	Country	Production volume 2015 in mill. hl	Percentage of world beer production
1. AB InBev	Belgium	409.9	21.2 %
2. SABMiller	United Kingdom	191.3	9.9 %
3. Heineken	Netherlands	188.3	9.7 %
4. Carlsberg	Denmark	120.3	6.2 %
5. China Res. Snow Breweries	China	117.4	6.1 %
6. Tsingtao Brewery Group	China	70.5	3.6 %
7. Molson-Coors	USA/Canada	55.8	3.0 %
8. Yanjing	China	48.3	2.5 %
9. Kirin	Japan	43.1	2.2 %
10. BGI / Groupe Castel	France	29.8	1.5 %
TOTAL		1,274.6	65.9 %
World beer production 2015		1,932.9	100 %

Table 1 illustrates the dominance of the multinational companies in brewery industry (66% of the global beer production in 2015 comes from the largest 10 breweries).

Source: Barth S., 2016[11]

In the United States, a craft brewer is defined[II] as a small, independent and traditional brewer[9]. Moreover, the annual production of beer is required to be lower than 6 million barrels per year. Additionally, not more than 25% of the craft brewery may be controlled by a non-craft brewery. And finally, the majority of its produced beverages should come from traditional or innovative brewing ingredients and their fermentation. It should be noted that 6 million barrels or 7.2 mill. hl (roughly 3% of the U.S. annual sales) is a large beer volume for a company presumed to be a craft or a small brewery. The definition of a craft brewery has been redefined several times, more specifically the beer volume threshold was raised. Several specialists of the beer brewing industry identify this as an act of U.S. protectionism since the (larger) craft breweries enjoy tax benefits[9].

Table 2: U.S. Craft brewery count

	2013	2014	2015	2016	2015 to 2016 change
Total U.S. Craft Breweries	**2,898**	**3,734**	**4,504**	**5,234**	**+ 16.2 %**
Regional craft breweries*	119	135	178	186	+ 4.5 %
Microbreweries**	1,471	2,071	2,596	3,132	+ 20.6 %
Brewpubs***	1,308	1,528	1,730	1,916	+ 10.8 %

Table 2 indicates the rapid rise of craft breweries in the U.S. (growth rate of 16.2% in 2016).

Source: Brewers Association, 2017[9]

[II] The UK makes a distinction between breweries producing more / less than 60,000 hl (in order to acquire tax and/or other economic benefits). With the EU, the distinction is made between breweries producing more / less than 12,000 hl.

Definitions of craft brewery categories:

*** Regional craft brewery:**

- An independent regional brewery with a majority of volume in "traditional" or "innovative" beer(s)

**** Microbrewery:**

- Produces less than 15,000 barrels per year (17,600 hectoliters)
- 75 percent or more of its beer sold off-site
- Sell to the public in three or more methods: (1) the traditional three-tier system (brewer to wholesaler to retailer to consumer); (2) the two-tier system (brewer acting as wholesaler to retailer to consumer); (3) directly to the consumer through carry-outs and/or on-site tap-room or restaurant sales.

***** Brewpub:**

- Sells 25 percent or more of its beer on site
- Brewed primarily for sale in the restaurant and bar

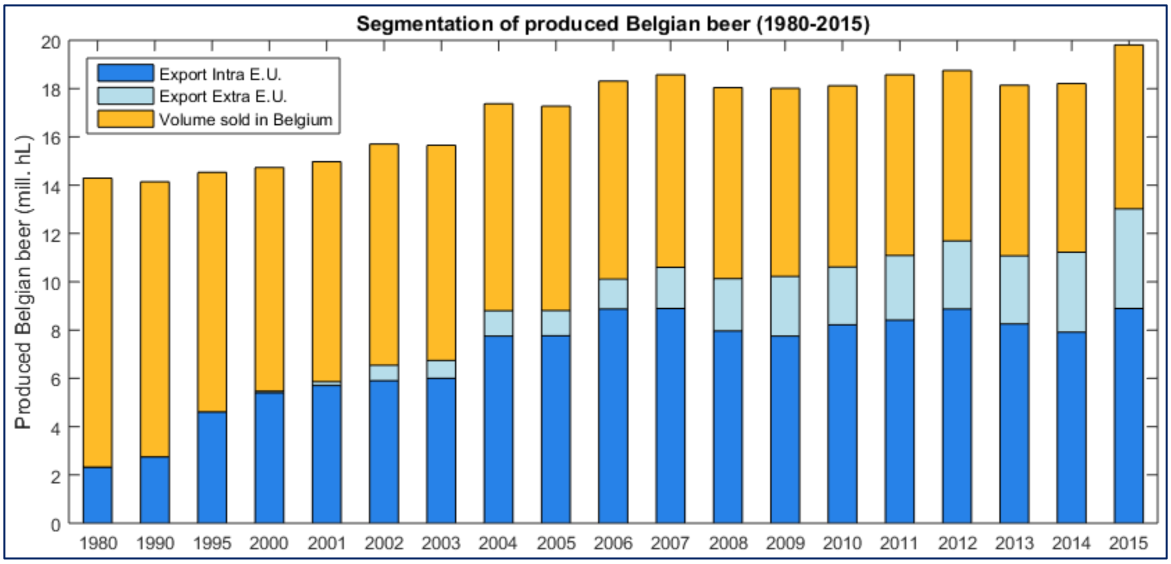
Source: Brewers Association, 2017[9]

2.1.3 The Belgian beer industry

Belgian beer is widely known for its high quality, diversity, and authenticity[1]. The fine art of making beer has been part of the Belgian tradition for ages. As a consequence, the Belgian beer industry has always been an important sector providing employment and significant governmental income[8]. The sector contributes 900 million euros on a yearly basis (2015) to governmental spending while providing employment for 54,000 people (direct and indirect). Due to 199 breweries being present in Belgium, 1,500 different beers of varying taste and aroma are available in the Belgian beer gamma. However, only roughly 1% of the globally produced beer is brewed in Belgium[1].

In order to identify the trends with respect to exports of Belgian breweries and Belgian domestic consumption, Figure 1 was introduced. The figure segments the produced and sold Belgian beer over the period 1980-2015 into three categories. In a first category, the volume Belgian beer sold in Belgium is identified. In category two and three, produced beer contributing to Belgian exports within and outside of Europe are presented. The chart indicates that the export of beer is increasingly more important to the industry. In 2015, 66% of the produced Belgian beer was exported. Beer exports to countries outside of Europe are in absolute numbers a relatively modest market segment. However, the growth rate is significantly increasing over time. Exports of beer within the E.U. has also increased significantly, but experienced stagnation in last years (2008-2015). From the same graph, it can be seen that domestic consumption of Belgian beer decreases drastically over time. The latter can be attributed to the Belgian people drinking less but enjoying the quality of their fine beer more[12]. Other explanations that justify this trend are the various campaigns to foster responsible drinking. Furthermore, the increasing variety of alcoholic beverages offered to the consumer has significantly extended over time which could have caused the decrease in beer consumption rates[1,6,13].

Figure 1: Segmentation of the produced Belgian beer (1980-2015)



The figure illustrates the increasing importance of exported beer (predominantly extra E.U.) and the decreasing domestic beer consumption. Source: Belgische Brouwers, 2016[1]

In Figure 2, the most important countries are mapped to which Belgian breweries export beer. In total, 13 million hl beer is exported of which 8.9 million hl within and 4.1 million hl outside of Europe[1]. In the global map of Figure 2, 84% of the total volume of exported Belgian beer is presented by country (i.e. Canada, USA, UK, France, the Netherlands, Germany, Italy, China, Japan, Korea). The importing countries within Europe, identified in Figure 2, correspond to 92% of the intra E.U. exports (i.e. UK, France, the Netherlands, Germany, Italy) and the importing countries outside Europe, correspond to 74% of the extra E.U. exports (i.e. Canada, USA, China, Japan, Korea). As a consequence, the main countries that import and consume Belgian beer are presented in the figure. It is noteworthy that the largest importers of Belgian beer are the neighboring countries France, the Netherlands, and Germany. The U.S.A. is the largest non-European country that imports Belgian beer. When comparing the export numbers of 2015 with the ones of 2014, there are some interesting findings. The export volume of Belgian beer to China and Korea increased by 60%, respectively 87% in the year 2015. The growth of Belgian beer imports in the UK and Italy raised with 20%, and in the U.S.A. and Canada with 5% in 2015. In France, the Netherlands, Germany and Japan the export volume of Belgian beer stagnated (2015). The latter indicates the increasing importance of the Asian markets as importers of Belgian beer.[13,14]

Figure 2: Exports of Belgian beer worldwide (2015)

Source: Belgische Brouwers, 2016[1]

From a survey, sent out to 33 Belgian breweries of which 23 brewers (including the four largest Belgian breweries) responded, the structure of the beer industry in Belgium can be deduced[III]. Breweries are segmented into three categories based on the volume of the produced beer[IV]:

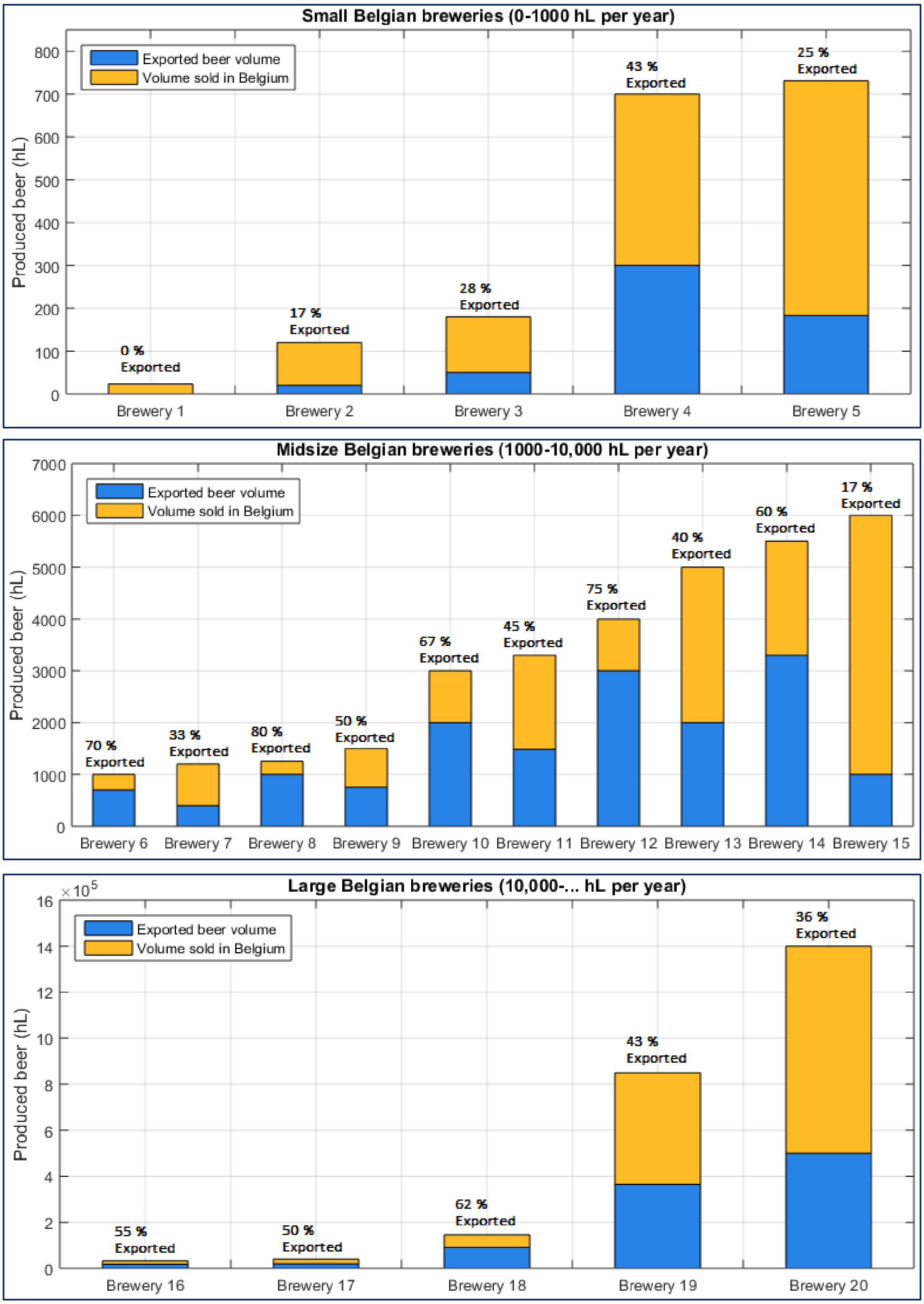
1. Small breweries: 0 – 1,000 hl per year
2. Midsize breweries: 1,000 – 10,000 hl per year
3. Large breweries: > 10,000 hl per year

Figures 3a-c indicate that small, midsize and large breweries all export beer to foreign countries. Furthermore, the figures present the market outlook and structure of breweries within Belgium. The dominance of the largest breweries can be determined from the figures, as well as the 'long tail' of the market or a large number of small breweries.

[III] The survey was performed during the master thesis of Dorien Van Cappellen (Topic: horizontal collaboration during transport and storage between breweries) and sent to the members of the VIS-project [71].

[IV] The European definition identifies (1) a *small organization* as < 50 FTEs, annual revenues of ≤ 10 M euro and at least 75% of the shares owned by the company itself (2) a *midsize organization* as < 250 FTEs, annual revenues of ≤ 50 M euro and at least 75% of the shares owned by the company itself (3) a *large organization* as > 250 FTEs, annual revenues of > 50 M euro and at least 75% of the shares owned by the company itself. Based on this definition two breweries are identified as large organizations, one brewery as a midsize organization, and all other breweries as small organizations. In order to analyze (and zoom in) on the studied breweries, the breweries were segmented based on an arbitrary chosen volume of the produced beer.

Figures 3a-c: Segmentation of the Belgian beer industry (2016)



The figures illustrate the dominance of the large breweries ('brewery 20 and 19') and the importance of exporting beer both for large and small Belgian breweries. Source: Van Cappellen & Paternoster, 2016[71]

In Belgium, roughly 70% of the consumed beer is represented by bottom-fermented lager beers[8]. Lager beer consumption accounts for 90% of the global beer consumption, which implies that in other countries, the dominance of lager beers is even more pronounced[8]. Since Belgium is known for its specialty beers[1], it can be presumed that a large share of the exported beer consists of non-lager beers. However, also lager beer is exported to foreign countries, for example, Stella Artois has already been exporting beer since the 1930s[8]. No exact figures were available to enable segmentation of the Belgium beer exported to foreign countries.

2.1.4 Consumer trends

Craft and imported beer, and the rise of the 'premiumization' of beer brands

In recent years, craft beer is well-known and widely appreciated resulting in considerable increases in sales[5]. The consumer group of 'millennials', i.e. people aged between 21 and 44 are the main contributors to the increase of consumption of the beverage[5]. The group of craft beer consumers is mainly well-educated, well-paid and willing to pay a premium price for new and unknown beers they never drank before[5]. The group perceives themselves to be adventurous in the choice of beers they drink. Furthermore, the higher price is justified by the consumer for two reasons: in order to support the local community and since craft beer is perceived to be high in quality due to the artisanal brewing processes[5].

However, also imported beer benefits from the search of consumers to find new beer brands and special beer flavors. In the USA, beer sales volume growth of imported beer (6.8%) overtook the growth in craft beer (6.2%) in 2016 (while the total U.S. beer sales volume growth remained stable at 0%)[9]. Market watchers identify a blurring effect between local craft beers and imported beer that is premium priced and focusses on the artisanal brewing process coming from an old but high-quality recipe[15,16]. The latter experts also identify a pronounced 'premiumization' in the price and positioning of the beer brands in the USA in recent years[9,16]. Also, Belgian beer is exported to foreign countries and sold as a premium product. However, it is remarkable that large beer brands in their country of origin develop towards stagnation in beer sales volume (since domestic beer sales volume is constant or declines), while the beer sales volume increases when being exported to foreign countries as a premium product[1,16]. For instance, the brand Stella Artois, which is a well-known brand in Belgium, grew by 20.1% in sold beer volume in 2015 due to being exported as a premium product to foreign markets[16].

In the Asian markets, a similar profile of the imported beer drinker is identified. A study of Chinese consumers indicated that the main consumers of European beer are living in a city environment, are male, have a good financial situation and a high-level employment position and are frequent beer consumers[17]. However, European imported beer is identified as a luxury good and is mainly targeted to the middle-class consumers[17].

Specialty beers in Belgium

Also within Belgium, consumer groups adopt similar habits as their American counterparts contributing to the rise of several micro- and craft breweries and the sales of a large variety of beer brands[1]. Furthermore, specialty beers increase in market share compared to lager beer. The Belgian brewer's annual report of 2015 indicates that 68.2% of the questioned consumers in a survey[V] drink more

[V] The survey was performed by the Federation of Belgian Brewers in partnership with Het Laatste Nieuws and La Dernière Heure. In total, 6,480 people were questioned on behalf of the study.[1]

specialty beers in the past year than they used to do before. Furthermore, the study also claimed that 14.4% of the respondents drink beer produced by local breweries, while ten years ago the number was only 5%[1].

Conclusion

Driven by consumers willing to taste a variety of different and new flavors, and willing to pay a premium price, consumer trends cause an increase of the volume of the sold craft and imported beer. Belgian breweries, widely known for their high-quality beer label, have specialty beers with authentic flavors that are increasingly appreciated by domestic and foreign consumers. Since local consumption of large domestic beer brands is decreasing, breweries will increasingly be forced to develop new and high-quality beers. Furthermore, a 'premiumization' in the price and positioning of beer brands will be a further developing market segment.

2.2 The chemical and sensorial quality of beer

The shelf-life of beer is mostly determined by its microbiological, colloidal, foam, color and flavor stabilities[3,4]. Since beer degradation due to micro-organisms is under control, increased attention goes to beer flavor stability. More specifically, beer aroma and taste tend to change, in an unfavorable manner, over time. When beer is exposed to undesirable ambient conditions, this process tends to accelerate[3].

In section 2.2.1, an introduction to beer flavor stability is presented with the intention to clarify the core concepts of this research domain. Afterwards, the qualitative and quantitative parameters that characterize or quantify beer quality, used in this research, are elaborated in section 2.2.2. In a last section 2.2.3, the status of the research (literature review) with regards to the influence of temperature, light, and vibrations and shocks on the beer flavor quality are identified.

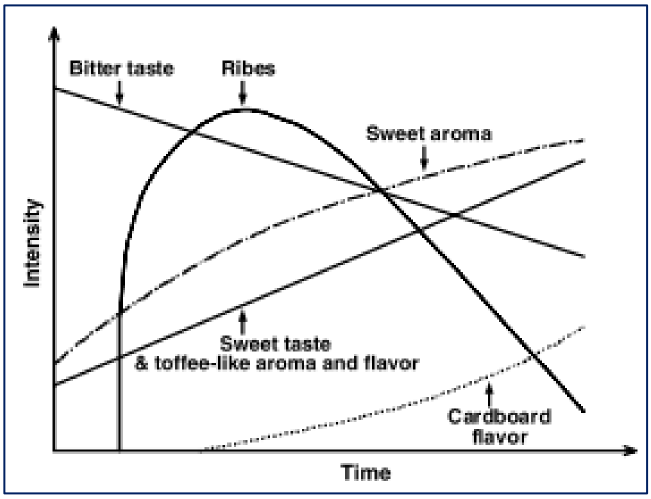
2.2.1 An introduction to beer flavor stability

As soon as the bottled beer leaves the brewery, the beer can experience various flavor modifications[12]. From a chemical point of view, the beer aging phenomenon is very complex. A myriad of chemical reactions generates chemical compounds that alter the sensorial properties of beer[3]. Formation of new molecules in aging beer may generate new undesirable beer flavors, whereas degradation of existing molecules, on the other hand, may lead to a loss of initial fresh beer flavors. Furthermore, different flavors of the beer may become too pronounced or, conversely, suppressed by the interactions between the different flavor molecules[3].

In Figure 4, an overview of the flavor changes that occur during beer aging is presented. As shown in this figure, the typical bitter taste of the beer is gradually decreasing during aging, whereas simultaneously a more sweet taste and aroma develops[3]. Furthermore, a rapid rise of a 'ribes' taste is noticeable. The latter term refers to the characteristic odor of blackcurrant leaves (*Ribes nigrum*). Over time, the intensity of the 'ribes' flavor diminishes, whereas an unpleasant cardboard flavor develops. Additionally, apart from the sensory changes presented in Figure 4, some of the positive flavor attributes of beer will also decrease over time, such as the fruity and flowery aromas of fresh beer. Next to sensory and chemical changes, in particular the development of permanent haze and a change in color also indicate beer aging[3].

Even after 40-50 years of research, the exact pathways leading to beer aging or beer staling are not entirely known[3]. More than hundred chemical compounds take part in the diversity of chemical aging reactions, among which Maillard reactions, the formation of unwanted staling aldehydes, ester degradation, degradation of hop-derived bittering acids and polyphenol oxidation/polymerization (accompanied by haze formation)[12]. Most of these reactions are initiated by oxidative mechanisms, although non-oxidative pathways may also occur (such as for instance release of staling aldehydes from non-volatile precursors). The beer type, the raw materials used in brewing, and exposure to harmful ambient conditions, all have an influence on the occurrence of the unwanted chemical aging reactions[12].

Figure 4: Sensory changes during beer aging



Source: Vanderhaegen et al., 2006[3]

Most beer aging reactions are related to the presence of oxygen. More specifically, reactive oxygen species (ROS) in their radical or non-radical form (which may potentially convert to oxidizing radicals) are the largest contributors to beer aging reactions[12]. The latter mentioned oxidizing radicals, which are formed by metal catalysts, are initiators of many flavor deterioration reactions. Metals, like iron, manganese, and copper catalyze reactions that facilitate the production of ROS. Furthermore, even when only present in trace amounts, metals also generate a metallic off-taste. Since oxygen in beer can lead to beer aging reactions, it is recommended to avoid excess of metal concentrations and to limit the dissolved oxygen level in packaged beer. In order to diminish undesirable beer flavors, metal concentrations should be lower than 50 ppb during all stages of the brewing process. The dissolved packaged oxygen level is required to be lower than 50 µg/l to limit beer staling reactions. With modern filling equipment, brewers should be capable of reducing the TPO-value (total packaged oxygen) to approximately 0.1 mg/l[12].

Hops or hop products are a unique raw material in beer preparation, having multiple advantages for the brewer, but, unfortunately, the use of hops is also related to beer flavor instability. The characteristic bitter taste of beer (indirectly) comes from hops, which also provide flavor and aroma, and contribute to beer foam and texture. Furthermore, hop-derived products act as antimicrobials (e.g. iso-α-acids) and hop-products such as polyphenols may improve the intrinsic flavor stability of beer, due to their strong, natural antioxidant activity. Of particular importance are the hop-derived isomerized alpha acids (iso-α-acids) because these unique compounds represent the main bittering principles of beer[18]. However, unfortunately, isomerized alpha acids are also susceptible to degradation during beer aging, resulting in a decrease in beer bitterness intensity and quality. Previous research revealed that oxidation, heat load, and light are the major parameters causing iso-alpha acids to degrade during beer transport and storage[3,4,12].

Next to degradation of iso-alpha acids, a decrease in beer quality, in particular in flavor stability, is always related to an increase in the level of typical beer staling aldehydes imparting major off-flavors to aging beer, such as the cardboard flavor caused by trans-2-nonenal. Both oxidation reactions, Maillard reactions, and degradation of amino-acids will cause the production of these highly unwanted aldehydes that will alter and destroy the sensorial properties of fresh beer[12,19].

2.2.2 Parameters to quantify beer (flavor) quality

Beer quality can be quantified by different means, comprising both sensorial and chemical methods. In the current section, several of these methods used in the research domain of beer quality and stability will be identified.

A first method deals with sensorial evaluation of beer. In this method the respondent is asked to profile the beer sample with regard to different (un)desirable aromas[VI]. Also, a general or overall aging score (GAS or OAS), which is a number between zero and eight and represents the degree of staling and overall satisfaction with respect to the taste of a beer sample, is asked from the taster. The categories of the general aging score are[20]:

- 0: fresh, oxidized flavor not detectable
- 2: very weakly aged
- 4: weakly aged
- 6: clearly aged
- 8: strongly aged, undrinkable.

Sensory profiling of the beer implies to have expert or trained tasters, capable of distinguishing between the different tastes and aromas of beer. The tasting is often accompanied with a list of questions, regularly using Likert scales. Since taste differs between respondents and people in general, it is evident that sensorial profiling is a complex task. Furthermore, also the repeatability and reproducibility of this complex test impedes a robust analysis. A more objective sensorial test is called a ‘triangle test’ in which the respondent is asked to identify the beer sample that is different from the two alternative samples out of a sample set of 3 beers. Afterwards, the taster is asked for its motivation when identifying a specific sample during the blind tasting. A ‘duo test’ can also be adopted if the respondent is asked to reveal his/her preference with respect to two beer samples.

An alternative and more objective method to quantify beer taste and aroma is to chemically profile the beer and relate this profiling to sensorial analysis. In this research, the objective is to identify the individual compounds (and their flavor thresholds) that contribute to the aroma and taste of beer[21]. However, research has not yet verged into the complexities of the interactions between compounds, which may further strengthen or weaken the taste and aroma of beer. As a consequence, there is still a lot of work to be done in modeling the chemical concentrations of flavor compounds and relating this to the beer flavor in general, and consumer acceptance and preference of the beer in particular. In this connection, big data and data mining models could facilitate in solving this intricate, highly-challenging task. Nevertheless, the chemical parameters that are related to beer aging can be distinguished and are presented[VII]:

1) Oxygen concentration

The oxygen concentration in beer is not a direct measure of beer aging. Nevertheless, a decrease in the oxygen level (which relates to the amount of ROS in beer) can indicate that the beer aging process already took place or will happen shortly. There are 3 categories of oxygen measurements in bottled beer. First, the available oxygen in the headspace, the volume of a beer bottle not filled with beer, is calculated (HSO: Headspace Oxygen). Second, the concentration of oxygen present in the beer itself is measured (DO: Dissolved Oxygen). Third, the overall level of oxygen was calculated taking into

[VI] For instance, the respondent is asked if notes of caramel, sherry/madeira, solvent, cardboard, red fruit, old hops are tasted. Panels are regularly trained to distinguish between the tastes of these different flavor notes.
[VII] Additional information on the specifications of the measurements of the chemical parameters are presented in Appendix 1.

consideration the volume ratio between beer and headspace (TPO: Total Package Oxygen). Measurements are performed with systematic error (accuracy) of 1 ppb +/- 2%.

2) Color

Measurements of color are performed by IOB method: 9.1[22], which is a standardized procedure. The color measurement can be specified as an absorption 430 nm test. The systematic error of the procedure is identified at 0.062 EBC [EBC – European Brewery Convention that proposed the unit measuring beer and wort color].

3) Turbidity

The turbidity or the haze of the beer was measured with the Haffmans Hazemeter – VOS ROTA 90/25. The systematic error of the measurements is equal to H90 = 0.08 EBC and H25 = 0.36 EBC.

4) Iso-α-acids

Iso-α-acids contribute to the bitter taste of beer[18]. By measuring the decrease in the concentration of individual iso-α-acids by high performance liquid chromatography (HPLC), beer aging can be estimated. Furthermore, the ratio of trans/cis-*iso*-α-acids can be used as a staling indicator[12,18,23]. The bitterness parameters used in this research are:

- *trans*-isocohumulone
- *cis*-isocohumulone
- *trans*-isohumulone
- *cis*-isohumulone
- *trans*-isoadhumulone
- *cis*-isoadhumulone
- Total iso-α-acids
- T/C-ratio (%)

with $$\mathrm{T/C}\ (\%) = \frac{[\textit{trans}\text{-isocohumulone}] + [\textit{trans}\text{-isohumulone}]}{[\textit{cis}\text{-isocohumulone}] + [\textit{cis}\text{-isohumulone}]} \times 100\ \%$$

5) Aldehydes

The increase in levels of particular aldehydes is generally regarded as an important marker for beer flavor quality deterioration. Aldehydes may formed from amino acids as a Strecker degradation product (e.g. methional), as fatty acid oxidation products (e.g. (E)-2-nonenal), or as a final product of a Maillard reaction (e.g. furfural)[19]. The above mechanisms all relate to the so-called *denovo* formation of beer staling aldehydes that may occur during beer distribution and storage. However, beer staling aldehydes might also be derived from several types of non-volatile precursors (such as aldehyde-bisulfite adducts or aldehyde-cysteine adducts) that may undergo non-oxidative dissociation during beer aging thereby releasing staling aldehydes[19]. Different off-flavors can be attributed to the different aldehyde compounds, each having a specific flavor or odor threshold. However, the overall stale flavor of the beer is caused by the interaction of a myriad of aldehyde compounds[12,19]. The list of aldehydes incorporated in this research, which is used to analyze beer flavor, is presented in Table 3.

Table 3: List of aldehydes (aging parameters)

Aldehydes (µg/l)	**Systematic error**	**Flavor threshold [* Odor threshold] (individual component)**	**Flavor description**
2-methylpropanal [Strecker degradation product]	1.605 µg/l	86* µg/l	Grainy, varnish, fruity
2-methylbutanal [Strecker degradation product]	0.603 µg/l	45 µg/l	Almond, apple-like, malty
3-methylbutanal [Strecker degradation product]	2.011 µg/l	56* µg/l	Malty, chocolate, cherry, almond
Hexanal [Fatty acid oxidation product]	0.200 µg/l	88 µg/l	Bitter, winey
Furfural [Maillard reaction product]	4.366 µg/l	15157* µg/l	Caramel, bready, cooked meat
Methional [Strecker degradation product]	0.719 µg/l	4.2 µg/l	Cooked potatoes, worty
Benzaldehyde [Strecker degradation product]	0.302 µg/l	515 µg/l	Almond, cherry, stone
Phenylacetaldehyde [Strecker degradation product]	1.239 µg/l	105 µg/l	Hyacinth, flowery, roses
(E)-2-nonenal [Fatty acid oxidation product]	0.005 µg/l	0.03 µg/l	Cardboard, papery, cucumber

Source: Baert et al., 2012[17], Saison et al., 2009[21]

2.2.3 Transport and storage conditions influencing beer flavor stability

The exact pathways that contribute to beer aging are not entirely known. Nevertheless, researchers were able to identify some of the parameters that positively or negatively affect beer flavor quality. The control of temperature (2.2.3.a), light (2.2.3.b), vibrations and shocks (2.2.3.c) to which beer is exposed, should result in flavor quality improvements. The latest research findings, disclosed in the literature, on this topic are presented in the sections 2.2.3.a-c.

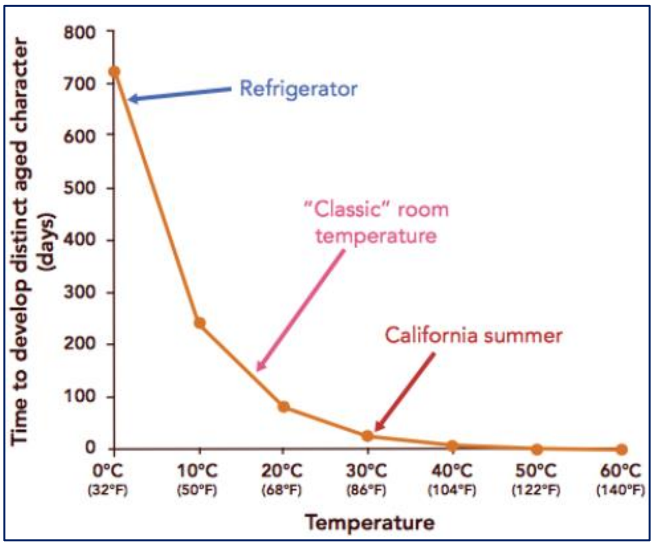
2.2.3.a Temperature

Temperature is widely identified as the main contributor to beer aging[3,4]. The process of beer quality degradation is characterized by diverse aging reactions, and, as a consequence, due to the Arrhenius equation accelerated (ageing) reactions can take place[24]. In other words, the freshness of beer decreases with higher temperatures, increasing energy (reaction kinetics) and thereby increasing a number of chemical reactions that take place. With an increase of temperature of 10°C, chemical ageing reactions arise two to three times faster[19]. Furthermore, every reaction type has a different level of activation energy, i.e. the energy required to initiate a reaction. This implies that with increasing temperature, reaction rates are different. As a result, with increasing temperature chemical compounds of different reactions are formed unequally[20]. For instance, beer storage at high temperature could generate a more pronounced cardboard flavor, whereas in low temperature an undesirable caramel flavor could be more prominent (this example is explanatory and not linked to reality)[25].

However, storage of beer in extremely low temperatures are also not recommended. Research indicated that when beer with high alcohol content was frozen an increased concentration of β-glucan (haze or precipitation) arose[12]. Of course, the brewer has not the intention to store beer below freezing point since, due to the property of water to expand, the integrity of the bottle, can or keg can be in danger. The optimal temperature to store beer is mostly a very low temperature, above freezing point, in order to preserve the beer and minimize the rate of beer degradation.

To frame the magnitude of the problem of beer flavor degradation at increased temperature, Figure 5 can be presented. The figure highlights the shelf life of beer when exposed to different temperatures. The problem is prevalent in the brewing industry, predominantly when transporting beer over long distances (in uncooled containers).

Figure 5: Shelf life of beer under increased temperature



The relation between the exposure of temperature and the beer flavor instability is exponential.

Source: Brewers association, 2017[9]

2.2.3.b Light

Quality deterioration of beer can also be caused by an exposure to light, a phenomenon referred to as 'lightstruck flavor'[26]. The latter can be attributed to the absorption of energy, generating intramolecular energy transfer which causes several chemical reactions to occur. The vulnerability of iso-α-acids to light can be indicated as the main contributor to photodegradation of beer or its 'lightstruck or skunky flavor'[26]. In order to prevent light-induced deterioration, breweries store their beers in light-proof containers (e.g. colored bottles or cans)[26]. Brown glass, cans, and kegs all block the wavelengths that cause the pungent and undesirable flavor. Beer packaged in blue, green or flint-glass, on the contrary, is susceptible to degradation caused by light. The latter packaging strategy might be adopted by marketing purposes.

2.2.3.c Vibrations and shocks

While the literature on beer being exposed to high temperatures and light is abundant, there is limited research on the effect of vibrations on the chemical and sensorial quality of beer. However, Janssen et al. (2014)[27] already suggested that vibrations could influence the quality of food products. Moreover, the authors indicated the contamination by moulds in fresh food products during transport. Also, the development of turbidity in beer caused by vibrations during transport was mentioned. As a consequence, the influence of vibrations and shocks on the beer quality is a research gap that needs to be explored. Two theories are presented that might describe the relation between vibrations and beer quality:

1) vibrations and shocks increase molecular energy and, as a consequence, increase the reaction rate of the aging mechanism (reaction kinetics)
2) vibrations and shocks could raise the uptake of oxygen from the beer bottleneck into the beer (more flavor active components or off-flavors can be formed/degraded)

The above theories (and the possible relation between the two theories) must be tested in order to identify to what extent vibrations and shocks during transport induce a decrease in beer quality.

An introduction on vibrations and vibration analysis

Vibration or oscillatory motion occurs when a particle, a body or a system of connected bodies are displaced from a position of stable equilibrium[35]. Due to restoring forces the system is inclined to return to its equilibrium position. A vibration can be a deterministic (periodic) excitation (harmonic vibrations, e.g. a pendulum) versus a random excitation (e.g. transport vibrations). With respect to harmonic oscillatory motions the displacement (1), the velocity (2), and the acceleration (3) and frequency (ω) can be defined.

(1) Displacement

$$\boxed{x = x_0 \sin\,(2\pi f t) = x_0 \sin\,\omega t}$$

(2) Velocity (First derivative of displacement)

$$\boxed{\dot{x} = x_0(2\pi f)\cos 2\pi f t = x_0\omega \cos \omega t}$$

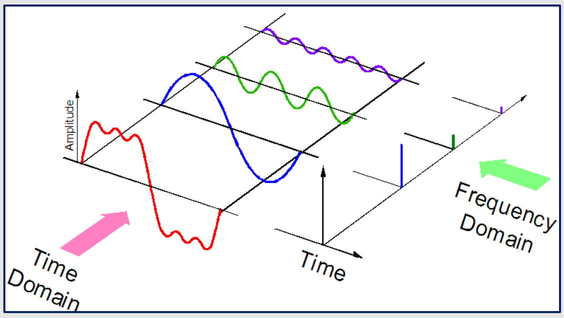
(3) Acceleration (Second derivative of displacement)

$$\boxed{\ddot{x} = -x_0(2\pi f)^2 \sin 2\pi f t = -x_0\omega^2 \sin \omega t}$$

Transport vibrations contain multiple frequencies with their corresponding amplitudes (displacement, velocity or acceleration). Therefore, a signal measured in time-domain can be decomposed in frequency domain (Figure 6a) by performing a Fourier transform and giving insights on the exposed vibration frequencies and amplitudes (normally displayed in a PSD or power spectrum – Figure 6b). When an object or a system is exposed to vibrations, resonance and damping phenomena may occur depending on the material properties (e.g. stiffness and elasticity).

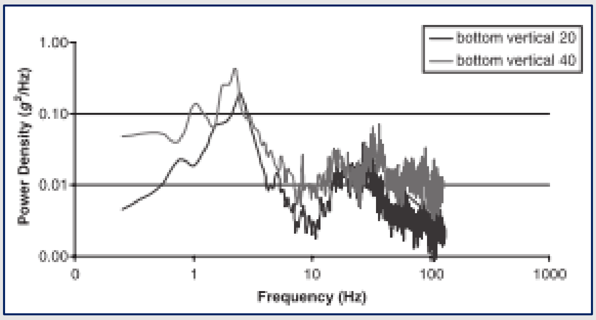
The research domain on the influence of transport vibrations on apples[92] is well-developed (loss rate of apples during transport: 10-25%). However, the awareness on the impact of vibrations on multiple other food products is also increasing (research on e.g. kiwis[93], strawberries[94], eggs[95], etc.)

Figure 6a: Vibrations – time and frequency domain



Source: Algoengines, 2018[96]

Figure 6b: Vibrations – Example power spectrum (PSD)



Source: Jarimpos, et al., 2005[97]

2.3 Research gaps

The beer flavor stability problem has been researched for over twenty years. However, the research available in the literature mainly focuses on the chemistry of beer. Deriving the pathways leading to beer aging and studying the impact of diverse molecules has been the predominant focus of beer scientists with respect to beer flavor stability. The research presented in this thesis aims to address the topic of beer flavor stability from a multidisciplinary angle. Moreover, research with respect to chemistry, physics, and economics is integrated into the current study. The latter results in identifying two main research gaps explored in this research.

The impact of vibrations and shocks during transit on the beer flavor stability is a first research gap that is identified. Apart from the study of Janssen et al. (2014)[27] that suggested the possible negative effect of vibrations and shocks on the turbidity of beer, no prior research touched upon the topic. In the literature, the severance of vibrations and shocks upon truck transport is assessed in order to identify the mechanical damage of fruits and vegetables, e.g. apples[28] or strawberries[29]. However, to the authors knowledge no prior research was executed on the impact of vibrations and shocks on the quality of fluids or beverages. The latter indicates that the current study (or the methods developed in the study) can be extended in order to investigate the effect of vibrations and shocks on beverages other than beer. The influence of the interaction and interplay between vibrations and shocks, on the one side, and temperature, on the other side, on the beer flavor stability have not been explored in the literature.

A second identified research gap is the economic impact of problems concerning beer flavor stability. Moreover, the potential preference for fresh over aged beer for different consumer groups should be assessed. Additionally, the potential increase in revenues when increasing beer quality should be identified. The increase in beer quality comes with an additional investment of which the feasibility should be identified. Introducing economics within the beer flavor stability problem is new (to our belief) to both industry and academia. For instance, the literature indicates that controlling temperature is crucial in order to maintain beer quality to accepted levels. Since beer is predominantly transported in uncooled containers, the economic feasibility of transporting beer in refrigerated containers should be investigated. Furthermore, the economic feasibility of horizontal collaboration in the distribution of beer between different breweries should be researched. Competition intensifies and additional measures to maximize profit are being searched after. Therefore, a collaboration between breweries might increase the competitiveness of the individual parties. While horizontal collaboration with respect to logistics is relatively new in industry and academia, case-studies in different sectors have been positively evaluated in the past[30]. However, there is no case-study or research as to what extent (the Belgian) breweries might experience significant merits from introducing horizontal collaboration. As a consequence, the latter is a research gap that will be explored.

2.4 Conclusion

Belgian breweries increasingly cope with decreasing sales volumes in the domestic market but increasing export sales volumes. The decreasing domestic consumption can be attributed to the large variety of available alcoholic beverages and mainly pressurizes large domestic brands. Furthermore, consumer trends cause the rise in craft and micro-breweries that offer a large variety of new, unknown and special beer flavors offered at premium prices. Belgian beer imported in foreign countries also benefits from the latter consumer trend. The latter results in Belgian breweries being more dependent on revenue coming from exports. Due to the increase in exported beer, a major share of the beer is exposed to longer transportation times and storage conditions that the brewer is not able to control. Moreover, the quality of the beer is not assessed after leaving the brewery, which regularly leads to severely degraded or aged beer when reaching the consumer.

In order to safeguard the future of the quality label of Belgian beer and to support breweries exporting beer abroad, further research is required on beer flavor stability. The influence of vibrations and shocks separately and in interaction with temperature has never been researched before, and therefore, is a research gap that should be explored. Furthermore, the economic impact of increased beer quality and economic feasibility studies on improved beer flavor stability is a research gap that should be investigated.

Part 3: Research goals, scope and research questions

3.1 Research goals and scope

The current study is conducted in order to support breweries with respect to beer flavor stability problems. More specifically, the objective is to identify the impact of vibrations and shocks on beer quality and stability, and to assess the potential economic loss of the current beer flavor quality (and the economic impact of an improved quality). The scope of the research limits itself to the impact of vibrations, shocks, and temperature and does not assess the interplay with light or other storage conditions. Furthermore, the economic feasibility studies that are executed in the current research are developed with a focus on the Belgian breweries.

3.2 Research questions

In order to structure the research presented in this work, four research questions were identified.

RESEARCH QUESTION 1a, 1b:

- Do fluctuations in temperature, vibrations and shocks during transport cause a decrease in the chemical and sensorial quality of beer?
- Does the interplay between temperature, vibrations and shocks (interaction effect) lead to an extra decrease in beer quality?

RESEARCH QUESTION 2:

Are consumers aware of the inferior quality of transported beer (or aged beer) relative to fresh beer and, as a consequence, prefer beer of high quality?

RESEARCH QUESTION 3:

Is the current packaging strategy adequately adapted to protect beer against unfavorable and harmful transport conditions (vibrations, shocks, temperature and light)?

RESEARCH QUESTION 4a, 4b and 4c:

- Can the use of refrigerated container transport be economically justified and desirable in order to supply foreign consumers with beer of high quality?
- Can co-shipment or horizontal collaboration in transport be implemented for brewers in an economically feasible way?
- Is it economically feasible to offer breweries the possibility to simulate beer transports and to evaluate the chemical and sensorial beer quality?

Research question 1 is divided into two sub-questions and aims to identify the relation between temperature, vibrations, shocks and beer quality. This research question will be dealt with in Part 5 Chapter 2. The second research question (Research question 2) aims at discovering the consumer awareness and preference with respect to fresh and aged or degraded beer, and is treated in Part 5 Chapter 3. Research question 3 is formulated to identify the performance of the beer packaging in protecting beer from vibrations, shocks, and temperature. The answers on this research question can be derived from Part 5 Chapter 1. Furthermore, there are three research questions that belong to research question 4 and that enable us to perform economic feasibility studies. In particular, the economic feasibility of refrigerated container transport will be verified (Research question 4a – Part 6 Chapter 1). Research question 4b (Part 6 Chapter 2) looks into the feasibility of implementing horizontal collaboration in transport. The last research question 4c examines the economic and operational feasibility of offering transport simulations in a dedicated environment to the brewers. The last formulated research question is tested in Part 6 Chapter 3.

Part 4: Research design & methodology

4.1 Research design and structure

In order to structure the study performed in the current PhD, the research design and structure was developed before commencing the research. It is crucial to visualize the flow of information and knowledge in order to come to research findings in a realistic and acceptable time frame. Therefore, the research was structured in five phases that were explored consecutively.

RESEARCH DESIGN AND STRUCTURE

Phase 1: Performing a literature research on

- The Belgian brewery sector and its trends
- Past research on the beer flavor stability problem
- Similar problems for other beverages or food products
- Vibrations, shocks and temperature levels that occur during transport
- The tools to measure vibrations and shocks during actual beer transport
- The analysis of vibrations and shocks

Phase 2: Measuring vibrations, shocks and temperatures during (beer) transport

- Transports executed by Belgian brewers (accurate temperature data, indication of the shocks)
- Vibration and shock measurements during beer transport with dedicated vibration measurement devices

Phase 3: Identifying the impact of vibrations, shocks and temperature on beer quality and stability

- Explorative experiments on vibrations and beer quality
- Explorative experiments on shocks and beer quality
- Explorative experiments on temperature and beer quality
- Experiments on vibrations, shocks in combination with temperature and beer quality
- Experiments on the beer packaging

Phase 4: Estimating the economic impact of improved beer quality by

- Identifying the preference and the willingness to pay for fresh beer over aged beer
- Estimating the effect of the drinkability (the willingness to drink multiple consumptions) of fresh beer over aged beer
- Performing economic feasibility studies on refrigerated beer transports
- Performing economic feasibility studies on horizontal collaboration in logistics

Phase 5: Developing an environment to simulate beer distribution by

- Building a model to theoretically estimate beer quality based on temperature (and possibly vibration and shock) data
- Performing economic calculations on the demand and the pricing for beer transport and storage simulations

Since all research starts with a literature review, a similar approach was followed in the current study (*Phase 1*). Desk research was executed in order to understand industry and consumer trends, past research on the beer flavor stability problem and the methods to measure and analyze vibrations and shocks. Additionally, the possibility to extrapolate the findings and methods used in current research to possible similar problems for other beverages or food products was identified. It should be noted that chemistry and physics are important domains within current research. Due to the complexity of the field, especially in chemistry with respect to beer flavor stability, only an in-depth review was executed on the most relevant topics concerning the current research. The findings of phase 1 are described in Part 5 Chapter 2.

In *Phase 2* of the research, the aim was to gather data on vibrations, shocks, and temperature during (beer) transports. There were two approaches that resulted in the acquisition of data. First, the breweries were offered equipment to measure temperature and shocks during transport. The latter approach enabled to measure transport conditions on the level of an individual bottle (due to the small size of the loggers) in diverse locations in the world. However, while the logger was able to accurately measure temperature, the vibration logger was only able to identify an indication of the exposed transient vibrations during long-haul transports due to sampling limitations and memory concerns. After transportation to its (foreign) destination, the temperature and vibration logger were retrieved and data on the transport conditions were acquired. In order to accurately measure the vibrations and shocks beer bottles are exposed to, another approach was followed. The measurement devices to perform accurate vibration measurements were gathered, and individual brewers were contacted to plan transports within Belgium on which vibrations could be measured. Since the transports were coordinated by myself, I was able to modify the experimental set-up, i.e. the type of packaging, the stacking of crates, etc. The latter methodology enabled to further research both temperature and vibrations and shocks in a real life context of beer transports. The research insights coming from this phase are described in Part 5 Chapter 1.

Phase 3 comprises experiments in order to identify the impact of vibrations, shocks, and temperature on beer quality and stability. The experimental designs of the experiments were validated by the measured data in *Phase 2.* Explorative experiments were executed on vibrations, shocks, and temperature while afterwards assessing the beer quality and stability parameters. Furthermore, experiments were performed on the interaction between temperature and vibrations and shocks, but also on the beer packaging. The findings derived from *Phase 3* are incorporated in Part 5 Chapter 2.

Subsequently, in *Phase 4* the economic impact of improved beer quality was investigated. Moreover, the ability of the consumer to distinguish between fresh and aged beer is identified, as well as the preference and willingness to pay. Additionally, the effect of aged beer on the drinkability, i.e. the willingness to drink multiple consumptions, of the beverage was assessed. The acquired data allowed us to validate the problem statement of the current study and to introduce a first framework that can benchmark and assess the feasibility investments in beer quality. Subsequently, two studies were executed, i.e. on the economic feasibility of refrigerated transports and an horizontal collaboration in logistics. The research insights coming from this phase are described in Part 5 Chapter 3 – Part 6 Chapter 1-2 of the current dissertation.

In *Phase 5* of the current research, the aim was to develop an environment that facilitates in simulating beer distribution. By simulating transport and storage of beer, beer samples can be exposed to extreme conditions, easily be extracted from the simulation and tested on the quality and flavor stability. Brewers will be supported in managerial decision-making concerning investments in beer quality. Moreover, brewers can test the beer quality and stability of the beers exported to foreign markets, new product introductions (e.g. beers or malts) and beer when changing the chemical components or made by innovative brewing processes. This research develops the pathway in building (machinery and software) and exploiting the simulation environment. Furthermore, a theoretical model was built that is able to estimate the beer quality based on temperature (and possibly vibration and shock) data. The insights of *Phase 5* are described in Part 6 Chapter 3.

4.2 Research methodology

In order to answer the research questions developed in Part 3, a well-defined research methodology is required. As indicated in section 4.1, the objective in the current research was to gather information from literature in order to design exploratory experiments. Afterwards, larger experiments are conducted to assess the impact of vibrations and shocks on the beer quality. Due to the complex nature of the experiments, it is important to validate the input parameters (temperature, vibration and shock signals) with the knowledge from literature and previous experiments. Furthermore, the multiple input and output parameters also cause different designs of experiments to be developed in order to gain as many insights as possible with a limited number of tests.

In the current study, both quantitative and qualitative research techniques were conducted. The qualitative techniques were predominantly used in the last Part of the study (*Phase 4* and *Phase 5*, section 4.1). Moreover, surveys were sent out to the brewers to gain information on the feasibility of horizontal collaboration in logistics of beer, and the interest of the brewers in simulating transport and storage. Furthermore, also logistics providers were contacted in order to study the pricing of dry and refrigerated containers and, afterwards, assess the feasibility of refrigerated transports.

While qualitative data was processed within the current study, the methods of the current dissertation mainly consist of techniques to acquire and analyze quantitative data. Moreover, multiple experiments were designed in order to measure temperature, vibrations and shocks, analyze the data (e.g. Fourier transforms and transmissibility curves), and design and execute temperature, vibration and shock experiments. However, the availability and the specifications of the devices for measuring temperature, vibrations, and shocks, and to execute experiments, determine to a large extent the research structure of this study. Therefore, an overview of the measurement devices[VIII] used in the current research is presented:

- Temperature and humidity logger (Extech RHT10)

  Breweries were provided with the logger to measure temperature and humidity on beer transports to (foreign) locations. Furthermore, the logger was used to validate the ambient temperature in temperature rooms and climate cabinets during multiple vibration and temperature experiments.
- Vibration logger (Extech VB300)

  The Extech VB300 logger was provided, in combination with the Extech temperature logger, to the breweries for measuring transport conditions on transports to (foreign) locations. The logger indicates the severance of the shocks the transported beer is exposed to. The Extech temperature and vibration loggers are small in size and low in cost, which enables to distribute the loggers to breweries and retrieve valuable data.
- Fluid temperature logger (PCsensor)

  The logger to measure the beer temperature was employed in the experiment to identify the temperature insulation properties of different packagings of beer.
- Vibration measurement setup: laptop + software (Matlab 2015a) - data acquisition board (National Instruments USB-6361) - accelerometers (Sparkfun ADXL 337) powered by an external battery linked with a transformer (Voltcraft SWD-300/12)

  The current experimental setup was built in order to perform vibration measurements on the beer bottle of coordinated beer transports. The accelerometers were mounted on the bottleneck of the beer itself, which enables to perform analysis on individual bottles as research object.

[VIII] The specifications (e.g. accuracy and precision) of the measurement devices and experimental machinery will be introduced in Part 5 (Research findings) or can be found in the papers in Annex.

- Camera (GoPro Hero 4)

  The high-speed camera was used to identify the turbulent behavior of beer in the bottleneck due to vibrations of different frequencies and accelerations. Furthermore, the camera was also utilized during vibration measurements of beer transports to visualize the road conditions and speed of driving.

Furthermore, an overview of the experimental machinery used in this research is described:

- Labo shaker (KU Leuven Campus Ghent)

  The shaker was used to perform explorative vibration experiments. Moreover, the first findings on the influence of vibrations (in combination with temperature) on beer quality resulted from the use of the shaker.
- Shaker (VUB / electro-dynamic shaker (Brüel & Kjær, type 4802T))

  The experiments concerning the vibration damping performance of the beer crates and the identification of the turbulent behavior of beer in the bottleneck due to vibrations were explored by using the latter electro-dynamic shaker.
- Shaker + climate cabinet (Bosal – Research & development unit Lummen / hydraulic shaker type MTS 258.05, max. amplitude 50 mm, max. force 50 kN)

  The company Bosal provided a pneumatic shaker that was used for two large experiments. In a first experiment, the impact of vibrations of diverse frequencies on different beers was identified. In a second experiment, the effect of vibrations in combination with temperature on the beer quality and stability was studied.
- Shock device: laptop + software (Matlab 2015a) - actuator and electromagnet

  In order to simulate shocks, a device was built that is able to automatically and repetitively pick up and drop a beer crate with the aim to impose shocks. The device was used to experimentally identify the impact of shocks on the beer quality.
- Temperature rooms and climate cabinets (KU Leuven Campus Ghent - Laboratory of Enzyme, Fermentation and Brewing Technology)

  The temperature experiments performed in current research were located in the Laboratory of Enzyme, Fermentation and Brewing Technology of the KU Leuven Campus Ghent, i.e. the experiment on the insulating performance of the beer packaging and on the effect of fluctuations in temperature on the beer quality.

The data that was generated from the different temperature and vibration measurements were analyzed by the software Matlab, Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States. With respect to the vibration data, Fourier analyses were performed and transfer curves were calculated. Shocks were individually analyzed and histograms of the peaks were calculated. Different temperature signals were gathered and patterns were identified that enabled the design of multiple experiments. Since quantitative data was generated as an output of the experiments (i.e. flavor stability parameters e.g. aldehydes, responses of taste experiments, etc.), statistical analysis of the data was important. The Mann-Whitney-U-test was frequently used in the current research in order to analyze data with limited samples, a mixed model was used in a vibration experiment (i.e. an ordinary least-square model in which the random effect is quantified) and a chi-square test was used (in the taste experiments). A further in-depth analysis of the methodology of the current research is described in the individual sections within Part 5 on research findings.

4.3 Conclusion

In the current research, it was crucial to structure and design the study according to the flow of information and results, and the availability and the specifications of equipment. Moreover, different experiments were designed and the information coming from literature and past experiments were incorporated in new experiments. Due to the large amount of input (frequency and acceleration of vibrations, temperature, etc.) and output parameters (beer quality parameters) in every experiment, the design of experiments, validation and benchmarking of the inputs and results were important. While current research mainly focuses on experiments to gather quantitative data, techniques to develop qualitative data were also incorporated.

Part 5: Research findings

Chapter 1: Temperature, vibrations, and shocks during the distribution of beer

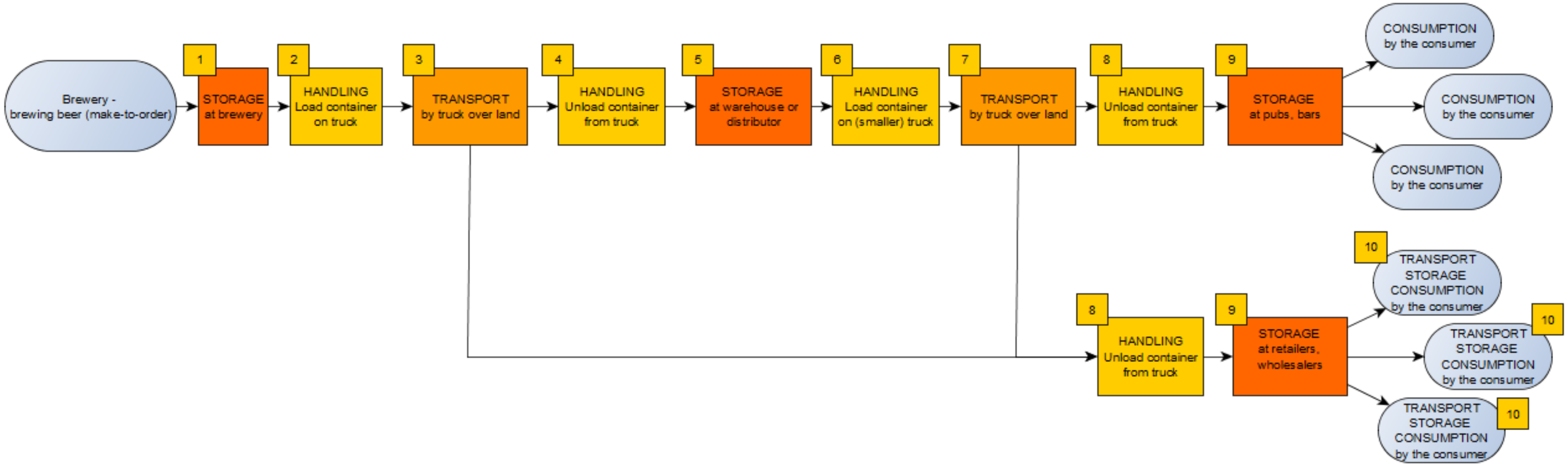
1.1 Schematic overview of the distribution of beer

In order to identify temperature, vibration and shock patterns during distribution, the logistics value chain is analyzed (presented in Figure 7a and 7b). Differences in both the transport processes and the packaging of bottled beer differentiates domestic from export beer distribution. As a consequence, bottled beer is exposed to different temperature, vibration and shock patterns (described in section 1.2, 1.3 and 1.4).

In domestic beer distribution, the fresh beer coming from the brewery is transported to central warehouses of supermarkets and other beverage warehouses. The objective of the warehouses is to receive the beer coming from the breweries, bundling the beer and further distributing it to supermarkets, small stores, pubs, and bars. The central location of the warehouses facilitates the optimization of the supply chain and to optimally fulfill the needs of its customers. Afterwards, the beer is transported to and stored at the selling point, respectively retailers and wholesalers (off-trade), pubs and restaurants (on-trade). The primary packaging of bottled beer distributed within Belgium consists of plastic crates, since the recycling logistics enables the reuse of the crates[31]. In Table 4a, the assessment of the risk to the exposure of heat, vibrations and shocks (performed by the author of this dissertation) is presented. Truck transport vibrations and shocks, as well as, the exposure to an elevated temperature (in the last phases of the supply chain) are considered important parameters that might influence the beer flavor stability with respect to domestic distribution.

Distribution of beer to foreign countries pursues exactly the same steps in the supply chain as transport within Belgium. Beer from the brewery is transported to warehouses distributing the beer to the diverse selling points. However, transport can be executed by different modes of transport depending on the foreign location. Beer is predominantly transported by truck to European countries (e.g. France, Germany, the Netherlands). Nevertheless, transport by train is occasionally executed over larger distances (e.g. Spain, Italy). When beer is exported to overseas locations the logistics provider makes use of several modes of transport, i.e. truck transport to the harbor, ship transport, possibly train transport, and again truck transport to the central warehouses. Cardboard or corrugated boxes are the industry standard for packaging beer over long-distance transports. The risk assessment in Table 4b (performed by the author of this dissertation) illustrates that the exposure to an elevated temperature in the last phases of the export logistics chain is a major parameter that might impact the beer flavor stability. In foreign countries, the climate might be warmer than in Belgium and the different phases of the logistics chain, beyond the reach of the brewery, might induce difficulties to monitor and control these external parameters.

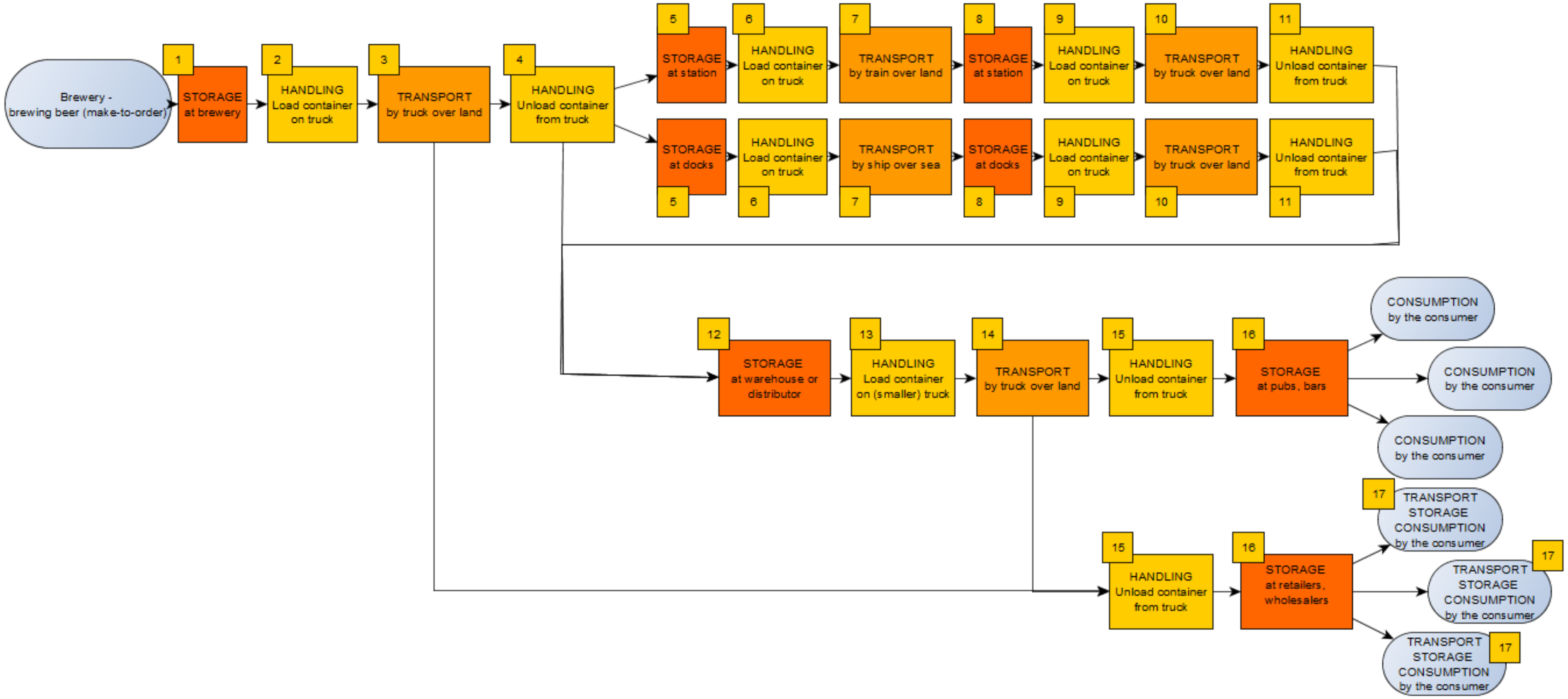
Figure 7a: Overview of the distribution of beer (the logistics value chain) – DOMESTIC DISTRIBUTION



Bottled beer is predominantly transported in plastic crates (with respect to domestic distribution).

Source: Own content

Figure 7b: Overview of the distribution of beer (the logistics value chain) – EXPORT TO FOREIGN COUNTRIES



Bottled beer is predominantly transported in corrugated boxes (with respect to export to foreign countries).

Source: Own content

Table 4a: Risk assessment, exposure to heat, vibrations and shocks – Domestic distribution

Process **DOMESTIC DISTRIBUTION**	**Exposure heat**	**Exposure vibrations**	**Exposure shocks**	**Explanation** (extensively in Part 5 Chapter 1 section 1.2-1.4)
1. Storage at brewery		/	/	Short duration of (indoor) storage (make-to-order), mild Belgian climate
2./4./6./8. Handling – (un)loading container				Beer in (open) plastic crates, peak temperatures and shocks possible
3./7. **Transport by truck**				Beer in (open) plastic crates, peak temperatures, vibrations and shocks possible
5./9. Storage at warehouses, distributors, pubs, bars, retailers, wholesalers		/	/	Storage in indoor environments for longer durations – within the reach and control of the brewery
10. Transport & storage by the consumer				Limited awareness of flavor stability problems & inappropriate storage conditions

Legend:	
	Low estimated impact of heat, vibrations or shocks on beer flavor stability due to low temperature / amplitude (of vibrations and shocks) and short time of exposure [estimation author of this study]
	Medium estimated impact of heat, vibrations or shocks on beer flavor stability due to low temperature / amplitude (of vibrations and shocks) and medium time of exposure [estimation author of this study]
	High estimated impact of heat, vibrations or shocks on beer flavor stability due to low temperature / amplitude (of vibrations and shocks) and long time of exposure [estimation author of this study]

Source: Own content

Table 4b: Risk assessment, exposure to heat, vibrations and shocks – Export to foreign countries

Process **EXPORT FOREIGN COUNTRIES**	**Exposure heat**	**Exposure vibrations**	**Exposure shocks**	**Explanation** (extensively in Part 5 Chapter 1 section 1.2-1.4)
1. Storage at brewery		/	/	Short duration of (indoor) storage (make-to-order), mild Belgian climate
2./4./6./9./11./13./15. Handling – (un)loading container				Beer in cardboard crates, thermal insulation and vibration damping
3./10./14. **Transport by truck**				Beer in cardboard crates, thermal insulation and vibration damping
7. **Transport by train, ship**				Low amplitude but long exposure of vibrations and shocks, Peak temperatures possible due to solar radiation of containers
5./8. Storage at docks, station		/	/	Peak temperatures possible due to solar radiation of containers
12./16. Storage at warehouses, distributors, pubs, retailers, wholesalers		/	/	Storage in uncooled, possibly outdoor, and warm environments might occur – Limited control by brewery
17. Transport & storage by the consumer				Limited awareness of flavor stability problems & inappropriate storage conditions

Legend:	
	Low estimated impact of heat, vibrations or shocks on beer flavor stability due to low temperature / amplitude (of vibrations and shocks) and short time of exposure [estimation author of this study]
	Medium estimated impact of heat, vibrations or shocks on beer flavor stability due to low temperature / amplitude (of vibrations and shocks) and medium time of exposure [estimation author of this study]
	High estimated impact of heat, vibrations or shocks on beer flavor stability due to low temperature / amplitude (of vibrations and shocks) and long time of exposure [estimation author of this study]

Source: Own content

1.2 Temperature during transport and storage of beer

Temperature is an important parameter with respect to beer aging. Since brewers rarely refrigerate while transporting and storing beer, the effect of temperature on the beer flavor quality is substantial[IX]. Therefore, it is interesting to identify the temperature patterns bottled beer is subjected to during distribution within Belgium and to foreign countries. Belgium has a temperate climate, however, within Belgium, beer in (open) plastic crates is subject to large variations in temperature. During international transport of beer, temperature variations are smaller caused by the insulation properties of the cardboard beer packaging. However, the temperature within a container can rise to 55°C under direct sunlight or solar radiation.

1) Methodology

In order to derive insights on the temperature patterns that occur during transport and storage of bottled beer, temperature measurements were performed during more than 15 beer transports organized by the Belgian breweries. Before the start of transport from the brewery, a temperature sensor (sensor: Extech RHT10 - resolution of 0.1°C and accuracy of 1°C) was included in the beer packaging to perform measurements. After the transport and storage at its destination, the sensor was sent back and the data was acquired. The sampling rate of the temperature measurements diverge and, therefore, are indicated next to the accompanying figures. The results of the measurements were combined with the insights coming from the literature in order to identify the temperatures beer bottles are exposed to.

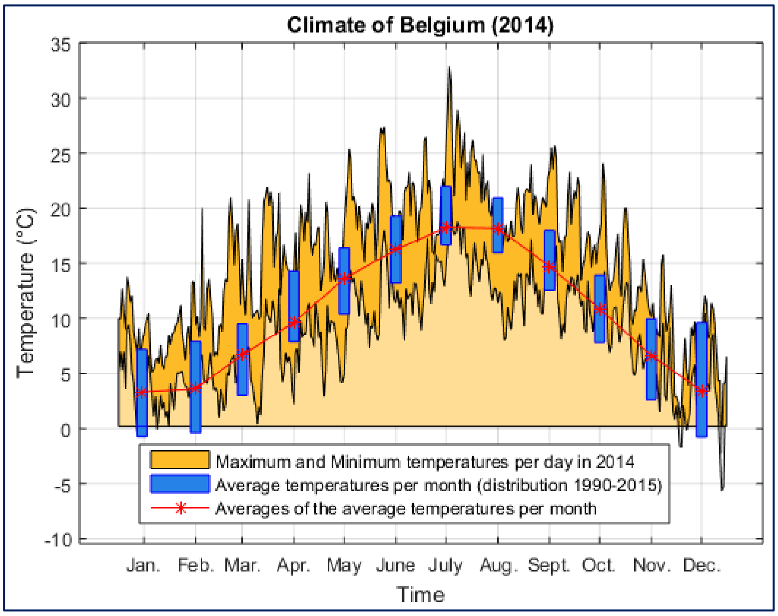
2) Results & Discussion

a. Transport and storage within Belgium

The Belgian climate can be characterized as a temperate climate with fresh and humid summers and mild and rainy winters[32]. However, different, sometimes exceptional, atmospheric conditions can be present on several consecutive days due to the Belgian location and its proximity to the Atlantic ocean. In Figure 8, an overview of the Belgian temperature climate (2014) is presented. The figure identifies the 2014 minimum and maximum temperature measured on a daily basis. Furthermore, the distribution of the average monthly temperature over the period 1990-2015 was presented for every month of the year. As can be derived from the graph, the average temperature is moderately cool with certain temperature spikes. In addition, the frequently occurring ten-degree temperature difference (between the minimum and maximum temperature) indicates the day and night temperature variations.

[IX] A survey performed by Van Cappellen & Paternoster (2016)[71] indicated that more than 80% of all brewers execute less than 20% of the transports in a refrigerated atmosphere. The survey was filled in by representatives of 24 out of 50 breweries present in Belgium.

Figure 8: Overview of the Belgian temperature climate (2014)

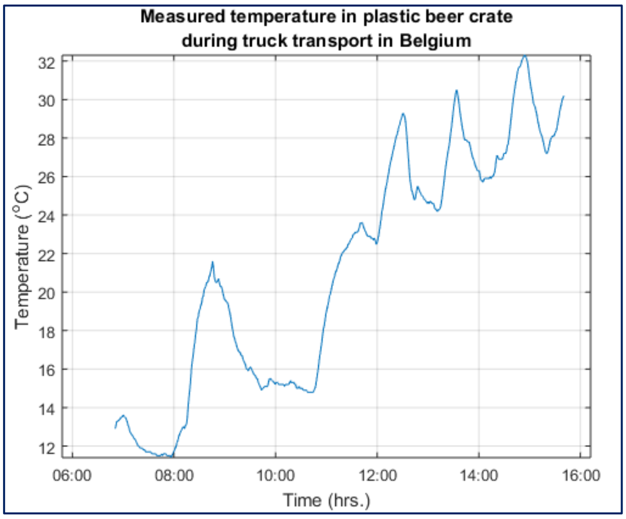


The figures illustrates the mild Belgian climate and day-night temperature variations of 10°C.

Source: Own formatting with information of KMI, 2017[32] and Deboosere, 2017[98]

Belgian beer, brewed for the domestic market is predominantly transported by trucks in kegs or in bottles in plastic crates. The trucks are equipped with plastic side covers which can be opened from the sides to facilitate a convenient delivery at its destination. Due to the seal not being air-tight, and in combination with the open plastic crates, heat can easily be transferred to the beer. In the current research, the temperature was monitored during several beer transports. Figure 9 shows the measured temperature of a beer transport that occurred during a summer day within Belgium. Temperature rises from morning to afternoon with spikes on certain time occasions. These spikes can be attributed to stops at delivery locations when the truck driver opens the side cover and, as a consequence, leads to an increase in temperature.

Figure 9: Measured temperature during beer transport by truck within Belgium – measured in plastic beer crates (Beer transport during summer)



The temperature variations (+/-8°C) during domestic transport of beer in plastic crates is illustrated.

Source: Own measurements (Extech RHT10 – 1 sample per minute)

Also during storage, beer is frequently located in an uncooled surrounding. Storage facilities may cause temperature variations to be lower. However, beer might be exposed to high temperatures since heat might be trapped in the storage environment for several days. In Belgian storage facilities, beer is predominantly stored inside and almost never outside. Every delivery of beer from the brewer is placed directly in the storage facilities and the empty bottles, mostly kept outside, are picked up by the transporter and transported back to the warehouse, brewery or bottling factory.

b. International transport and storage of beer

When beer is transported to foreign locations, the packaging primarily consists of cardboard (Figure 7b). Moreover, nonreturnable glass bottles are packaged in cardboard crates and stacked on top of each other on a pallet. The latter construction and also the packaging influences the heat that is transmitted to the beer in the bottle. Furthermore, research on inside container temperatures during long-haul maritime transport and during storage was already performed in literature[33]. Some of the key findings can be summarized as follows[33]:

- Daily temperature differences are more extreme on land than on sea
- The temperature in different containers of a ship is usually identical unless some containers are stored below and others above deck (due to solar radiation).
- Under direct sunlight or solar radiation, the temperature inside a container regularly peaks at 50°C at sea. The inside container temperature can be up to 15°C warmer than the outside temperature.
    (recorded peak container temperature on a shipment to Memphis in July: 57°C / recorded peak container temperature on land during summer: 70°C)
- Inside a container, there may be a temperature difference of 20°C between the container floor and the upper part of the container.

Furthermore, an experiment executed during the VIS/Brewers-project in 2014 identified that the difference between the outside and inside container temperature is minimal[X]. As a consequence, the cargo inside a container is exposed to a similar temperature pattern as the ambient temperature. The study also verified that the use of cardboard in packaging beer will average or smooth day and night temperature variations. The latter results were validated by the international shipments that were monitored as part of this research. In Figure 10a, the measured temperature of a transport to the USA is presented. In the transport to the USA, the measured temperature is constant, which indicates that presumably the container was stored below deck[XI]. Furthermore, the temperature measurement indicates that no substantial fluctuations of the temperature due to day and night are present. The packaging of the beer, cardboard crates, insulates and protects the beer from high ambient temperatures and, as a consequence, reduces fluctuations in temperature[34].

In Figure 10b, a temperature logging of a container stored on the quay of the dock near Antwerp harbor was performed during the summer and autumn of 2014. The logger was attached in the cardboard beer crate. The container filled with pallets of beer coming from a Belgian brewery was originally prepared for export to the United States. Due to reasons that are unknown, the container was sent to its destination after several months of storage in the Antwerp harbor. The temperature measured in the container, presented in Figure 10b, can be benchmarked with the ambient Belgian temperature in Figure 8. Figure 10b indicates that during storage in the container not all temperature fluctuations

[X] The container was not surrounded by other containers. [Experiment executed by VIS/brewers-project in 2014]
[XI] A similar pattern was observed in a temperature measurement of a beer transport to Japan [VIS/brewers-project in 2016].

were smoothed, but modest temperature variations are present that are attributed to the difference in temperature between day and night.

Figure 10a: Measured temperature (USA)
(Beer transport during summer 2016)

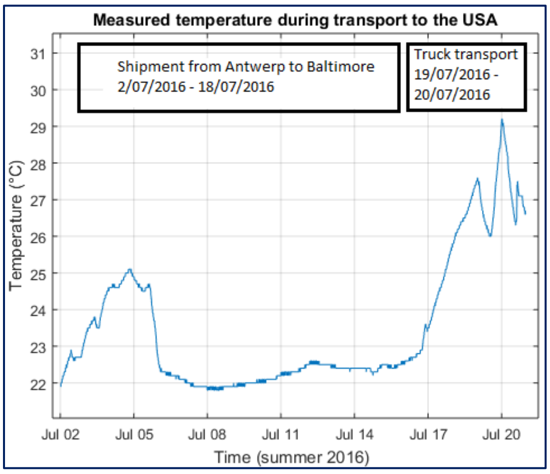
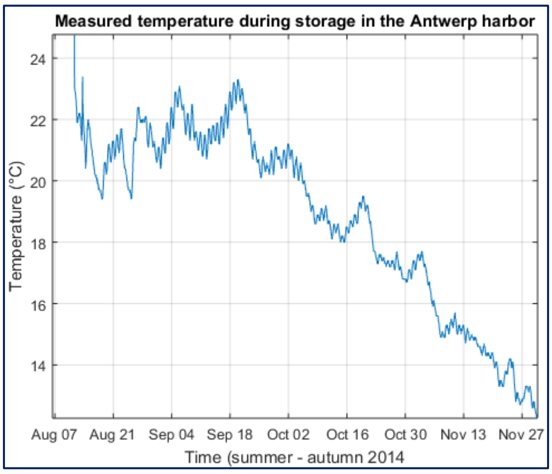


Figure 10b: Measured temperature (Belgium)
(Beer storage in container during summer/autumn 2014)



During the shipment of beer (Figure 10a), a uniform temperature (22°C) is measured. When unloading the container, a peak in temperature is observed. During storage of beer in a container in the Antwerp harbor (Figure 10b), temperature variations are limited. The limited temperature variations (Figure 10a and 10b) are attributed to the insulation properties of the cardboard beer packaging in which the logger was installed.

Source: Own measurements (Extech RHT10 – Beer transport to the USA: 1 sample per 10 minutes / Beer storage in Antwerp harbor: 1 sample per 10 minutes)

Storage conditions in foreign warehouses, supermarkets, pubs, and bars are difficult to monitor and control for the brewery. The dispersity of the locations beer is marketed to and a large amount of trade Partners causes the complexity in monitoring storage (and transport) conditions and controlling the quality of the beer. As a consequence, the brewery looks into the quality of the beer after brewing, but there are no (or limited) procedures to control quality further away in the value chain. The latter becomes problematic when the beer is stored in uncooled surroundings in regions with a warm climate. In the current study, it was impossible to retrieve information on the storage conditions in the last part of the value chain.

1.3 Vibrations and shocks during the transport of beer

Bottled beer is transported by trucks, trains, and ships. Trucks impose the most severe vibration load on cargo, followed by trains and, finally, ships. In the current section, the occurrence of vibrations and shocks during truck transport are analyzed based on the vibration measurements that were performed during beer transport. The prevalence of vertical vibrations with a frequency between 1 and 5 Hz, and time-domain RMS-accelerations up to $1 m/s^2$ were identified. Furthermore, also transient vibrations are frequently observed during truck transport. The analysis of the vibrations and shocks that are observed during train and ship transport is also presented. The vibration measurements that were performed are less reliable and, therefore, the findings in the literature are predominantly considered with respect to the current research. Trains induce a periodic vibration response with frequencies up to 20 Hz. The vibrations, cargo is exposed to during ship transport, are characterized as low-frequency wave-induced vibrations between 0.03 and 0.2 Hz, which are almost seismic in nature.

In order to understand the vibrations bottled beer is exposed to, it is essential to define the input vibrations. These input vibrations are further modified by the packaging of beer and the stacking of the crates (section 1.4).

For further information on the vibrations during truck transport we refer to the papers “Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit” and “Vibration and shock analysis of specific events during truck and train transport of food products” in Annex.

1) Methodology

a. Experimental design

In the current research, vibrations and shocks, defined as periodic or random in nature [35], respectively a single-event or transient phenomenon, were measured during truck and railway transport. The aim was to develop insights on the vibrations and shocks that occur during regular transport. Furthermore, the measurements enable us to benchmark the findings of vibration spectra in the literature. However, since the literature only provides us with averaged vibration spectra and limited evidence on the transient vibrations, the current measurements generate an additional and unique perspective on the specific vibration phenomena that occur during truck transport. The devices used to measure the vibrations included the following (illustrations and schematic overview on Figure 11a and 11b):

(1) 3-Axial Accelerometers (SparkFun Triple Axis Accelerometer Breakout - ADXL337 – SEN 12786, SparkFun Electronics, Niwot, Colorado, USA)
(2) Data acquisition board (National Instruments USB-6361 - Part Number: 782256-01, National Instruments, Austin, Texas, USA)
(3) Laptop (Dell 1708FP, Dell, Round Rock, Texas, USA with MATLAB Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States.)
(4) External battery (Solar-accu 12 V 60 Ah GNB Sonnenschein - NGSB120060HS0CA, Conrad, Oldenzaal, Netherlands)
(5) Transformer (Voltcraft SWD-300/12 Omvormer 300 W 12 V/DC 12 V/DC - 513124 - 8J, Conrad, Oldenzaal, Netherlands)
(6) Camera (GoPro Hero 4, GoPro, Paris, France)

The first five elements of the experimental set-up, listed above, are connected to each other. The accelerometers (1) had a sampling rate of 10k samples per second in order to also analyze high-frequency vibrations (and since no antialiasing filter was installed) [bandwidth: 1600 Hz (X- and Y-axis

/ noise density: 175 µG/√Hz rms) and 550 Hz (Z-axis / noise density: 300 µG/√Hz rms)][XII] and were linked by cable with the data acquisition board (2). The latter device transforms the electrical current passed along by the transducers to a digital signal that can be read by the programmable software of the computer (3). The software used in this research is Matlab 2015a. The devices were electrically charged by an external battery (4) connected with a transformer (5). The transformer converts the 12V DC into a 220V AC current. While performing measurements, a GoPro-camera (6), mounted over the shoulder of the driver, recorded the events during transport. As a consequence, these events were matched with the corresponding vibration data.

Measurements were performed during seven transports ranging over two different modes of transport, more specifically train and truck transport (information on the transports is described in Appendix 2).

Figure 11a: Schematic overview of the measurement devices
Figure 11b: GoPro (Hero 4) camera mounted on the driver seat

Figure 11a

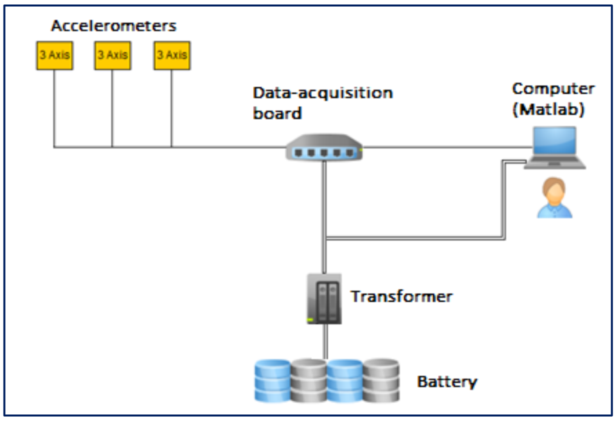


Figure 11b

Source: Own content

b. Data analysis

Complex shock motions, typically a half-sine function, are present during transport [35]. However, field data revealed that the shock responses measured during truck and railway transport are best represented by a decaying sinusoid, due to the structural dynamics of the transport vehicles. Shocks occurring during truck transport (due to potholes, metal joints, etc.) or train transport (due to railway switches, etc.) might be represented by impulses that are damped over time due to the vehicle structure (e.g. tires, suspension, etc.). The transport shocks were analyzed by calculation of the damping ratio (β). The damping ratio is a function of the logarithmic decrement (λ), the frequency of the damped oscillation (ω_d) and the damped period (T_d), which is the time between the two highest consecutive peaks. The logarithmic decrement is defined as the natural logarithm of the ratio between the acceleration amplitude of the highest peak $(x(T_1))$ and the acceleration amplitude of the second highest peak $(x(T_1 + T_d))$. Also the natural frequency of the damped oscillation (ω_n) can be calculated [36].

[XII] In the current study, no filter was applied to the signal. However, in order to prevent aliasing phenomena and to investigate the measured high-frequency vibrations, the sampling rate was fixed substantially high. The researcher is aware that the current results are predominantly informative within the bandwidth of the sensors.

$$\beta = -\frac{\lambda}{\sqrt{\lambda^2 + T_d^2\omega_d^2}} = -\frac{\lambda}{\sqrt{\lambda^2 + (2\pi)^2}}$$

with

$$\begin{cases} \lambda = \frac{1}{\mathrm{d}}\ln\left(\frac{x(T_1)}{x(T_1+T_d)}\right) & with\ 'd' = integer\ number\ of\ successive\ peaks \\ \omega_d = \frac{2\pi}{T_d} & in\ \ \frac{rad}{s} \\ T_d = (T_2 - T_1) & in\ \ sec. \\ \omega_n = \frac{\omega_d}{\sqrt{(1-\beta^2)}} & in\ \ \frac{rad}{s} \end{cases}$$

Furthermore, a shock analysis was performed to evaluate the number of the measured accelerations (time-domain) above 5 m/s^2 that occurred during transport. Moreover, the measured time-domain vibration signals were divided into intervals of 20 seconds. Afterwards, a histogram of all time-domain vibration data, measured above 5 m/s^2, was calculated. The presented histograms indicate the average number of peaks during transport and one standard deviation up (respectively down). When dividing the average number of peaks by the sampling rate, the histogram is independent of the sample rate and can be compared with other vibration measurements (with different sample rate).

Matlab R2015a was used to analyze the vibration signals and to build cumulative distribution functions (CDF) of the RMS and kurtosis values for different time-domain vibration segments. Moreover, the vibration data were partitioned in 1-second intervals, root mean square (RMS – the average vibration intensity) and kurtosis was calculated and, afterwards, the cumulative distribution function was identified. Kurtosis is a statistical concept in which the shape of the measured signal is compared to the standard normal distribution[35]. A positive kurtosis indicates a heavy-tailed distribution and a negative kurtosis a light-tailed distribution. Furthermore, average power spectral density (PSD) plots were also calculated by performing multiple fast Fourier transforms and taking the linear average (bandwidth/frequency resolution 0.2 Hz). The technique can be presented by the formula:

$$Average(PSD)_f = \frac{1}{n}\sum_{i=1}^{n} PSD_{f,i}$$

with

$f = given\ frequency\ of\ the\ selected\ event$

$n = the\ amount\ of\ selected\ events$

2) Results & Discussion

a. Occurrence of vibrations and shocks during truck transport

In Figures 12a-c, an overview of the results of the vibration measurements during truck transport is presented. The cumulative distribution function of the time-domain RMS accelerations during truck transport are presented in Figure 12a. The accelerometers that performed the measurements were mounted on top of a wooden pallet on which beer crates were stacked. Vibration measurements were executed on trucks with air-ride suspension and trucks with leaf spring suspension. In the western world, trucks with an air-ride suspension are the industry standard. However, the measurements on a truck with a leaf spring suspension were also included in the test. The figure indicates the higher amplitude of vertical over lateral and longitudinal vibrations. Furthermore, the vertical RMS accelerations of air-ride trucks are identified between 0.5 and 1 m/s² while for leaf spring trucks higher vertical RMS accelerations between 2 and 4 m/s² are measured. The power density plot of the vertical vibrations in Figure 12b indicate that vibrations between 1 and 5 Hz are the highest in amplitude. Truck vibrations between 1-5 Hz are typically attributed to the suspension (and road roughness), 15-20 Hz to the tires and 40-55 Hz to the structure floor[37].

Figure 12a: Empirical cumulative distribution function of time-domain RMS-accelerations of pallet measurements during truck transport (air-ride and leaf spring suspension)
Figure 12b: Power density plot of vertical vibrations, Pallet measurements during truck transport (air-ride spring suspension)
Figure 12c: Histogram of time-domain vibrations (> 5m/s²), Pallet measurements (Vertical vibrations)

Figure 12a

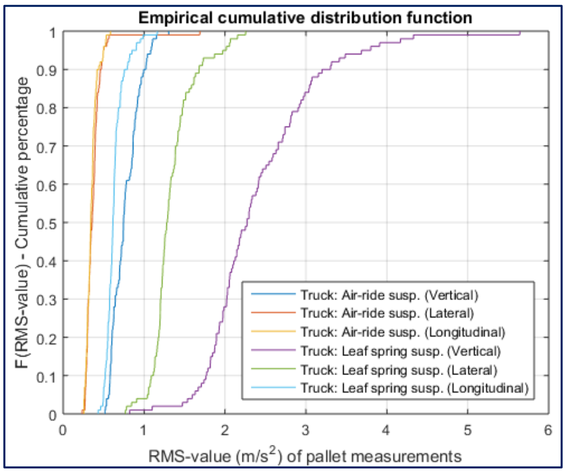


Figure 12b

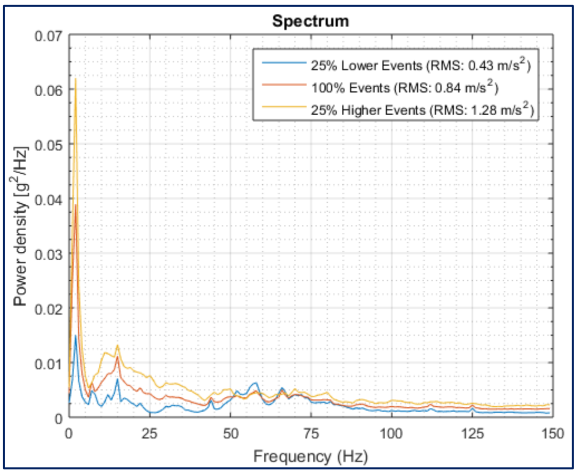


Figure 12c

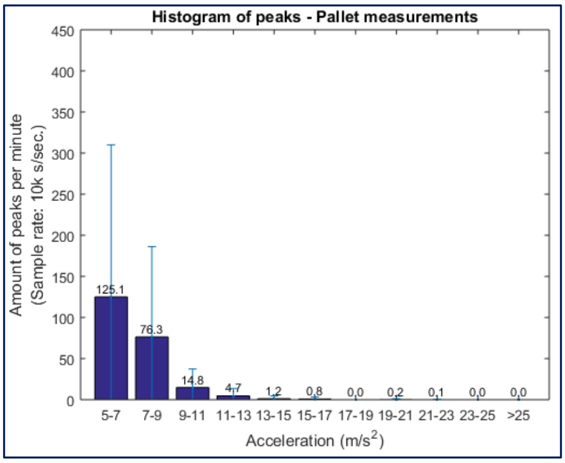


Figure 12a: The RMS (0-peak) segments were calculated from one second intervals of time-domain vibrations.
Figure 12b: Bandwidth / frequency resolution 1 Hz. The logarithmic plots of the spectrum is presented in Annex.
Figure 12c: Time-domain vibrations were split into intervals of 20 seconds and a histogram of the vibration samples higher than 5m/s² is presented.
Source: Own measurements

In Figure 12c, a histogram of the vertical time-domain vibrations higher than 5m/s^2 measured on a wooden pallet during truck transport (air-ride spring) is presented. This histogram makes a strong case for the number, the peak amplitudes and the frequency of occurrence of the transient vibrations during truck transport. While the accelerations between 5 and 7 m/s^2 are primarily attributed to the damping effect of the transient vibrations, higher accelerations contribute to the peaks of the transient vibrations. Furthermore, during truck transport the frequency of the damped oscillation is on average 153 Hz ± 148 Hz. The damping ratio is on average equal to the dimensionless number 0.08 ± 0.02, which means that the amplitude of the second peak is estimated to be 60 ± 8% of the amplitude of the first peak.

Further information on the RMS plots and the histograms of time-domain vibrations (> 5m/s^2) measured when traveling over different road typologies is presented in the paper entitled "Vibration and shock analysis of specific events during truck and train transport of food products" in Annex. Also, the spectrum of vertical, longitudinal and lateral vibrations (loglog plots) are presented in this paper.

b. Occurrence of vibrations and shocks during train and ship transport

While vibrations and shocks during truck transport were accurately identified, measurements during train and ship transport were more difficult to execute. Moreover, due to the sealing of transport containers and safety issues, we were not able to perform measurements inside a transport container. However, measurements during train transport were performed on the bogie of the train. While the measured spectrum and RMS results are not representative for the vibrations on cargo inside the train containers, the events that contribute to transient vibrations are identified. For instance, transient vibrations are observed when traveling over train switches, and when the train accelerates, brakes or stops. The movement of the railcars and the tension between the couplers are important contributors to the transient vibrations that occur during train transport. During ship transport, vibration measurements were performed on a sailing vessel in order to have an indication of the vibration magnitudes and frequencies that occur during ship transport. The results indicate the prevalence of low-frequency vibrations of 0.1-0.2 Hz (and time-domain accelerations ≤ 1 m/s^2) that is attributed to the wave-induced vibrations (almost seismic in nature, difficult for accelerometers to measure) [XIII].

Since the findings of the vibration measurements during train and ship were limited, the literature and ISO-norms are a more reliable source. Ostrem & Godshall (1979)[38] and Böröcz & Singh (2016)[39] investigated the vibration impacts that occur during transport of different transport modes. The study identified trucks to impose the severest vibration loads on cargo, followed by the railcar and, finally, ships and airplanes. Vibrations on trains diverge from trucks due to the periodic inputs associated with the rail system. Furthermore, the research indicates that the driving frequencies of train transport can be identified below 20 Hz. With respect to the vibration response on ships, the literature validates the occurrence of wave-induced vibrations with the frequency between 0.03 and 0.2 Hz. Additionally, Ostrem & Godshall (1979)[38] indicates the presence of vibrations at 1.5 Hz, respectively in the range of 5 to 20 Hz due to whipping, respectively slamming. Slow rolling and pitching motions, and vibrations (of higher frequency) related to the engine can also be observed during ship transport.

[XIII] Research was performed by Arnout de Munck (2016-2018) in the context of a bachelor and master dissertation.

1.4 The performance of the beer packaging: vibration damping and thermal insulation

The beer packaging should protect beer from an elevated ambient temperature, and from vibrations that could alter the sensorial properties of the beer or that could cause mechanical damage harming the integrity of the beer bottles. Therefore, a temperature experiment was developed in order to test the insulation performance of three beer packagings in section 1.4.a. Best practice is to use cardboard, an insulator material, and plastic foil to reduce air movement. Furthermore, vibrations were measured during truck transport on beer bottles stacked in corrugated boxes and plastic crates (section 1.4.b). The results indicate the damping performance of corrugated boxes and vibration amplification of plastic crates.

Further information on the performance of the beer packaging with respect to vibrations damping and thermal insulation can be derived from the papers entitled “The performance of beer packaging: vibration isolation and thermal insulation” and “Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit” in Annex.

1.4.a Thermal insulation

1) Methodology

During long-haul transport, temperature typically remains constant, but when the containers are unloaded the temperature can significantly rise. Therefore, an explorative experiment was designed in order to identify the thermal insulation performance of three types of beer packagings. Moreover, the beer temperature (by using the sensor of the brand ‘PCsensor’) was measured when transferring the package from a cold environment of 5°C into a warmer environment of 30°C. The beer packaging that has the best thermal insulation properties, performs best in protecting the beer from heating up. The following three different types of beer packagings A, B, and C were tested:

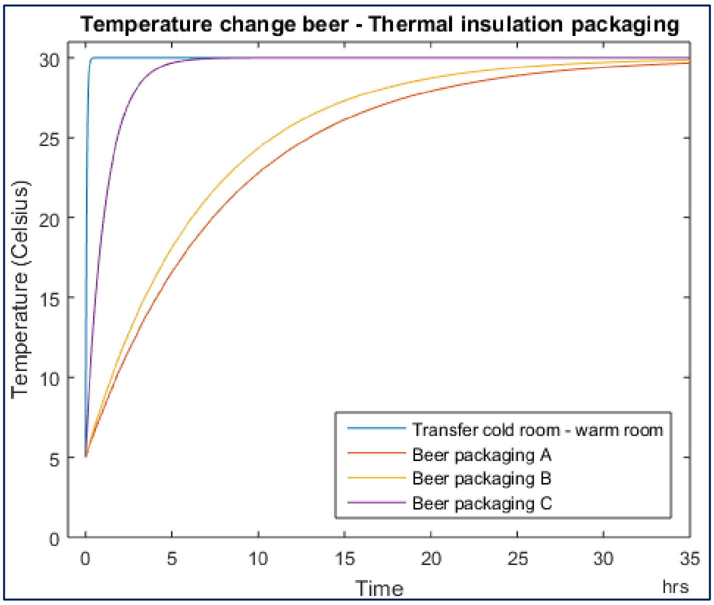
- Beer packaging A: 24 bottles of 33cl in cardboard crate – Longneck (green) – mass bottle: 553 g – mass: 14.76 kg
- Beer packaging B: 4 packages with 6 bottles of 25cl in cardboard crate with plastic foil per 6 bottles – Vichy (brown) – mass bottle: 494 g – mass: 11.86 kg
- Beer packaging C: 24 bottles of 25cl plastic crate – Vichy (brown) – mass bottle: 494 g – mass: 16.96 kg

Packagings A and B are frequently used in international transports and packaging C is mainly used in domestic transports. Due to the scope of the project and the stakeholders involved, the three beer packages, including bottle types, were selected for being most commonly used by breweries. Although packagings A, B and C are a packaging standard in industry, breweries might add minor changes to their packaging by altering the basic components (cardboard, plastic foil and hard plastic).

2) Results & Discussion

In Figure 13, the results (30°C) of the experimental study are presented. The figure indicates that the process of increasing beer temperature is exponential. As a consequence, the first three hours, respectively 15 hours, of exposure to 30°C with respect to beer package C, respectively beer package A and B, the beer temperature approaches 25°C before asymptotically reaching 30°C. Regarding thermal insulation, beer packagings A and B perform relatively similar. Furthermore, beers from packagings A and B have significantly better thermal insulation properties than beers of packaging C. The use of cardboard, which is an adequate insulator material, combined with plastic tape or foil to reduce the air movement, is the best packaging (of the three used in the study) in terms of thermal insulation.

Figure 13: Results beer temperature (30°C) (Thermal insulation of the beer packaging; beer temperature reaching the ambient temperature of 30°C)



Source: Own measurements

Further information on this temperature experiment and on the results of an experiment using an ambient temperature of 40°C (which were similar to the results of the experiment using an ambient temperature of 30°C) are presented in the paper "The performance of beer packaging: vibration isolation and thermal insulation" in Annex.

1.4.b Vibrations and shocks in relation to the beer packaging

In an initial explorative experiment, the three beer packagings (presented in Part 5 Chapter 1 section 1.4.a) were exposed to vibrations by an electrodynamic shaker in a lab environment. The aim of the experiment was to identify the vibration damping properties of the beer packaging. The study contributes to insights on the behavior of beer bottles in its packaging as a response of the exposed vibrations. From the study, it can be recommended to strap individual bottles in order to prevent further vibration excitation (e.g. such as for bottles in plastic crates, bottles in corrugated boxes without separation panels). Furthermore, the research following the latter experiment indicated that the vibration damping performance of the beer packaging must always be considered together with the stacking of the crates[40]. As a consequence, the explorative experiment is less relevant compared to the actual transport measurements. Additional information on the experiment can be found in the paper "The performance of beer packaging: vibration isolation and thermal insulation" in Annex.

In order to further identify the vibrations bottled beer is exposed to, vibration measurements were performed on real beer transports.

1) Methodology

The methodology of the current section complements the described methodology of Part 5 Chapter 1 section 1.3.

During the four truck transports that were attended, vibrations were measured with accelerometers on the pallet and on the beer bottleneck of bottles packed in plastic crates and corrugated boxes. A stacking of the crates was constructed, as is performed during regular transport. In Figures 14a-c the experimental setups are presented.

Figure 14a: Accelerometer mounted on the beer bottleneck
Figure 14b: Plastic crates stacked on top of each other during truck transport
Figure 14c: Corrugated boxes stacked on top of each other during truck transport

Figure 14a

Figure 14b

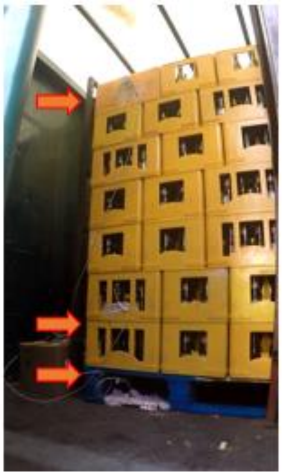


Figure 14c

Source: Own content

Additionally, the acceleration transmissibility function between different stacked packagings was calculated. The acceleration transmissibility function represents the vibration attenuation and vibration amplification between two measured vibration signals in the frequency domain[35]. The function (g^2/g^2) is calculated by dividing the Fourier transform of the accelerations measured by the accelerometer on the beer bottleneck (in the stacked crates) by the Fourier transform of the accelerations measured by the accelerometer mounted on the pallet.

2) Results & Discussion

Since vibrations were measured on the pallet and on the beer bottlenecks inside the crates that were stacked on top of each other, the transmissibility curve was determined. The transmissibility curve larger than one (the red line) indicates an amplification of the vibrations and smaller than one an attenuation of the vibrations. The transmissibility curve of the bottles in the plastic crates (Figure 15a) diverges from the transmissibility curve of the bottles in the corrugated boxes (Figure 15b). While the same peak in the transmissibility curve between 10 and 25 Hz is observed due to the stacking of crates, corrugated boxes tend to damp vibrations higher than 50 Hz (depending on the height of stacking) and plastic crates amplify the vibrations. In the plastic crates, beer bottles have free space to move and, as a consequence, are susceptible to increased high-frequency vibrations (75-150 Hz) that are up to nine times the amplitude of the vibrations measured on the pallet. In cardboard crates, bottles are separated with cardboard panels, which avoid bottles bumping into each other and absorb the energy of the vibrations.

Figure 15a: Transmissibility curve, plastic crates stacked on top of each other (Vertical vibr.)
Figure 15b: Transmissibility curve, corrugated boxes stacked on top of each other (Vertical vibr.)
Figure 15c: Power density plot of plastic crates during truck transport (Vertical vibr.)
Figure 15d: Power density plot of corrugated boxes during truck transport (Vertical vibr.)
Figure 15e: Histogram of time-domain vibrations (> 5m/s²), (high) plastic crate (Vertical vibr.)
Figure 15f: Histogram of time-domain vibrations (> 5m/s²), (high) corrugated box (Vertical vibr.)

Figure 15a

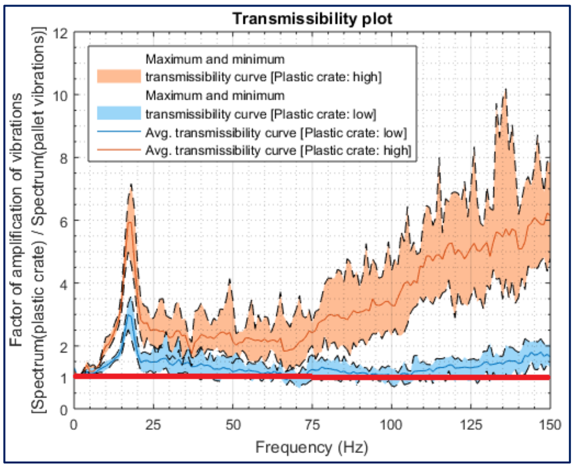


Figure 15b

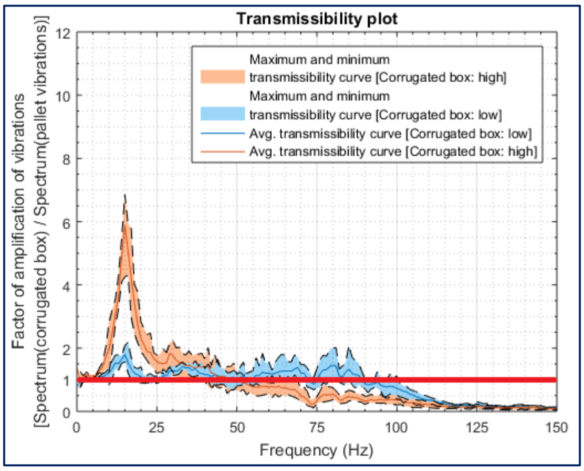


Figure 15c

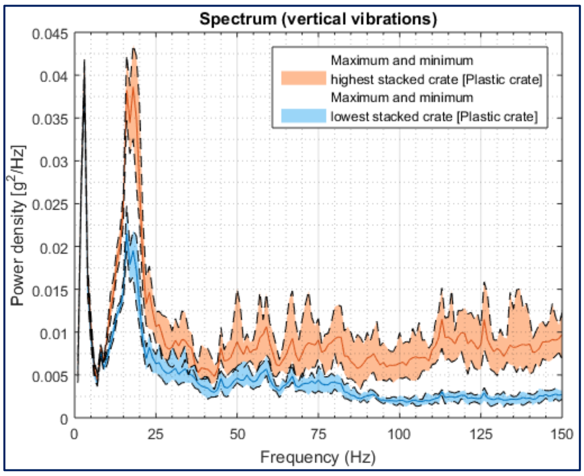


Figure 15d

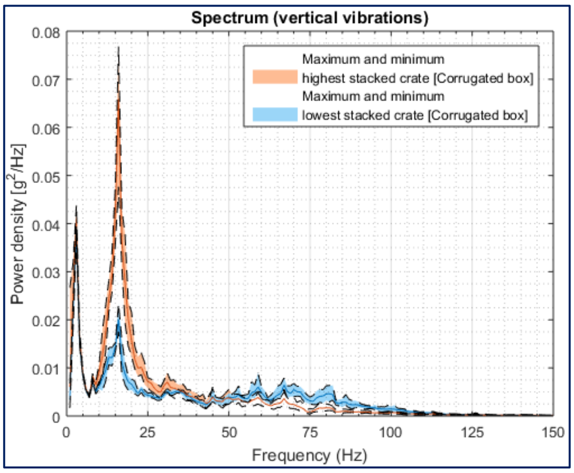


Figure 15e

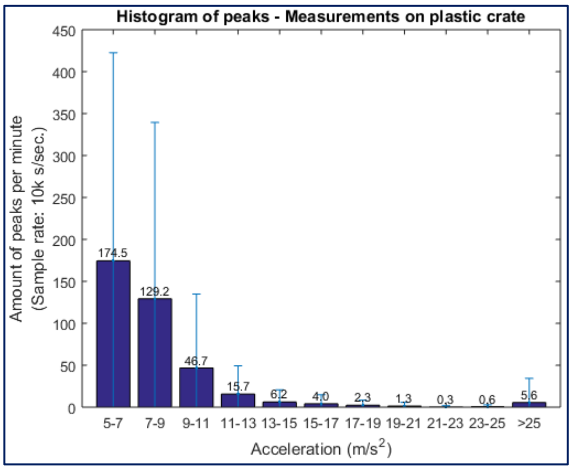
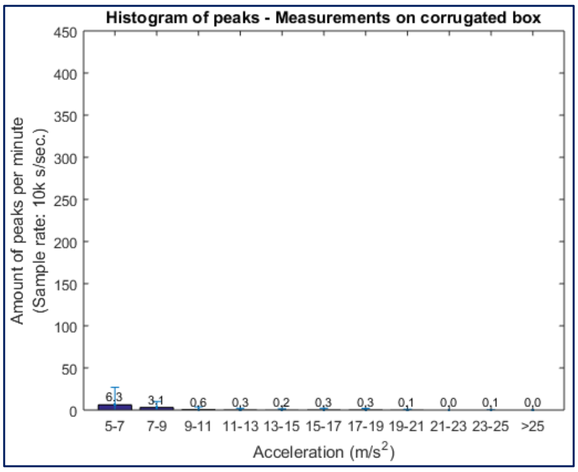


Figure 15f



The transmissibility plots (Fig. 15a-d) illustrate the vibration frequencies that are amplified and attenuated or damped. The packaging (cardboard and plastic crates) and stacking induce a different vibration pattern (Fig. 15a-d) as well as the number of peaks related to the occurrence of transient vibrations (Fig. 15e and 15f). Source: Own measurements

Since the transmissibility curve of the stacking of beer crates is known, the resulting spectrum of the vibrations beer bottles are exposed to can be estimated from all possible input signals. In Figures 15c and 15d, the spectrum of the vertical vibrations on beer bottles in plastic crates and corrugated boxes during truck transport is depicted (scale of the Y-axis is different on Figure 15c and Figure 15d). Moreover, the averaged spectrum of vibrations measured on the pallet (Figure 12b) is used as an input signal. From the figures can be derived that a first peak in the spectrum between 1 and 5 Hz is observed for both beer packagings, which is attributed to the suspension and road roughness. The second peak between 10 and 20 Hz due to the stacking of the crates is higher for the highest stacked crates compared with the lowest stacked crates. This peak is higher for the corrugated boxes since the peak of the transmissibility curve at 16 Hz coincides with the peak in the spectrum of the pallet measurements (attributed to the tires)[XIV]. The figures also show that vibrations with the frequency higher than 25 Hz are attenuated by the corrugated boxes and amplified by the plastic crates.

In Figure 15e and f, the histogram of time-domain vibrations (> 5m/s^2) measured on the beer bottles in the highest plastic crate and corrugated box is presented. The figures should be compared with the vibrations measured on the wooden pallet (Figure 12c). The impacts bottles in corrugated boxes are exposed to are damped and, therefore, the occurrence of the time-domain vibrations (> 5m/s^2) are significantly reduced. In plastic crates, bottles have free space to move and, as a consequence, the number of peaks increases compared to the pallet measurements. The frequency of the damped oscillation with respect to beer in corrugated boxes, respectively plastic crates, is on average 115 Hz ± 60 Hz (lower than transient vibrations measured on the wooden pallet), respectively 321 Hz ± 287 Hz (higher than transient vibrations measured on the wooden pallet). The damping ratio with respect to beer in corrugated boxes, respectively plastic crates, is on average equal to the dimensionless number 0.076 ± 0.023 (slightly lower than transient vibrations measured on the wooden pallet), respectively 0.082 ± 0.031 (equal to transient vibrations measured on the wooden pallet). The damping ratio of bottled beer in corrugated boxes, respectively plastic crates, indicates that the amplitude of the second peak is estimated to be 62 ± 8%, respectively 60 ± 11%, of the amplitude of the first peak.

Further information on the vibration measurements on beer bottles during truck transport are presented in paper "Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit" in Annex.

[XIV] The peak of the transmissibility curve of stacked plastic crates arises at 19 Hz.

Chapter 2: Impact of temperature, vibrations, and shocks on the beer quality

2.1 Temperature fluctuations and beer quality

Due to the abundant literature on the influence of temperature on beer flavor instability, an experiment was designed to identify an uninvestigated phenomenon of temperature: the influence of variations in temperature on the beer quality. When beer is packaged in plastic crates, the bottles are subjected to temperature variations during transport and possibly also during storage. For packaged beer in corrugated boxes, on the contrary, temperature fluctuations are inhibited.

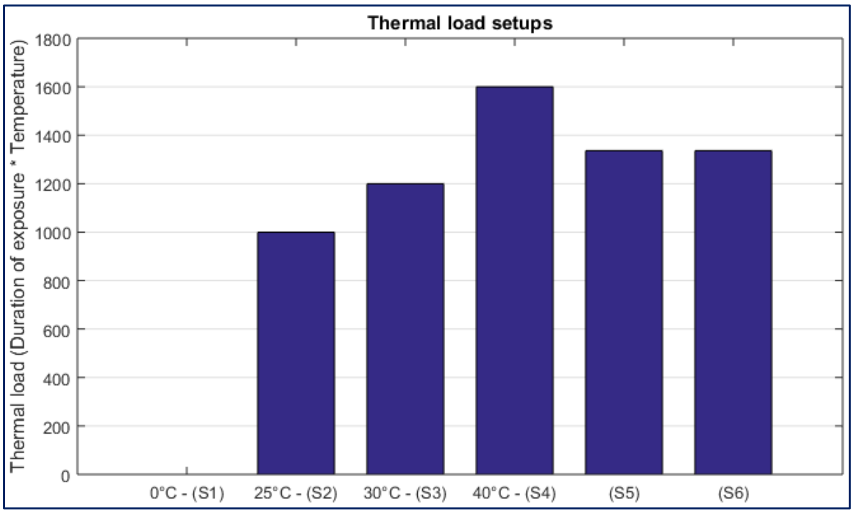
Since every beer aging reaction starts at a different reaction activation energy, variations in temperature might induce an increased formation or degradation of flavor-associated metabolites[3]. Furthermore, the author of this study noticed that during the VIS/brewers-project a brewery exported beer in a reefer container in which the temperature was kept constant at 22°C with the aim to exclude temperature variations. Therefore, an experiment was designed to chemically profile and compare beer that was subjected to temperature variations and beer exposed to a constant temperature. A first explorative experiment (with only one type of beer) identified that the possible negative impact of temperature variations between 25°C and 40°C on the beer flavor quality is not observed. Therefore, there is evidence that transport simulations may be performed with a constant temperature without the need to replicate the correct temperature signal.

1) Methodology

a. Experimental design

In order to identify the influence of variations in temperature on the beer quality, an experiment over 40 days was executed that involved exposing beer samples to different temperature patterns. In total, there were 6 setups that were incorporated in the study. In experimental setups 1-4, beer is exposed to a constant temperature of 0°C, 25°C, 30°C, and 40°C. Beer samples of experimental setups 1 (0°C) and 3 (30°C) were stored in a temperature chamber (still air), while beer samples of setup 2 were exposed to room temperature (25°C) and beer samples of setup 4 (40°C) were stored in a climate cabinet (forced air). Experimental setup 5 was designed to expose the beer samples to temperature variations of 15°C (between 40°C and 25°C), which is comparable to the difference in temperature between day and night. The samples were stored in a climate cabinet (forced air) and a temperature cycle was imposed; first, the samples are heated for 12 hours at 40°C and afterwards the climate cabinet is turned off for 24 hours, which enables the samples to cool down until 25°C. Due to the insulation properties of the climate cabinet, the cooling process from 40°C to 25°C took 12 hours and 30 minutes while the heating process only took 1 hour and 40 minutes. In setup 6, it was ensured that exactly the same thermal load was transmitted to the beer samples as in setup 5 (Figure 16). As a consequence, the integral of the temperature pattern of setup 5 was calculated and resulted in the decision to expose the beer samples for 56% of the time to 40°C and 44% of the time to 25°C. In total, the beer samples were stored in a climate cabinet of 40°C (forced air) for 22 days and 10 hours and, afterwards, stored at room temperature of 25°C for 17 days and 4 hours. The thermal load of the setups in the temperature experiment is depicted in Figure 16.

Figure 16: Thermal load – setups in the temperature experiment



Legend: Setup 1: constant 0°C for 40 days // Setup 2: constant 25°C for 40 days // Setup 3: constant 30°C for 40 days // Setup 4: constant 40°C for 40 days // Setup 5: variable temperature 25°C-40°C for 40 days // Setup 6: constant 40°C followed by constant 25°C (for 40 days)

The thermal load of the different setups is displayed. The equal thermal load of setup 5 and 6 is important in the current experimental context.

Source: Own measurements

Due to the explorative nature of the study and practical limitations, the experiment was limited to including only one type of beer, a domestic lager beer. The samples were acquired in the supermarket and made sure they were bottled during winter time. The beer samples were chemically analyzed on color (absorption 430nm) and the concentration of iso-α-acids and aldehydes. In total, 5 samples were analyzed per setup and chemically tested.

b. Data analysis

The data of current experiment was analyzed by the Independent samples Mann-Whitney U-test[XV]. The aim of the nonparametric statistics test is to compare medians between two independent groups. The hypothesis that samples come from the same population is tested, however, without invoking the assumption of normality of the test samples. The latter is required since in the current experiment only a limited number of samples is present (5 samples per setup and per chemical test). SPSS Statistics was used to perform the statistical data analysis.

2) Results & Discussion

In Figures 17a-d, the results of the color measurements, the sum of bitterness compounds and aldehydes are presented. From the figures, it can be derived that the relation between temperature and beer quality is exponential (setup 1-4). If the samples are exposed to an increased temperature the EBC value, which indicates color, as well as the concentration of aldehydes will exponentially increase. The concentration of bitterness compounds decreases when imposing an elevated temperature to the beer samples. Moreover, after performing the Mann-Whitney U-test, the results indicate that there is no significant difference between setup 5 and 6 for color, bitterness compounds,

[XV] The researcher is aware that the data samples should be acquired independently when using the Mann-Whitney U-test. The latter was not the case in the current experimental setup and, therefore, the results should be interpreted with caution.

and aldehydes[XVI]. On the contrary, the beer samples of setup 5 that have been exposed to a varying temperature pattern between 25°C and 40°C tend to be slightly less aged than the beer samples of setup 6. The latter might be explained, but cannot be proven, by the thermal conductivity of beer. When the climate cabinet heats up from 25°C to 40°C the beer will reach the temperature of 40°C in delay. As a consequence, the beer bottles of setup 5 and 6 have been exposed to the same heat, but the beer itself has not.

Figure 17a: Results color – Temperature fluctuations and beer quality
Figure 17b: Results aldehydes – Temperature fluctuations and beer quality
Figure 17c: Results sum of iso-α-acids – Temperature fluctuations and beer quality
Figure 17d: Results bitterness T/C ratio – Temperature fluctuations and beer quality

Figure 17a

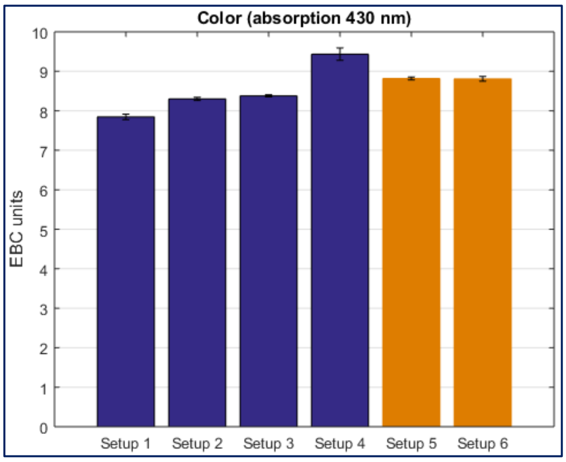


Figure 17b

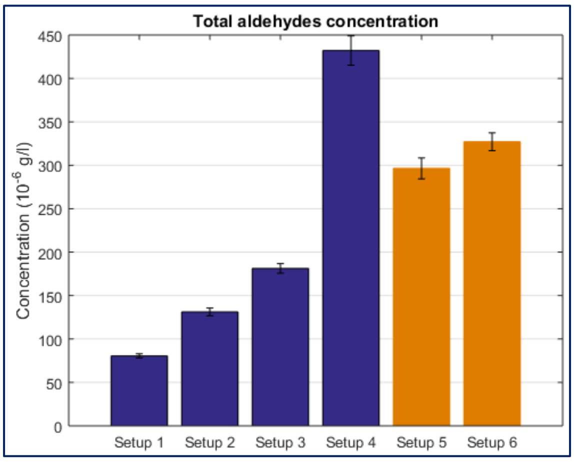


Figure 17c

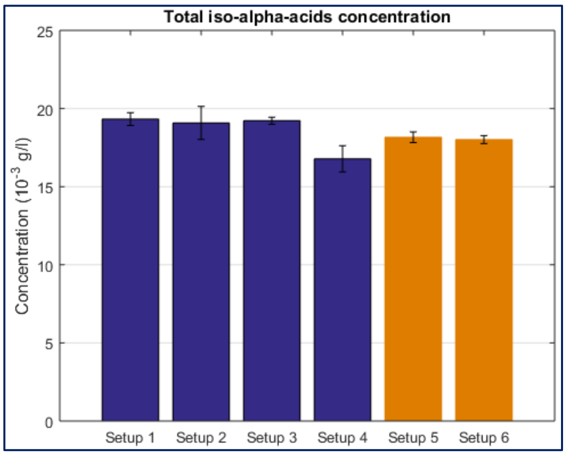
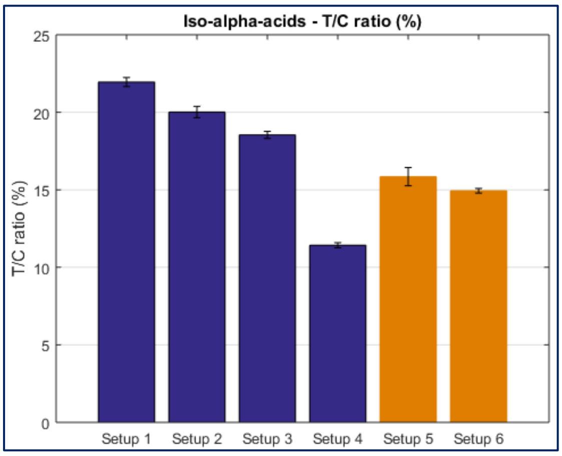


Figure 17d



Legend: Setup 1: constant 0°C for 40 days // Setup 2: constant 25°C for 40 days // Setup 3: constant 30°C for 40 days // Setup 4: constant 40°C for 40 days // Setup 5: variable temperature 25°C-40°C for 40 days // Setup 6: constant 40°C followed by constant 25°C (for 40 days)

The figures illustrate that temperature variations (setup 5) do no contribute to an additional decrease in beer flavor quality. Nevertheless, the exposure to an elevated temperature should be minimized.

Source: Own measurements

[XVI] The data samples of setup 5 and 6 are compared since an equal time of exposure at 25°C and 40°C was imposed. The comparison between samples of setup 5 and 6 is particularly relevant since beer ages differently at every given temperature (e.g. exposure to a temperature of 30°C could result in an increase of one particular aldehyde while exposure to a temperature of 31°C could result in an increase of another particular aldehyde).

Temperature variations between 25°C and 40°C were tested and, therefore, conclusions and recommendations are limited with respect to the tested temperature interval. However, temperature variations lower than 25°C can also occur during beer transport and storage but are believed to be less harmful to beer quality. The lower the temperature beer is exposed to, the less beer aging reactions occur[3]. As a consequence, the boundaries of the temperature interval used in the current experiment (25°C-40°C) are more extreme and, therefore, more relevant than an experiment with lower temperature boundaries (< 25°C).

In the current experiment, glass beer bottles without packaging were subjected to an elevated temperature. One of the critical reflections of the current experiment is to what extent packaged beer is subjected to temperature variations. In Part 5 Chapter 1 section 1.2, it was illustrated that outside temperature variations of 15°C are extreme but do frequently occur in Belgium. However, beer is packaged in corrugated boxes or plastic crates, stacked next to and upon each other, and transported in a container or kept in a storage facility. From a temperature experiment, prior to this study, executed in the course of the VIS/Brewers-project in 2014 was found that when beer is packaged in corrugated boxes (primarily for export), stacked on top of each other on to a pallet, then all temperature variations are reduced to a constant temperature that is the average of the two temperature extrema (day and night temperature). The measured temperature was identical for crates stacked on the sides of the pallet as well as in the middle of the pallet (specifically for corrugated boxes). Furthermore, the study revealed that extra isolation will not improve the temperature conditions beer is exposed to. When beer is transported in plastic crates (mainly used for domestic consumption), temperature conditions will fluctuate more since the packaging is open to the ambient air (Figure 13 in Part 5 Chapter 1 section 1.4.a). As a consequence, beer is only subjected to temperature variations when packaged in plastic crates during transport (and possibly storage), which almost exclusively occurs within the Belgian distribution setting.

3) Conclusions & Recommendations

Based on the current findings and taking into consideration that the experiment was performed on one type of beer, a temperature variation between 25°C and 40°C does not have an increased effect on beer quality of the tested beer samples. However, limiting the exposure of beer to an elevated temperature in order to delay flavor aging reactions remains essential. Furthermore, the results of the study are beneficial when simulating transport and storage since temperature can be approximated by a constant temperature instead of imposing the identical (fluctuating) temperature pattern.

Only beer in plastic crates, which are primarily used in a Belgian setting, will experience temperature variations. For beer that is packaged in corrugated boxes, on the contrary, temperature variations will be minimal. Since flavor quality degradation of beer is limited (although is present) within Belgium and is more prominent when exported to foreign markets, the practical applications of the study are narrow. Therefore, the author of this research decided to not further investigate the influence of temperature fluctuations on grounds of allocation of time and resources.

2.2 Vibrations and beer quality

2.2.a Turbulence in the beer bottleneck caused by vibrations

The chemical reactions resulting in aging compounds are mostly initiated by oxidative reactions. Therefore, in the beginning of the current research, there was a focus on the relation between vibrations, oxygen (measured under the bottle cap and dissolved in the beer) and beer flavor instability. Moreover, the research question was posed whether the turbulent movement in beer due to vibrations might induce an additional uptake of oxygen in beer. Therefore, in the current experiment, beer was subjected to different vibration patterns in order to experimentally identify the turbulent movement of beer in the bottleneck (surface fluid flow). In the current section 2.2.a, a stability chart depicting the turbulent phases of beer is presented in which five distinct areas are identified (dependent on the bottle type). The results were adopted in the design of the experiments of Part 5 Chapter 2 section 2.2.b and c.

1) Introduction

In 1831, Michael Faraday discovered that a fluid in a container subjected to a vertical vibration will develop a pattern of surface waves[41,42]. The Faraday waves, as the phenomenon is called, can form complex patterns made up of three primary shapes: stripes, squares, and hexagons. In the years after, extensive experimental and analytical research has been done regarding this topic. Furthermore, also the appearance of turbulent fluid flows has been explored to a great extent. A turbulent flow refers to an unpredictable or chaotic flow, which in other circumstances would be ordered or 'laminar'. Markatos (1986)[43] defined a turbulent fluid motion as: ''three-dimensional, rotational, intermittent, highly disordered, diffusive and dissipative''.

In the current explorative experiment, the fluid flow at the surface of beer when being exposed to vertically oscillating vibrations is analyzed. It may be relevant to determine whether beer behaves in a turbulent manner, or Faraday waves emerge or whether no visible effects emerge on the surface when being exposed to vibrations of different frequencies and accelerations. Moreover, since it is inevitable that oxygen is built up in the upper part of the beer bottleneck, the appearance of eddying or turbulent motions can mix the beer with the oxygen. As a result, an extra oxygen uptake could be present and might facilitate an acceleration of the beer aging process. If vibrations have an impact on the flavor quality of beer, one could assume that the quality degradation of beer is most distinct when the fluid flow of beer behaves in a turbulent way.

The different phases of fluid flow are known to be dependent upon the viscosity of the fluid, depth of the fluid and geometrical shape of the container[44]. Also, the temperature could influence the threshold between the phases. Finally, frequency and acceleration of the forcing vibrations are crucial parameters when mapping out the phases. From a mathematical point of view fluid flow could be modeled using the Navier-Stokes equations. However, the complicated nature of the equations (e.g. nonlinear partial differential equations) causes the theoretical understanding of the solutions to be incomplete. In particular, mathematicians are not versed in the complexities of the phenomenon turbulence. Solutions can be found, starting from initial conditions that simplify the original Navier-Stokes equations[45]. A theoretical approximation of the motions of bottled beer is not included in the scope of this research.

The main objective of this study is to experimentally describe turbulent movement of beer in the beer bottleneck (surface fluid flow). The findings were used in the design of additional experiments to identify the influence of frequency and acceleration on beer quality. Experiments regarding fluid flow beneath the surface and a theoretical approximation are not covered in this research due to the experimental complexity. However, exploration of this domain may be topics of further research.

2) Methodology

In this experiment, a beer bottle is attached to the shaker plate with an adhesive (professional vibration equipment) with the aim to impose the bottle to a predefined vibration pattern. The bottle was subjected to different sine sweeps. A sine sweep is a vibration pattern in which the frequency of the generated sine signal goes up by every time step[35]. Diverse sweeps were generated with the frequency between 1 Hz and ending at 100 Hz with different acceleration levels (1 m/s^2 – 15 m/s^2). The shaker, an electro-dynamic shaker (Brüel & Kjær, type 4802T) generated the vibration signal. The vibration signal was measured by an accelerometer, mounted on the shaker plate. The specifications of the vibration measurement devices used in the current research are described in Part 5 Chapter 1 section 1.3.

Simultaneously, a video recorder (GoPro Hero 4) filmed the beer fluid surface in the bottle with 120 frames per second[XVII]. In order to have a visual on the beer surface, the camera was oriented at a slight angle (+/- 30°). The test was performed on lager and non-lager types of beer, however, no significantly different results were discovered. Beer bottles in green glass[XVIII] of the type Ale Long Neck (33 cl) and Steinie (33cl) were included in the experiment. In Figure 18, a picture of the experimental set-up is presented. The experiment was performed three times to validate the obtained results.

Figure 18: Experimental set-up
(Turbulent beer experiment)

Experimental set-up of turbulence measurements. The beer bottle was fixed to the shaker plate with instant glue, an accelerometer was mounted on top of the shaker plate and a GoPro Hero 4 filmed the events with 120 frames per second.
Source: Own measurements

[XVII] Due to the Nyquist frequency and filming rate of 120 frames per second, analysis was limited up to 60 Hz.
[XVIII] Beer bottles in green glass were incorporated in the experiment (preferred over beer bottles in brown glass) in order to increase the visibility.

3) Results & Discussion

A stability chart, depicting the turbulent phases of beer is presented in Figure 19 (x-axis: frequency [Hz] y-axis: acceleration [m/s^2]). The plot presents five distinct areas which can identified as:

1. Slight movement at the beer surface
2. Swell/wave pattern (turbulent behavior)
3. Swell/wave pattern + leaping bubble in the middle (high amplitude)
4. Leaping bubble in the middle (low amplitude)
5. Leaping bubble in the middle (low amplitude) [Steinie bottle (33cl)]

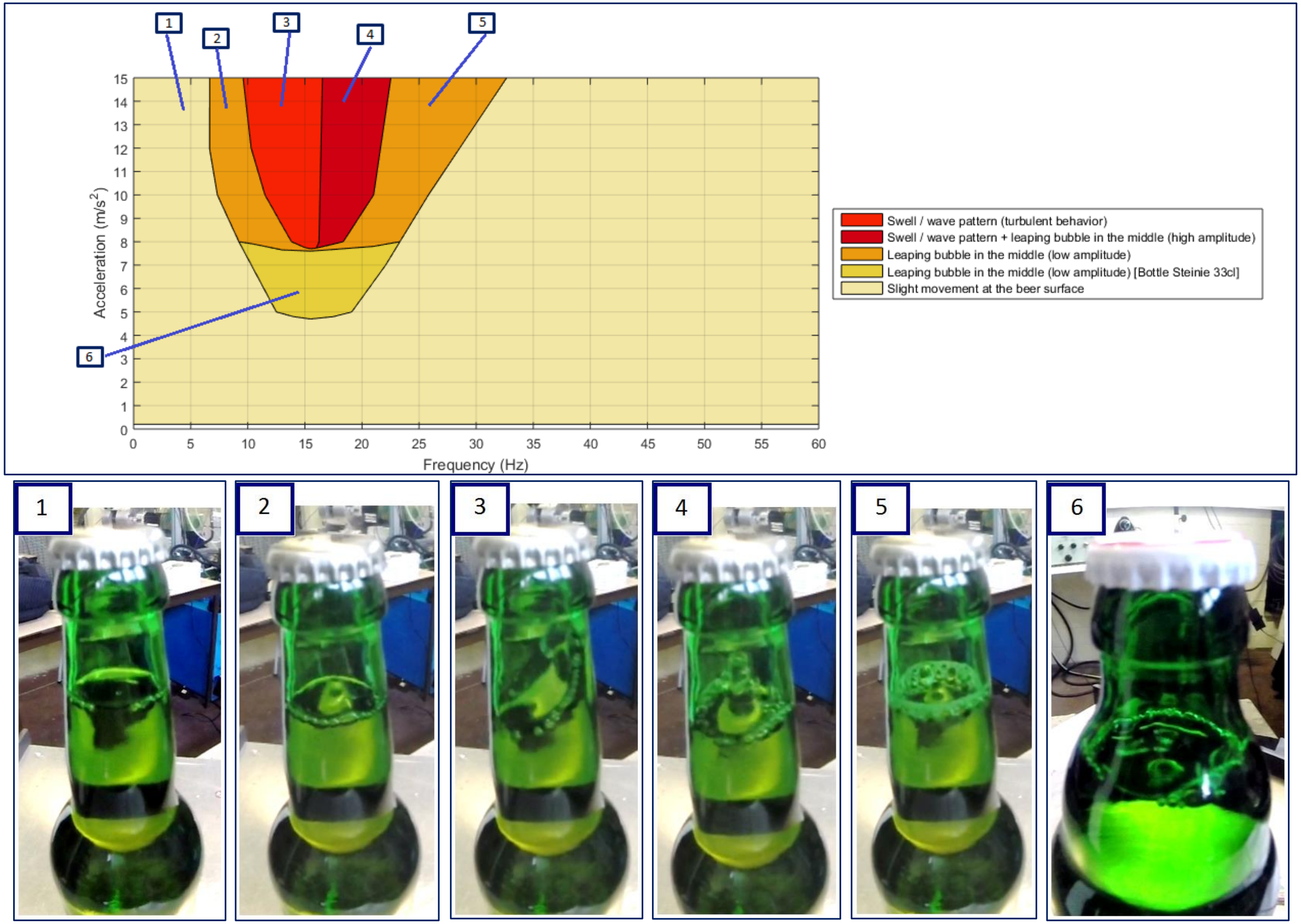
The largest area of the figure is characterized as 'slight movement at the beer surface'. Since the fluid surface has a small diameter and due to boundary effects near the bottle wall, it is challenging to distinguish between fluid flow on the surface (Faraday waves) and normal oscillatory motions (of the shaker and bottle). The Steinie bottle (33cl) has an extra turbulent area on the chart which can be defined as 'Leaping bubble in the middle (low amplitude)'. Presumably, the larger bottle diameter induces a lower surface tension and, as a consequence, will result in turbulence at lower acceleration levels. Beer bubbles can be exempted more easily to the force of gravity. Additionally, the plots indicate that beer completes different stages of turbulent behavior in which foam was generated in the end.

The findings coming from this experiment were used in the design of various other experiments in this research. However, the significance and the practical implications of the results are rather limited. For example, it might be possible that nonlinear effects arise when other vibration patterns are generated. Furthermore, the plot presents turbulent behavior of beer when being exposed to vibrations of a specific frequency and acceleration. In reality, transport vibrations consist of multiple frequencies and its corresponding accelerations that are much lower in amplitude than the presented accelerations at which turbulent behavior occurs.

4) Conclusions

From this study, it can be concluded that different laminar and turbulent flows of liquid can be characterized by the frequency and acceleration of the exposed vibrations. In addition, the bottle type (Ale Long Neck vs. Steinie) influences the occurrence of turbulent motions in the bottleneck. The Steinie bottle possesses a larger bottleneck diameter and this results in a lower beer surface tension and the occurrence of turbulent behavior at lower accelerations. It is recommended to further develop knowledge on the influence of turbulent motions on the uptake of oxygen and the flavor stability of beer.

Figure 19: Turbulence of beer in the beer bottleneck [Bottle type: Ale Long Neck (33 cl) / Steinie (33cl)]



The behavior of the beer in the bottleneck was investigated when exposed to vibrations with a variable frequency and acceleration. Source: Own measurements

2.2.b The influence of the frequency of vibrations and beer style on beer quality

Multiple parameters come into play when identifying the impact of vibrations on beer quality. Vibrations come in different patterns depending on the transport mode and are further modified by the packaging and stacking. Furthermore, the frequency and acceleration, in combination with the occurrence of turbulent behavior in the beer bottleneck (Part 5 Chapter 2 section 2.2.a) and the duration of exposure to the vibrations might also influence flavor stability. Also other parameters, i.e. the type of beer, the relation with oxygen in the bottleneck and the exposure to an elevated temperature when vibrating add to the complexity. Therefore, an explorative experiment was designed of which the main objective was to identify the influence of vibrations with different frequency on the beer quality. The vibration patterns were determined in order to also identify the influence of turbulent behavior in the beer bottleneck on the flavor quality of beer. The scope of the experiment was limited to four vibrations patterns (four frequencies) and four types of beer.

The current experiment identifies that all beer types (lager beer, dark beer with refermentation after bottling and blond specialty beer with and without refermentation after bottling) experienced decreased oxygen concentrations due to vibrations of all frequencies. Moreover, the dark specialty beer with refermentation after bottling that had high initial oxygen concentrations was sensitive to vibrations with respect to all aldehyde markers. However, no influence of vibrations was observed for the three other beer types, nor for color or iso-α-acids of the dark beer. The most extreme increase in aldehyde concentrations of the dark beer is observed when imposing vibrations of 50 Hz and 15 m/s^2 (0-peak)[XIX].

1) Methodology

a) Experimental design

Current vibration experiment was conducted in collaboration with the company Bosal[XX]. The company provided a large shaker that was used for executing the vibration test. A large pneumatic shaker (type MTS 258.05, max. amplitude 50 mm, max. force 50 kN) was used for the vibration experiment (Figure 20). In total, 24 bottles of beer were placed in an aluminum shaker frame, specifically built for this experiment. A plastic crate with 24 beers, the reference samples, was placed next to the shaker. An accelerometer was attached to the beer bottleneck and to the shaker plate to iteratively adapt the generated vibration signal to the preferred pattern or frequency and acceleration.

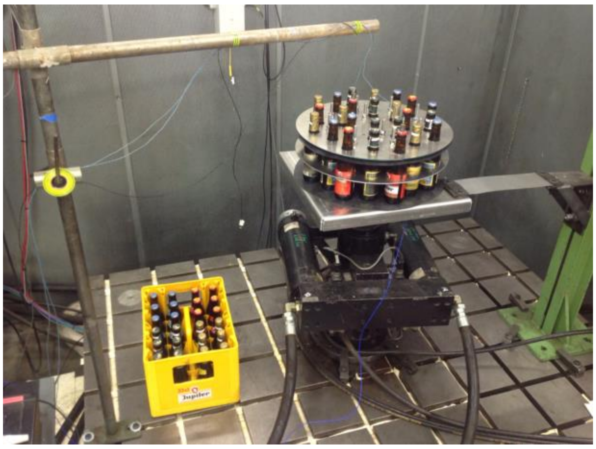
The beer was shaken over a period of 90 hours, approximately four days, at room temperature (21°C). In the vibration experiment, four setups were tested in which vibrations of different frequency were generated:

- *Setup 1 (S1):* Frequency 5 Hz / Acceleration 15 m/s^2 (0-peak)
  [Stability chart (Figure 19): Slight movement at the beer surface]
- *Setup 2 (S2):* Frequency 15 Hz / Acceleration 15 m/s^2 (0-peak)
  [Stability chart (Figure 19): Swell / wave pattern (turbulent behavior)]
- *Setup 3 (S3):* Frequency 30 Hz / Acceleration 15 m/s^2 (0-peak)
  [Stability chart (Figure 19): Leaping bubble in the middle (low amplitude)]
- *Setup 4 (S4):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak)
  [Stability chart (Figure 19): Slight movement at the beer surface]

[XIX] 0-peak refers to the amplitude of the signal, i.e. if the reference is zero, this is the maximum absolute deviation. Other amplitude measures are 'peak-to-peak' and 'root-mean-square'

[XX] Bosal is a leading manufacturer of exhaust systems. (Research and development subsidiary, Dellestraat 20 - 3560 Lummen [Belgium] - http://www.bosal.com/)

Figure 20: Experimental set-up
(Shaker experiment Bosal)



Beer samples were vibrated on the shaker, while reference samples were placed next to the shaker.
Source: Own content

Since the location of the vibration experiment (Bosal – Lummen) is at a distance from the lab facilities, the samples were transported in cooled conditions by using a refrigerator in the car. Therefore, external effects that could alter the results coming from the vibration experiment are minimal. In the lab, half of all samples (vibration and reference samples) was aged over a period of 30 days at 30°C. The other half of the samples were stored over the same period at 0°C. Afterwards, all samples were analyzed together. The reason to age half of the samples comes from the idea that after transport beer is often stored in a warm environment. This period of storage might induce delayed aging reactions.

b) Vibration signal

In the literature, vibration experiments are regularly conducted by imposing vibrations of one specific frequency and acceleration. However, transport vibrations consist of multiple frequencies (and its corresponding accelerations) that not only diverges over different modes of transport but which are also altered by the packaging and the stacking of beer crates[46]. However, when the input spectra of trains and trucks are compared with the transmissibility curves of packaged beer, an important prevalence of vibrations between 1 and 50 Hz with an amplitude considerably lower than 15 m/s^2 is observed. Therefore, the vibration signal imposed on the beer samples in the current experiment had a frequency of 5 Hz, 15 Hz, 30 Hz and 50 Hz with an acceleration of 15 m/s^2 (0-peak). The vibration patterns used in this experiment were assigned to also identify the influence of turbulent motions of beer in the beer bottleneck (Part 5 Chapter 2 section 2.2.a).

c) Beer samples and chemical tests

Since there was limited information on the impact of vibrations on beer quality in general, in the current explorative experiment a diverse set of beer types were included in the test. Four types of beer, bought in the supermarket and assured that they came from the same batch, were included in the experiment:

- Lager beer
  [Label: LB]
- Blonde specialty beer (top fermented) without second fermentation after bottling
  [Label: BSWithout]

- Blonde specialty beer (top fermented) with second fermentation after bottling
  [Label: BSWith]
- Dark specialty beer (top fermented) with second fermentation after bottling
  [Label: DSWith]

The beer profiling parameters in this experiment are the oxygen concentrations (TPO, HSO, DO), beer color, iso-α-acids (*trans*-isocohumulone, *cis*-isocohumulone, *trans*-isohumulone, *cis*-isohumulone, *trans*-isoadhumulone, *cis*-isoadhumulone, total iso-α-acids, T/C-ratio), and aldehydes (2-methylpropanal, 2-methylbutanal, 3-methylbutanal, hexanal, furfural, methional, benzaldehyde, phenylacetaldehyde, (E)-2-nonenal, total aldehydes). Specifications of the performed chemical tests are described in Appendix 1.

d) Data analysis

Due to the explorative nature of the experiment, a large number of different parameters were included in this experiment (e.g. beer types, aged vs. fresh beer, chemical tests, different vibration patterns). However, the latter segmentation jeopardizes the statistical significance of the measurements and the statistical tests that can be performed. As a consequence, the analysis of the available data was predominantly focused on an extensive descriptive analysis. Furthermore, since chemical data is available of beer samples that have been vibrated at 0 Hz (Reference samples), 5 Hz, 15 Hz, 30 Hz, 50 Hz the Pearson R and Spearman ρ or the degree of linear association between frequency and chemical concentration was calculated (JMP Pro 12). The limited data samples that are available for calculation of the correlation parameters (i.e. 10 or 12 samples) imposes the results to be interpreted with caution. Nevertheless, the insights of the explorative experiment gave insights that were used in the design of other (larger and more important) experiments.

2) Results & Discussion

The findings of the experiment indicate that a decrease in the oxygen concentrations for TPO, HSO and DO was measured for all beer types when being exposed to vibrations (over all frequencies) (Table 5). Furthermore, there is no transfer of oxygen observed between the headspace and the beer itself since both HSO and DO concentrations indicated a decrease due to vibrations (Figures 21a and 21b). As a consequence, there is strong evidence that exposing beer samples to vibrations of 5, 15, 30 and 50 Hz and $15 m/s^2$ results in an substantial uptake of oxygen by the beer (although the researcher is aware that beer bottles have oxygen scavenging crown corks that reduce oxygen concentrations). This is an important insight since dissolved oxygen can catalyze beer flavor instability.

From Table 5, it can also be derived that the measured oxygen concentrations (TPO, HSO and DO) are not lower after vibrating at 15 and 30 Hz compared to the other frequencies. When exposing beer samples to vibrations of 15 and 30 Hz and $15 m/s^2$, turbulent behavior in the beer bottleneck is observed (stability chart - Figure 19). Therefore, the turbulent behavior is believed not to induce a higher uptake of oxygen in beer in the current experimental set-up[XXI]. Furthermore, Table 5 indicates that the dark specialty beer with second fermentation after bottling contained up to seven times more oxygen (TPO, HSO and DO) than all other beers included in the experiment. The high concentration of oxygen in the dark specialty beer is an unusual practice for commercially available beer but added

[XXI] The current explorative experiment tested the hypothesis of vibrations inducing an increase in the uptake of oxygen, which is more pronounced when turbulent behavior is noticed in the beer bottleneck (Part 5 Chapter 2 section 2.2.a).

unintentionally a new and rich dimension to the experiment since also the influence of oxygen was incorporated in the experiment.

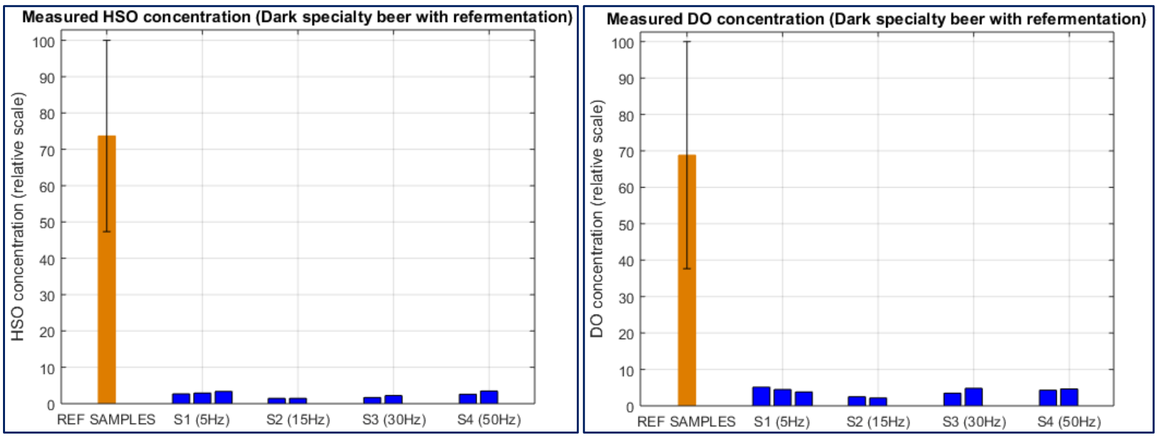
Table 5: Measured oxygen concentrations (TPO, HSO, DO) after the vibration experiment

in ppb		TPO (measurements in ppb)	HSO (measurements in ppb)	DO (measurements in ppb)
Reference samples	LB	Avg. 251 (STD: 66)	Avg. 232 (STD: 64)	Avg. 19.0 (STD: 9.4)
	BSWithout	Avg. 169 (STD: 23)	Avg. 159 (STD: 23)	Avg. 10.4 (STD: 2.5)
	BSWith	Avg. 118 (STD: 21)	Avg. 110 (STD: 21)	Avg. 7.1 (STD: 1.0)
	DSWith	Avg. 700 (STD: 252)	Avg. 658 (STD: 235)	Avg. 41.5 (STD: 18.8)
Setup 1: vibrations of 5 Hz and 15 m/s^2 during 4 days (raw data)	LB	219 / 75 / 77	214 / 69 / 74	5.7 / 5.2 / 3.0
	BSWithout	21 / 29 / 48	18 / 26 / 43	2.3 / 2.6 / 5.7
	BSWith	62 / 43 / 21	59 / 40 / 19	3.8 / 3.1 / 2.7
	DSWith	28 / 29 / 32	24 / 26 / 30	3.1 / 2.7 / 2.3
Setup 2: vibrations of 15 Hz and 15 m/s^2 during 4 days (raw data)	LB	27 / 240	23 / 237	3.1 / 3.4
	BSWithout	16 / 21	14 / 19	1.5 / 2
	BSWith	16	14	1.7
	DSWith	14 / 14	13 / 13	1.5 / 1.3
Setup 3: vibrations of 30 Hz and 15 m/s^2 during 4 days (raw data)	LB	323 / 51	319 / 48	4.6 / 3.2
	BSWithout	25/ 28	22 / 26	2.4 / 2.1
	BSWith	23 / 24	21 / 22	2.4 / 1.9
	DSWith	18 / 23	15 / 20	2.1 / 2.9
Setup 4: vibrations of 50 Hz and 15 m/s^2 during 4 days (raw data)	LB	84 / 58	80 / 54	4.7 / 4.4
	BSWithout	33	29	3.5
	BSWith	13 / 17	11 / 15	1.7 / 2.3
	DSWith	26 / 34	23 / 31	2.6 / 2.8

Legend: LB: Lager beer, BSWithout: Blonde specialty beer without second fermentation, BSWith: Blonde specialty beer with second fermentation, DSWith: Dark specialty beer with second fermentation, TPO: Total package oxygen , HSO: Headspace oxygen, DO: Dissolved oxygen // There is strong evidence (due to limited samples) that oxygen concentrations TPO, HSO and DO decrease for all beer types when exposing to vibrations of 5, 15, 30 and 50 Hz. The raw data is displayed – the number of samples is dependent on the initial design of experiments and the number of successful chemical analyses of KU Leuven Technology Campus Ghent. The variation in oxygen concentration with respect to lager beer is remarkable and may be attributed to individual bottles and a non-conformity during bottling, or an incorrect analysis in the lab.

Source: Own measurements

Figure 21a: Measured HSO concentration (relative scale) of DSWith-beer (experiment Bosal)
Figure 21b: Measured DO concentration (relative scale) of DSWith-beer (experiment Bosal)



Both HSO and DO concentrations of DSWith beer samples decrease due to vibrations of 5, 15, 30 and 50 Hz and 15m/s^2. This indicates that an uptake of oxygen in the beer and the resulting beer flavor quality degradation might take place.

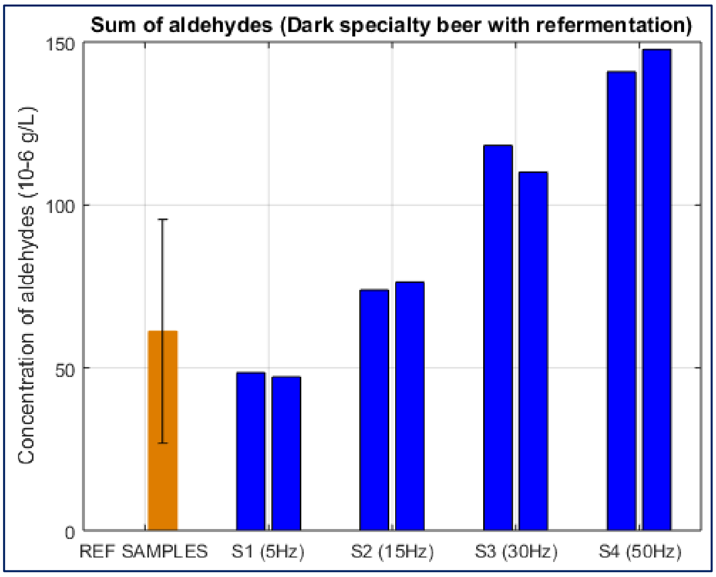
Source: Own measurements

Within the limitation of the experiment, we can state that no influence of vibrations is observed on the change of color and the measured iso-α-acids of the studied beers [Data shown in Appendix 3]. This is remarkable since literature indicates that both color and the iso-α-acids are sensitive to oxidation[18,23]. Since color and iso-α-acids reveal to be stable (of fresh beer and after an aging period of 30 days at 30°C) and HSO and DO concentrations decreased due to vibrations, the dissolved oxygen might cause the creation of molecules alternative to the measured iso-α-acids and (the compounds contributing to) color.

The aldehyde concentrations of the beer samples, i.e. LB, BSWithout and BSWith, indicate to be stable after the vibration treatment, which is conform the measurements of the color and the iso-α-acids [Data shown in Appendix 3]. However, the concentrations of the aldehydes of the dark (oxygen rich) specialty beer, DSWith, change after being exposed to vibrations, and, therefore, it is analyzed more into depth. In Table 6, an overview of the measured aldehyde concentrations of the DSWith samples is presented. The concentrations of aldehydes of the DSWith samples tend to form a linear trend over the different setups, i.e. with higher frequency also an increase in aging compounds is observed. The Pearson R and Spearman ρ correlations indicate correlations larger than 0.729 for 8 out of 9 aldehyde components and, as a consequence, the hypothesis of having a monotonically increasing aldehyde concentration as a function of the vibration frequency is accepted on a significance level of 10%[XXII]. The researchers of the current study are aware that the correlation calculations were performed with 12 samples and, therefore, the results should be interpreted with caution. However, the latter relation is not counterintuitive, since a rising frequency (and constant acceleration) of the exposed vibrations induces an increase in the kinetic energy of the system (due to an increase in the velocity of the system). Furthermore, when the dark beer is vibrated at 50 Hz, an increase of the individual aldehyde compounds up to 150% is present when compared with the reference samples (Table 6). After aging the beer samples, the samples that have been vibrated still demonstrate a higher aldehyde concentration. However, the linear relation (higher frequency, higher aldehyde concentration) is less manifest. The same result can be derived from the measured total aldehyde concentrations in Figure 22. The researcher of the current study is aware that the total concentration of aldehydes should be studied in relation to the absolute values of the contributing parameters (Table 6). Furthermore, previous analysis also indicates that no significant difference is observed between the aldehyde concentrations after vibrations with frequencies at which turbulence in the bottleneck occurs (15 Hz and 30 Hz) and vibrations of the other two frequencies (5 Hz and 50 Hz). This indicates that turbulence in the beer bottleneck in current experimental setup is believed not to be a parameter that contributes to the changing aldehyde concentrations.

[XXII] The significance level for Pearson's correlation using 4 degrees of freedom (numbers of pairs – 2): Level of significance for a two-tailed test 0.10 (=0.729), 0.05 (=0.811), 0.02 (=0.882), 0.01 (=0.917). The significance level for Spearman's correlation is calculated by JMP Pro 12.

Figure 22: Measured total aldehyde concentrations of DSWith-samples after the vibration treatment of 5, 15, 30 and 50 Hz and 15m/s² during 4 days



The total aldehydes concentration rises when beer samples are exposed to vibrations of higher frequency (e.g. 50 Hz and 15m/s²) relative to the reference samples. The reader should be aware of the absolute values of the parameters contributing to the total concentration of aldehydes (Table 6). The parameter phenylacetaldehyde is of major importance, as well as, but to a lesser extent 2-methylpropanal, furfural, methional, and 3-methylbutanal.

Source: Own measurements

Table 6: Measured aldehyde concentrations of DSWith-samples after the vibration experiment and after an additional aging of 30 days at 30° (raw data)

(raw data) 10^{-6} g/l	*2-methylpropanal*	*2-methylbutanal*	*3-methylbutanal*	*hexanal*	*furfural*
Reference samples	11.9 / 11.7 / 7.0 / 7.3 **45.6 / 49.4**	0.9 / 0.9 / 1.9 / 2.0 **4.2 / 4.4**	2.5 / 2.8 / 7.6 / 7.6 **15.4 / 16.7**	0.2 / 0.2 / 0.4 / 0.5 **0.5 / 0.5**	3.0 / 2.8 / 10.9 / 13.3 **35.4 / 37.6**
Setup 1: vibr. 5 Hz and 15 m/s² during 4 days	6.3 / 6.7 **51.7 / 57.1**	1.5 / 1.6 **5.3 / 5.4**	6.0 / 6.1 **20.2 / 21.4**	0.3 / 0.3 **0.6 / 0.6**	11.4 / 12.1 **44.8 / 45.2**
Setup 2: vibr. 15 Hz and 15 m/s² during 4 days	9.0 / 8.9 **46.1 / 51.7**	2.2 / 2.2 **5.7 / 5.9**	9.0 / 8.9 **19.9 / 21.5**	0.6 / 0.6 **0.6 / 0.6**	14.1 / 15.2 **46.8 / 47.7**
Setup 3: vibr. 30 Hz and 15 m/s² during 4 days	9.9 / 9.9 **42.1 / 47.6**	2.4 / 2.4 **5.1 / 5.3**	9.0 / 8.7 **18.6 / 20.2**	0.4 / 0.5 **0.7 / 0.5**	17.6 / 18.7 **51.7 / 51.6**
Setup 4: vibr. 50 Hz and 15 m/s² during 4 days	14.4 / 14.1 **46.7 / 50.7**	3.3 / 3.3 **5.7 / 5.8**	11.5 / 11.6 **21.5 / 22.1**	0.7 / 0.8 **0.6 / 0.6**	23.2 / 23.8 **47.8 / 50.9**

10^{-6} g/l	*methional*	*benzaldehyde*	*phenylacetaldehyde*	*(E)-2-nonenal*
Reference samples	3.2 / 3.9 / 15.6 / 13.2 **19.5 / 21.5**	0.8 / 0.8 / 1.3 / 1.4 **1.0 / 0.9**	8.8 / 8.4 / 48.3 / 43.4 **18.4 / 19.4**	0.02 / 0.02 / 0.03 / 0.04 **0.04 / 0.03**
Setup 1: vibr. 5 Hz and 15 m/s² during 4 days	6.7 / 5.0 **25.3 / 32.9**	0.9 / 0.9 **1.3 / 1.3**	15.3 / 14.6 **24.0 / 28.0**	0.02 / 0.02 **0.04 / 0.04**
Setup 2: vibr. 15 Hz and 15 m/s² during 4 days	10.0 / 9.7 **22.5 / 22.4**	1.5 / 1.6 **1.3 / 1.4**	27.5 / 29.2 **22.2 / 23.3**	0.03 / 0.04 **0.03 / 0.04**
Setup 3: vibr. 30 Hz and 15 m/s² during 4 days	20.5 / 14.3 **24.9 / 24.8**	1.4 / 1.4 **1.3 / 1.3**	57.0 / 54.1 **18.3 / 19.7**	0.04 / 0.04 **0.04 / 0.04**
Setup 4: vibr. 50 Hz and 15 m/s² during 4 days	15.9 / 21.3 **28.1 / 26.1**	2.0 / 2.2 **1.5 / 1.6**	69.8 / 70.5 **26.6 / 24.7**	0.06 / 0.07 **0.03 / 0.04**

Legend: Fresh beer (normal fond) - Aged beer after vibration experiment for 30 days at 30°C (**Bold fond**)

The aldehydes concentration rises when beer samples are exposed to vibrations of higher frequency (i.e. 50 Hz and 15m/s²) relative to the reference samples. The raw data is displayed – the number of samples is dependent on the initial design of experiments and the number of successful chemical analyses of KU Leuven Technology Campus Ghent.

Source: Own measurements

3) Conclusions & Recommendations

Limited research has been executed on the impact of mechanical vibrations on beer quality and, therefore, a multiplicity of parameters (different vibration patterns, types of beer, interaction with temperature, etc.) should be tested. The objective of the current experiment was to have an indication of the impact of the exposure of vibration patterns, i.e. different frequencies, on the flavor stability of four different beer types. The insights coming from the current explorative experiment, which only have limited statistical significance, are used to better design and optimize the consecutive experiments.

From the results, it can be concluded that vibrations, irrespective of the frequency (5 Hz, 15 Hz, 30 Hz, 50Hz), cause a decreased oxygen concentration (TPO, HSO, DO) for all beer types. Additionally, no significantly different concentrations were noticed between reference samples and the vibrated beer samples with respect to color and iso-α-acids for fresh beer and when measured after a period of aging for 30 days at 30°C. The aldehyde measurements, on the contrary, revealed that dark specialty beer that contained an elevated oxygen concentration prior to executing the vibration experiment, was unstable when the beer is being exposed to vibrations. Moreover, the analysis indicated the higher the frequency of the imposed vibrations, the higher the aldehyde concentration. Therefore, the most severe decrease in beer quality with respect to the dark specialty beer is observed when exposing the beer samples to vibrations of 50 Hz (and 15 m/s^2). After the aging period of 30 days, the relation between the vibration frequency and aldehyde concentration is less manifest. The same analysis was performed for the other beer types, however, the phenomenon is less pronounced or seems to be not present.

The current explorative experiment indicates that there might be a dependency on the oxygen concentration prior to performing the vibration experiment with respect to beer flavor degradation. As a consequence, the initial oxygen concentration in beer is an important parameter in consecutive experiments and open for further research. Furthermore, it can be recommended that in future experiments beer should be exposed to vibrations of 50 Hz and 15 m/s^2, rather than vibrations of lower frequency in order to acquire more extreme findings with respect to the concentration of aldehydes.

2.2.c The interaction of vibrations and temperature on the beer flavor quality

The experimental study of section 2.2.b indicated the susceptibility of beer samples to vibrations. Therefore, in the current section 2.2.c, an additional experiment was designed to further investigate the interaction of vibrations and temperature on the beer flavor quality. Similar to prior results, decreased oxygen concentrations due to the vibrations (and elevated temperature) were observed. Furthermore, there was no effect on color and only limited effect of temperature and vibrations on iso-α-acids. However, the parameters temperature and vibrations have a significant influence on aldehydes concentrations, i.e. total aldehydes, and especially '2-methylpropanal', '2-methylbutanal' and 'furfural'. The impact of vibrations on the aldehydes concentrations is substantial when subjected to elevated temperature. There are strong indications that the uptake of oxygen causes haze in beer. Moreover, the current study indicates that a forced aging test of shorter duration than traditional methods might be developed.

Further information on the experimental study on the interaction between vibrations and temperature during transport and the beer flavor stability is presented in the paper entitled "The influence of the interaction between vibrations and temperature, simulating transport, on the flavor quality of beer" in Annex.

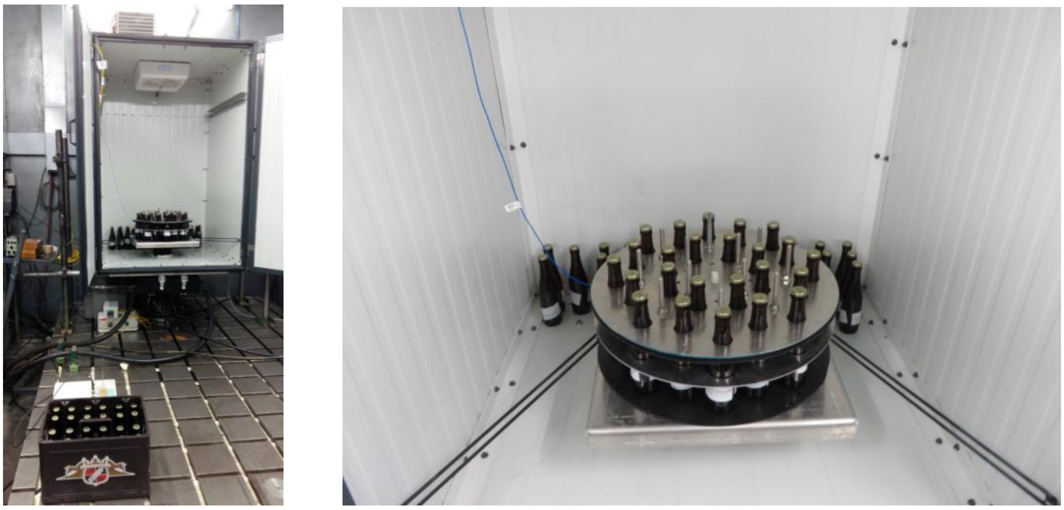
1) Methodology

a) Experimental design

The vibration experiment in this study was conducted in collaboration with the company Bosal. A thermostatic cabinet (Figure 23) was built over the shaker frame and enabled to perform a vibration experiment while exposing the beer samples to a decreased (5°C) or an elevated temperature (30°C, 45°C). In total, 24 bottles of beer were installed in an aluminum shaker frame, specifically built for this experiment. Furthermore, 24 bottles of beer were placed next to the shaker but inside the insulated cabinet to expose the samples to the same heat as the beer samples on the shaker. Before the start of every setup of the experiment, the climate cabinet was conditioned for two hours. A plastic crate with 24 beer bottles, the reference samples, was placed next to the shaker and was exposed to the ambient temperature (25°C ± 2°C). An accelerometer was attached to the beer bottleneck and to the shaker plate to iteratively adapt the generated vibration signal to the preferred pattern or frequency. Since the facilities of Bosal were located approximately one hour driving from the laboratory of KU Leuven technology campus Ghent, the samples were transported in an isomo box filled with cool elements to protect from heat. An overview of all setups is presented below.

- *Setup 1 (S1):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak) during 90 hours at 5°C
- *Setup 2 (S2):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak) during 90 hours at 30°C
- *Setup 3 (S3):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak) during 90 hours at 45°C
- *Setup 4 (S4):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak) during 90 hours at 45°C
- *Setup 5 (S5):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak) during 22 hours at 45°C
- *Setup 6 (S6):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak) during 22 hours at 45°C
- *Setup 7 (S7):* Frequency 50 Hz / Acceleration 15 m/s^2 (0-peak) during 38 hours at 45°C

Figure 23: Experimental equipment (beer samples in the climate cabinet // beer samples on the shaker frame in the climate cabinet // beer samples in ambient temperature)



Beer samples were vibrated on the shaker in the climate cabinet, while reference samples were placed next to the shaker in and outside the climate cabinet. Source: Own measurements

b) Vibration signal

The experimental study in section 2.2.b indicated that the most extreme results with respect to the beer flavor markers were identified when imposing a vibration signal of 50 Hz and 15 m/s^2. Therefore, the same vibration pattern was adopted in the current experiment. When comparing this signal with the acceleration amplitude and the spectrum of the vibrations beer bottles are exposed to during truck transport (Part 5 Chapter 1 section 1.3), 50 Hz and 15 m/s^2 (0-peak) is not representative for transport. During transport a peak between 1 and 5 Hz and a peak between 10 and 25 Hz (dependent on the stack height) are noticed. Furthermore, the imposed acceleration of 15 m/s^2 is approximately ten times higher than the values observed in reality. Nevertheless, the extreme signal was chosen to unravel the relation between temperature, transport vibrations and the beer flavor stability.

c) Beer samples and chemical tests

In the current experiment, a blond beer without refermentation after bottling was taken (chemical characteristics in Table 7). The batch of beer used in the experiment was brewed in the KU Leuven technology campus Ghent to optimally control the brewing process and to identify the chemical parameters. Since the uptake of oxygen due to vibrations might cause an increased generation of beer ageing compounds, half of all samples were bottled with diminished oxygen levels (bottled with O_2 scavengers) while in the other samples no measures were taken to prevent oxygen under the metal cap (bottled by hand without overfoaming). The latter methodology enables to identify the influence of oxygen in the beer aging process when beer is under a regime of vibrations. In Table 7, an overview of the oxygen concentrations (TPO, HSO, DO), measured directly after bottling, as well as the chemical characteristics of the beer samples, is presented. While a distinction was made between samples with high and low initial oxygen content, the oxygen concentration was still considered high in comparison with industry standards.

The beer profiling parameters in this experiment are the oxygen concentrations (TPO, HSO, DO), beer color, iso-α-acids (*trans*-isocohumulone, *cis*-isocohumulone, *trans*-isohumulone, *cis*-isohumulone, *trans*-isoadhumulone, *cis*-isoadhumulone, total iso-α-acids, T/C-ratio), and aldehydes (2-methylpropanal, 2-methylbutanal, 3-methylbutanal, hexanal, furfural, methional, benzaldehyde, phenylacetaldehyde, (E)-2-nonenal, total aldehydes). Additionally, haze measurements were executed on some of the remaining beer samples. Specifications of the performed chemical tests are described in Appendix 1.

Table 7: Oxygen concentration after bottling – chemical characteristics beer samples

Avg. in ppb (STD)	**Samples with higher initial oxygen content**		**Samples with lower initial oxygen content**	
TPO after bottling	1265 (185)		523 (382)	
HSO after bottling	1207 (180)		472 (380)	
DO after bottling	58 (44)		51 (38)	
Chemical characteristics	pH:	4.44	Eorg. (°P)	12.43
	Alc. (v/v%)	5.11	RDF (%)	63.71
	Alc. (w/w%)	4.00	ADF (%)	77.00
	Er (°P)	4.70	Cal. (kJ/100 ml)	188.19
	Ea (°P)	2.86		
Legend: TPO (Total Package Oxygen), HSO (Headspace Oxygen), DO (Dissolved Oxygen), pH (acidity), Alc. (Alcoholic volume or weight in %), Er (Real extract), Ea (Apparent extract), Eorg. (Original extract), RDF (Real degree of fermentation), ADF (Apparent degree of fermentation), Cal. (Caloric content)				

Source: Own measurements

d) *Data analysis*

In the current experiment, multiple parameters may have an influence on the chemical output parameters, i.e. the influence of temperature and vibrations, the duration of vibrations, the aging after the vibration test, and the influence of samples with and without inhibiting oxygen after bottling. Therefore, a mixed model[XXIII] that is able to integrate and estimate the influence of random effects (e.g. bottles together in climate cabinet, bottles together in the setup and crate) was built in the statistical software JMP PRO12.

2) Results

Analysis of the results indicates that oxygen concentration (TPO, HSO and DO) of both samples with higher and lower initial oxygen content decreased significantly due to vibrations. As a consequence, the uptake of oxygen in beer can be assumed since it is unlikely that the oxygen scavenging crown corks cause the decreased oxygen concentrations. Furthermore, the results indicate no substantial change of color and the concentration of iso-α-acids. Only a negligible change in the T/C-ratio is observed due to the more sensitive character of individual *trans*-iso-α-acids over *cis*-iso-α-acids. The decreasing oxygen concentrations and the stability of color and iso-α-acids are noteworthy, since literature indicates that the presence of oxidation is highly related to the change in the beer color and the decrease of the *trans*- and *cis*-iso-α-acids[18,23]. Similar results were found in the earlier executed experiment in Part 5 Chapter 2 section 2.2.b.

In contrast to color and iso-α-acids, aldehydes show to be more sensitive when exposing the tested beer samples to the different temperatures in combination with vibrations. Moreover, the aldehydes '2-methylpropanal', '2-methylbutanal' and 'furfural' change considerably in concentration under an elevated temperature and vibrations while the other aldehydes do not increase significantly over all setups. In Figures 23a and b, the concentration of the total aldehydes measured directly after the

[XXIII] The researcher is aware that the data samples should be acquired independently when using the mixed model. The latter was not the case in the current experimental setup and, therefore, the results should be interpreted with caution.

vibration experiment (Figure 24a) and after an aging period of 60 days in 30°C (Figure 24b) is displayed. Also, a more detailed view on the results of '2-methylpropanal', '2-methylbutanal' and 'furfural' is presented in Table 8. Figure 24a indicates the exponential effect of exposure to elevated temperature and the additive effect of vibrations that further increase aldehyde concentrations. The effect of vibrations on the aldehydes concentration is visible at all temperatures (5°C, 30°C and 45°C) and all durations (90hrs, 38 hrs. and 22hrs.). Furthermore, the figure also indicates that the higher the exposed temperature, the more pronounced the effect of vibrations on beer quality. The latter indicates the possible presence of an interaction effect between temperature and vibrations.

The results of Figure 24a demonstrate a significant increase of the total aldehydes concentration due to vibrations when the samples are exposed to an elevated temperature of 45°C in combination with vibrations during 90 hrs. However, after an aging period of 60 days at 30°C, no significant difference is observed between the total aldehydes concentrations of the reference samples (ambient temp. 25°C) and the other samples (Figure 24b). Figure 24b indicates that the total aldehydes concentration possibly saturates, i.e. the samples that have been vibrated under a regime of 45°C for four days only increase marginally in total aldehydes concentration after aging for 60 days. The latter also implies that the total aldehydes concentration reached after 60 days of exposure to 30°C can be approximated by 90 hours of exposure to vibrations and an elevated temperature of 45°C. As a consequence, there is potential to further develop the latter method into a beer aging test that can be used to assess the chemical stability of beer. In current methods, beer is predominantly aged at 30°C for two to four months, since the taste of beer exposed to 30°C best represents storage conditions in contrast to aging over a shorter time span with a higher temperature. A shorter duration of the test improves the number of analyses the beer scientist is able to perform, and, therefore, results in a significant reduction of time and money. However, further analysis is required to validate the possibility to substitute the beer aging method.

Table 8: A more detailed investigation of the results of '2-methylpropanal', '2-methylbutanal', and 'furfural' (after storage for 60 days at 0°C - fresh beer - and after aging for 60 days at 30°C)

Avg. x 10^{-6} g/l (STD)	2-methylpropanal (fresh beer)	2-methylpropanal (aged 60d. at 30°C)	2-methylbutanal (fresh beer)	2-methylbutanal (aged 60d. at 30°C)	Furfural (fresh beer)	Furfural (aged 60d. at 30°C)
90hrs. in 25°C	17.8 (2.0)	73.4 (6.5)	3.1 (0.3)	5.2 (0.6)	24.9 (4.7)	189.1 (27.6)
90hrs. in 5°C	11.6 (0.5)	82.4 (12.9)	2.7 (0.1)	5.5 (0.3)	10.5 (0.6)	199.7 (14.2)
90hrs. in 5°C shaking	12.3 (0.9)	64.4 (1.9)	2.6 (0.2)	4.7 (0.2)	12.3 (1.4)	177.1 (13.3)
90hrs. in 30°C	18.8 (1.1)	70.8 (2.5)	3.1 (0.2)	4.7 (0.2)	26.7 (1.4)	166.6 (5.7)
90hrs. in 30°C shaking	23.7 (1.0)	67.5 (2.5)	3.6 (0.3)	5.0 (0.3)	39.9 (2.0)	172.4 (23.4)
90hrs. in 45°C	59.2 (6.9)	92.8 (7.1)	4.4 (0.2)	5.9 (0.5)	143.6 (17.8)	253.4 (28.7)
90hrs. in 45°C shaking	79.6 (7.7)	95.2 (8.9)	4.9 (0.4)	6.0 (0.6)	217.1 (15.0)	314.1 (57.0)

* There was no statistical significant difference observed between the samples with high and low oxygen content, and, therefore, all samples are included in the former graph.

The aldehyde concentration of the selected aldehydes rises when the beer samples are exposed to vibrations and an increased temperature.

Source: Own measurements

Figure 24a: Total aldehydes as a function of temperature, vibrations and time (after the vibration experiment the samples were stored for 60 days at 0°C - fresh beer -)
Figure 24b: Total aldehydes as a function of temperature, vibrations and time (after the vibration experiment the samples were aged for 60 days at 30°C)

Figure 24a

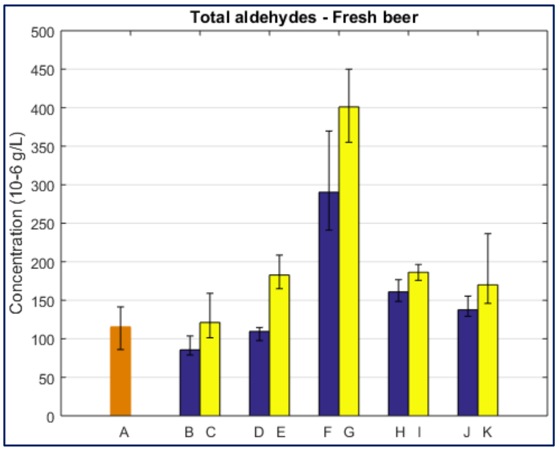
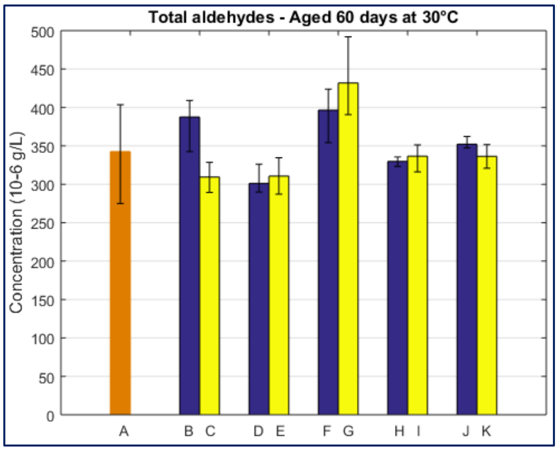


Figure 24b



Legend: [BLUE: without shaking / YELLOW: with shaking] A: samples stored for 90hrs. at 25°C / B: samples stored for 90hrs. at 5°C / C: samples stored for 90hrs. at 5°C while shaking / D: samples stored for 90hrs. at 30°C / E: samples stored for 90hrs. at 30°C while shaking / F: samples stored for 90hrs. at 45°C / G: samples stored for 90hrs. at 45°C while shaking / H: samples stored for 38hrs. at 45°C / I: samples stored for 38hrs. at 45°C while shaking / J: samples stored for 22hrs. at 45°C / K: samples stored for 22hrs. at 45°C while shaking

* There was no statistical significant difference observed between the samples with higher and lower initial oxygen content, and, therefore, all samples are included in the former graph. The average with confidence intervals (minimum and maximum value) was calculated for each setup.

Source: own measurements

From Table 8, an additional remarkable finding is derived, i.e. the reactivity of 2-methylpropanal and furfural. The identified aldehyde markers indicate to be susceptible to both temperature and vibrations after exposure of a short duration of only 90 hours. As a consequence, alternative and more simple chemical reactions might rather contribute to the increased aldehyde concentrations than the complex (and known) Strecker degradation or Maillard reactions. However, additional research beyond the scope of the current dissertation is required on the current findings.

A mixed model (i.e. ANOVA model with batch as randomness parameter) was established in order to test the statistical significance of the research findings. The model indicated that the influence of temperature on *trans*-iso-α-acids is significant. Furthermore, the influence of vibrations and temperature (and the interaction effect) is significant with respect to the formerly identified aldehydes. In Table 9a, the fixed-effects parameter estimates of the initial model are illustrated. Since the variation of the measured total aldehydes concentration becomes larger when temperature increases, the logarithm of the concentration of aldehydes was identified as the output variable in order to increase the performance and the correctness of the presented model. The single effect of temperature, the quadratic effect of temperature and the single effect of vibrations are described as significant by the model (significance level of 5%). The effect of oxygen ($p = 0.4571$) and the interaction effect between temperature and vibrations ($p = 0.8528$) are not assessed as significant by the model. The nonsignificant effect of oxygen was not expected before initiating the vibration experiment. However, the descriptive analysis of the beer aging parameters already indicated the latter relation. The interaction effect between temperature and vibrations is intuitively expressed by the plot of the results in Figure 24a. Due to the increased variance in aldehydes concentration when the temperature rises, an interaction effect between temperature and vibrations is not addressed as significant by the model. Furthermore, the optimal model (Table 9b) and the 'effect summary' indicates that temperature (and the exponential effect) is the predominant parameter that describes the concentration of aldehydes. In other words, vibrations have a significant effect on the total aldehydes concentration, but the importance of the parameter is considerably lower compared to temperature. Beer aging due to vibrations is only prominent with respect to aldehydes when the samples are subjected to an elevated temperature (45°C). Similar results and the same significant parameters were found for the aldehydes '2-methylpropanal', '2-methylbutanal' and 'furfural'.

Table 9a: Mixed model – total aldehydes after vibration experiment (first model - JMP output) (after the vibration experiment stored for 60 days at 0°C)

Fixed Effects Parameter Estimates							
Term	**Estimate**	**Std. Error**	**DFDen**	**T Ratio**	**Prob>|t|**	**95% Lower**	**95% Upper**
Intercept	3.98	0.16	5.0	24.13	< 0.01	3.56	4.40
Oxygen	-0.02	0.02	28.1	-0.75	0.46	-0.06	0.03
Temperature	0.04	< 0.01	5.0	9.42	< 0.01	0.03	0.05
(Temperature)^2	< 0.01	< 0.01	5.0	2.85	0.04	8.29e-5	< 0.01
Vibrations	-0.16	0.05	5.0	-2.91	0.03	-0.30	-0.02
Temperature x Vibrations	< 0.01	< 0.01	5.0	-0.20	0.85	-0.01	0.01

Source: Own content

Table 9b: Mixed model – total aldehydes after vibration experiment (optimal model - JMP output) (after the vibration experiment stored for 60 days at 0°C)

Fixed Effects Parameter Estimates							
Term	**Estimate**	**Std. Error**	**DFDen**	**T Ratio**	**Prob>|t|**	**95% Lower**	**95% Upper**
Intercept	3.98	0.15	6.0	26.80	< 0.01	3.62	4.35
Temperature	0.04	< 0.01	6.1	10.35	< 0.01	0.03	0.04
(Temperature)^2	< 0.01	< 0.01	6.0	3.12	0.02	< 0.01	< 0.01
Vibrations	-0.16	0.05	6.1	-3.22	0.02	-0.28	-0.04
Random Effects Covariance Parameter Estimates					**Effect Summary**		
Covariance Parameter	**Estimate**	**Std. Error**	**95% Lower**	**95% Upper**	**Source**	**LogWorth**	**PValue**
Batch	0.02	0.01	-0.01	0.04	Temperature	4.35	< 0.01
Residual	0.02	< 0.01	0.01	0.03	Vibrations	1.75	0.02
					Temperature)^2	1.69	0.02

Source: Own content

Further information can be found in the paper entitled "The influence of the interaction between vibrations and temperature, simulating transport, on the flavor quality of beer" in Annex.

<u>3) Discussion</u>

While a decrease in oxygen concentrations (HSO and DO) was measured, color and iso-α-acids were stable, and the aldehyde markers changed. Since the selected aldehydes are not considered as the main contributors of the uptake of oxygen, other molecules or chemical products are assumed to be formed. Janssen et al. (2014)[27] already indicated the development of turbidity in beer in a first exploratory vibration experiment (without an in-depth analysis of the other beer flavor parameters).

The development of turbidity in beer can be one of the causes of the uptake of oxygen (and the increased interaction between proteins and polyphenols[47]). Therefore, additional measurements of the colloidal stability were performed with the left-over samples (Appendix 4). The raw data indicates (without statistical significance) that vibrations might induce a change in the turbidity of the beer samples as is described in literature. Consecutive experiments[XXIV] executed by the VIS/brewers-project in 2017 validated these findings. Moreover, the same interaction effect between vibrations and temperature was observed, as well as the development of turbidity in beer when imposing vibrations at an elevated temperature. The effect of vibrations on the turbidity of the beer samples was multiple times larger than the observed effect on color, iso-α-acids, and aldehydes in the performed experiment[XXV]. Furthermore, the results also indicated that the effect of temperature is more dominant over the effect of vibrations.

Additionally, the researcher of the current study indicates that the chemical characteristics and profile of the beer varies (i.e. the beer type, the batch, etc.) and, therefore, also the effect of vibrations (and temperature) may diverge. As a consequence, additional experiments with different beer types are recommended.

4) Conclusions & Recommendations

The main conclusions of the experimental study are summarized as follows:

- Vibrations (and elevated temperature) induce an uptake of oxygen since reduced oxygen concentrations were measured (HSO, DO). It remains crucial for breweries to limit the exposure of beer to oxygen in order to prevent beer aging reactions.
- No difference in color was detected for beer samples that were subjected to an increased temperature or vibrations.
- The cis-iso-α-acids are stable and do not change when exposed to temperature and vibrations. The trans-iso-α-acids, on the contrary, are more sensitive (especially *trans*-isocohumulone and *trans*-isohumulone) and induce both the total iso-α-acids and the T/C-ratio to decrease in concentration, respectively percentage, when exposing the samples to an increasing temperature. There was no effect of a change in trans-iso-α-acids attributed to vibrations.
- Three aldehydes, i.e. '2-methylpropanal', '2-methylbutanal' and 'furfural', indicate to be sensitive to vibrations and/or in combination with temperature. As a consequence, the total aldehydes concentration significantly increases when exposing beer to vibrations in combination with an elevated temperature. The temperature and vibrations have a significant impact on the total aldehydes concentration. However, the importance of vibrations is considerably lower compared to the influence of elevated temperatures. Also, the interaction effect between vibrations and temperature in the current experiment is substantial, although not identified as significant due to the increased variability at higher temperature. Since the impact of vibrations on the aldehydes is only substantial when being subjected to an elevated temperature, reducing temperature during transport and storage should be the main focus to breweries with respect to beer flavor quality.

[XXIV] In the experiments, performed at the KU Leuven technology campus Ghent, beer samples were exposed to vibrations of 100 rpm (lab shaker, horizontal 1 dimension) and 10-12 m/s^2 during 7 and 30 days at variable temperatures (5°C-30°C).

[XXV] While only an incremental change was observed with respect to iso-α-acids, and aldehydes, the turbidity of beer (cold and permanent haze) doubled in concentration (EBC FU) when comparing beer samples that had been exposed to the temperature of 30°C for 30 days with simples without exposure to horizontal one-dimensional vibrations of 1.7 Hz – 15m/s^2.

- There is strong evidence that transport vibrations have influence on the turbidity of beer, as is indicated in the current experiment and the additional experiments performed during the VIS/brewers-project.

Furthermore, the results indicated that there is potential to further develop a beer aging method that is shorter in time and duration than traditional methods (with respect to aldehydes). Due to the increasing importance of flavor stability in the brewing industry, caused by the global demand for beer, additional aging methods that can assess beer quality in a time and cost feasible fashion are highly recommended. Additional experiments with similar input vibrations and different beer types are recommended.

2.3 Shocks and beer quality

Bottled beer is frequently exposed to transient vibrations during beer distribution. However, the number of transient vibrations bottled beer experiences depends to a large extent on the packaging of the beer bottles. Moreover, former analysis (Part 5 Chapter 1 section 1.4) indicates that the use of corrugated boxes protects bottled beer by reducing both the number and the magnitude of the transient vibrations. When utilizing hard plastic crates, transient vibrations do frequently occur due to the vibrations not being damped and since bottles have free space to move.

Transient vibrations in truck and train transport are studied in previous Part 5 Chapter 1 sections 1.3 and 1.4, but also during handling transient vibrations occur. Handling involves the loading and unloading of cargo from a storage unit, container or trailer. Frequently, a forklift is used to move beer stacked onto pallets. The objective of the current explorative study is to identify the impact of simulated transient vibrations on bottled beer. Since bottled beer experiences most transient vibrations during domestic beer distribution and when packed in plastic crates, the latter is the unit of analysis and scope of the current research.

1) Methodology

When studying the impact of transient vibrations on the flavor stability of bottled beer, it is crucial to approximate the signals that occur during real-life transport. Therefore, the methods to simulate the transient vibrations, the benchmarking with transport (a), the experimental design (b), and the chemical tests of the beer samples (c) are discussed.

a) The simulation of transient vibrations & benchmarking with measurements during transport

In order to simulate transient vibrations, a drop device was manufactured that is able to mechanically and repetitively lift and drop a plastic beer crate filled with beer bottles (Figure 25). More specifically, by controlling an engine that pulls a rod up and down that is fixed to an electromagnet, a small metal plate anchored to the plastic crate will induce the system to go up and to drop the crate[XXVI]. A laptop with Matlab (MATLAB Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States) was connected to a data acquisition board (National Instruments USB-6361) to control the device. The extensive calibration measurements that were executed prior to the experiment are described in Appendix 5.

Since transient vibrations on bottled beer in corrugated boxes are limited, transient vibrations on beer bottles in hard plastic crates are studied. Therefore, the histogram of time-domain vibrations (> 5m/s^2) during truck transport described in Part 5 Chapter 1 section 1.3 was analyzed. The histogram indicates that during truck transport on average between 5 and 6 transient vibrations per minute are observed on bottled beer in plastic crates (with measured acceleration of the highest peak higher than 25m/s^2). As a consequence, bottled beer transported within Belgium will experience on average between 2700 and 3240 transient vibrations with peaks higher than 25m/s^2 per day (5-6 transient per minute vibrations within 9 hours a day[XXVII]). This information was used to design the experiment of the current study.

[XXVI] Linear actuator: Nanotec, DC Linear actuator, L5918L3008-T10X2-A50
Controller: Nanotec, SMCI35 - Stepper Motor Driver, Positioning Control, 6 A, 24 Vdc to 48 Vdc
Elektromagnet: Stephenson Gobin, 58-0250 24 VDC - Electromagnet, Type 58, 24VDC, 5.4W, 750N, IP51
Spindel: Nanotec, ZST5-5-200-1 - Threaded Screw Spindle, Linear ActuatorsT5x5, 200 mm

[XXVII] The daily driving period of European truck drivers may not exceed 9 hours (Regulation (EC) No 561/2006)[90].

Figure 25: Device for simulating transient vibrations – experimental setup

Beer samples were exposed to transient vibrations, while reference samples were placed next to the shock device. (The calibration measurements of the studied transient vibrations are presented in Appendix 5.)

Source: Own content

b) Experimental design

Distances within Belgium can be traversed within a single day, but in other countries travelling time can be longer. Therefore, in the current study, the selected beer samples were exposed to 8100 transient vibrations with a drop height of 4 mm, corresponding to transient vibrations with a peak of on average 34.69 ± 4.75 m/s^2, spread over a period of three days. The latter imposed signal corresponds to a truck transport of three days, for instance from Belgium to Italy. The beer bottles were exposed to extreme conditions in order to study the relation between transient vibrations and beer flavor quality.

The experiment comprised three consecutive days in which 10 cycles per day of 270 transient vibrations were imposed, in total 8100 transient vibrations. There were two setups, setup 1 performed at the ambient temperature of 25°C ± 3°C and setup 2 in a temperature room (in still air) of 30°C ± 1°C. During both setups a crate with reference samples was placed next to the vibrated samples. In total, two random selected Belgian lager beers (beer A and beer B) were incorporated in the current study. Lager beer is frequently exported to foreign countries and was, therefore, included in the current experimental study.

c) Chemical analysis of beer

The beer profiling parameters in this experiment are the oxygen concentrations (TPO, HSO, DO), haze measurements, beer color, iso-α-acids (*trans*-isocohumulone, *cis*-isocohumulone, *trans*-isohumulone, *cis*-isohumulone, *trans*-isoadhumulone, *cis*-isoadhumulone, total iso-α-acids, T/C-ratio), and aldehydes (2-methylpropanal, 2-methylbutanal, 3-methylbutanal, hexanal, furfural, methional, benzaldehyde, phenylacetaldehyde, (E)-2-nonenal, total aldehydes).

2) Results & discussion

While a realistic pattern of transient vibrations was imposed on the beer samples, the results indicated no statistical significant effect with respect to color, haze, iso-α-acids and aldehydes. Only the oxygen concentrations (HSO and DO) decreased marginally due the exposed transient vibrations, as presented in Table 10. The same results were observed for beer A and B. Furthermore, there is no need to input more extreme transient vibrations in amplitude or number since the likeliness of occurring during beer distribution is low. As a consequence, no additional research was performed on the matter.

Table 10: A more detailed investigation of the oxygen measurements (TPO, HSO, DO) after the shock experiment (data shown of beer A)

Avg. in ppb (STD)	TPO	HSO	DO
4 days in 25°C reference	272 (23)	246 (29)	26 (7)
4 days in 25°C with shocks	213 (27)	188 (24)	26 (4)
4 days in 30°C reference	235 (31)	210 (31)	25 (2)
4 days in 30°C with shocks	216 (19)	196 (17)	20 (4)

Only a limited effect with respect to oxygen concentrations (TPO, HSO, DO) was observed when beer samples were exposed to transient vibrations. Source: Own measurements

3) Conclusions & Recommendations

From the results of the current study, it can be concluded that individual transient vibrations will have limited effect on the beer flavor stability. Transport vibrations are considered as more important since they are continuous of nature. However, transient vibrations that occur during beer distribution might add to the vibration load and, therefore, may considered to be undesirable with respect to beer flavor stability.

Chapter 3: Taste experiments on beer flavor instability

In this chapter, the taste experiments that were performed are described. The objective of the experiments was to quantify the severity of the beer flavor instability problem by researching the consumption pattern of the general consumer. The research was performed in three phases:

- Assessing the differentiating ability between fresh and aged beer (section 3.1)
- Assessing the preference for fresh over aged beer (section 3.2)
- Assessing the drinkability of fresh and aged beer (section 3.3)

From this research, we aim to find out whether the questioned respondents are capable of differentiating between fresh and aged beer (3-4 months at 30°C). However, the preference test indicated that the questioned respondents showed no significant preference for fresh nor aged beer. In the drinkability test, on the other hand, the results indicated that the drinkability of fresh beer is higher compared to aged beer.

3.1 The differentiating ability between fresh and aged beer

1) Methodology

a) Experimental design

In the present study, consumer perception of fresh relative to aged beer of a non-expert test panel was assessed. Since a non-expert taste panel is not familiar with the concept of the general aging score (GAS) and, as a consequence, is not able to frame the experienced taste and to give a rational score, the use of Likert scales and aging scores was avoided in the current experiment. Moreover, the respondent was confronted with a triangle test in order to assess the ability of the consumer to distinguish fresh from aged beer. In a triangle test, the test panel is presented two samples that are the same and one sample that is different from the other two samples. The respondent is asked to indicate the odd sample of this triplet. Before starting the experiment, the respondent filled in a general questionnaire with questions regarding the demographic information and his/her drinking habits (questionnaire in Appendix 6).

b) Participants

In the current research, the aim was to survey people from Belgium and countries other than Belgium. Therefore, the respondents of this research are Belgians but also foreigners of different nationalities staying in Belgium for holidays, working or studying purposes. Although the university communication channels (i.e. e-mail lists – therefore, no random sample of respondents) were used to distribute the time and location of the event, tasters participated out of their own free will and without a preceding selection process. Prior to the experiment, the respondent had to ensure to be of legal drinking age or older.

The author of this study emphasizes that the use of the university communication channels induces that the sample of respondents was not random.

c) Beer samples

In this experimental set-up, the respondent participates in three triangle tests of three different beer types. A dark and blonde specialty beer was available for doing the triangle test since specialty beers are mostly exported, and a lager type of beer because this type of beer is particularly susceptible to flavor quality degradation. The three beers used in triangle tests are Beer A (pilsner beer), Beer B (blond specialty beer without in-bottle fermentation), Beer C (dark specialty without in-bottle fermentation). Specialty beers without in-bottle fermentation are adopted for the experiment, since yeast strains may counteract the flavor quality degradation and, therefore, may be less susceptible to beer aging[12].

For the purpose of this experiment, the aged beer was artificially aged by storing the beer in 30°C during four months (120 days) [Beer A and B] and three months (90 days) [Beer C]. The fresh beer, coming from the same batch as the aged beer, was stored at 0-5°C during the same period. A transport and storage period of three to four months (in combination with an elevated temperature) is realistic and occurs frequently during export to foreign countries[2]. Furthermore, the research indicates that after a period of three to four months in 30°C significant aged flavors and aromas are present in beer[4,20]. A general aging score between 4 and 6 can be attributed to the aged beer[4,20].

d) Procedure

The beer tasting experiment was organized in a specifically arranged room of the university building. When participants enter, a seat was assigned to every respondent and the questionnaire was handed over. After finishing the general part of the questionnaire, beer samples of beer A were brought to the respondent. After finishing the tasting of beer A, the samples of beer B and, afterwards, beer C were handed over to the participant. The triangle test with the lighter beers were performed first, and water and small pieces of bread were given, to avoid influencing the consecutive triangle tests. Considering the experiment is a blind tasting experiment, the beer samples were served in black opaque plastic cups and the beer brand was not mentioned to the respondents. The cups were labeled with random numbers of three digits (e.g. 671, 524, 985) and the fresh and aged beer samples were placed in a randomized order in front of the participant. It was ensured that the room was silent in order to allow the respondents to focus on the tasting experiment.

e) Data analysis

It is possible to test with statistical methods the competence of the respondents to distinguish fresh from aged beer with a triangle test. The hypothesis (H_0: the respondents are indifferent between the beer samples) can be tested using a chi-square distribution, X2=Σ (|O-E|)2/E, where O=observed and E=expected, and the probability of a correct answer is 1/3 and an incorrect answer is 2/3.

2) Results & Discussion

a) Participants & drinking habits

In total, 191 respondents enrolled in the consumer investigation of which 121 were foreigners and 70 Belgians. The international participants came from a wide range of countries, predominantly in Europe (Figure 26a). Furthermore, most foreign participants were only recently in Belgium (75% less than 4 months) and, therefore, were not biased by Belgian drinking habits or used to drinking Belgian beer. Since 90% of all respondents were between 20 and 30 years old (Figure 26b), the overall test population was relatively young (millennials). In addition, 49% of the enrolled respondents was male and 51% female. As presented in Table 11, the test population revealed relative moderation in their drinking habits.

Figure 26a: Segmentation of foreign respondents by home country – triangle test
Figure 26b: Histogram of the age of the respondents – triangle test

Figure 26a

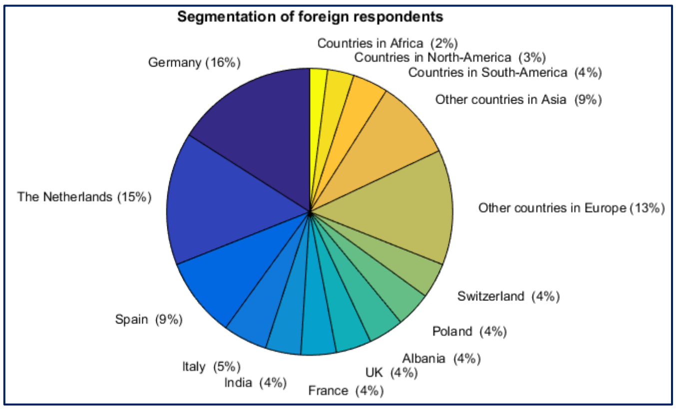
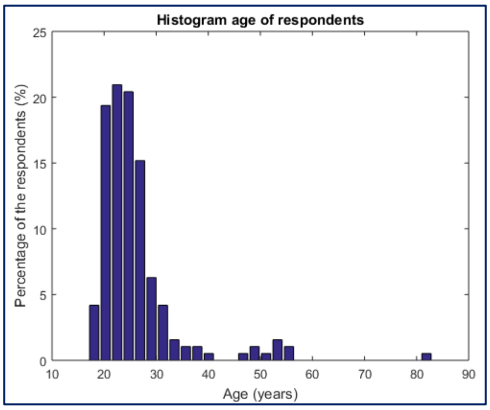


Figure 26b



Source: Own content

Table 11: Drinking habits – triangle test

	Beer A (Pilsner)	Beer B (Blond specialty beer)	Beer C (Dark specialty beer)
≤ 4 beers per month	38%	70%	85%
> 4 beers per month	62%	30%	15%

Source: Own measurements

b) Expert panel evaluation of the beer samples

As a measure of reference, the studied beer samples were also tasted by an expert panel of 5 to 7 tasters (i.e. tasters of the KU Leuven Technology Campus Ghent that are trained in identifying aged flavors and aromas). The samples were tasted, profiled by flavor and a GAS-score was assigned to every beer sample (Table 12). The results indicate that a clearly aged beer flavor was observed for the aged beer samples. Furthermore, the chemical analysis of the beer samples indicated that the measured color (EBC) increased 6 to 16% for the aged samples of all beer types. The total iso-α-acids decreased by 13-27%, while the TC-ratio decreased by 46-52% for the aged samples. The total aldehydes increased by 70-400% for the aged samples compared to the fresh beer samples (chemical analysis in Appendix 7).

Table 12: GAS-score for Beer A, B and C – triangle test

	Beer A (Pilsner)	**Beer B (Blond specialty beer)**	**Beer C (Dark specialty beer)**
GAS-score fresh beer	Avg. 0.2 – Med. 0 (STD: 0.4 – MAD: 0)	Avg. 0.0 – Med. 0 (STD: 0.0 – MAD 0)	Avg. 0.1 – Med. 0 (STD: 0.4 – MAD: 0)
GAS-score aged beer	Avg. 4.8 – Med. 4 (STD: 1.6 – MAD: 0)	Avg. 5.5 – Med. 5 (STD: 1.5 – MAD: 0)	Avg. 4.6 – Med. 5 (STD: 1.5 – MAD: 0)

The GAS-score developed by 5 (beer A and B) to 7 (Beer C) professional / trained tasters indicates that considerable aged flavors and aromas were observed in the beer samples.
Source: Own measurements

c) Non-expert panel evaluation of the beer samples

In Table 13, the results of the experiment for all respondents, foreigners and Belgians are presented. The table indicates that all three consumer groups were capable (with statistical significance) of distinguishing the fresh from the aged samples. No significant difference was observed with respect to the results for male and female respondents, people that like or dislike the beer samples, and respondents segmented within the different consumption patterns. Furthermore, the results (percentages) and the answers of the respondents indicated that the test was difficult, which is presumably due to the nature of the experiment and the complexities of the human psychology in comparing aroma and taste of three beer samples.

Table 13: Results of the performed triangle tests – fresh and aged (3 to 4 months at 30°C) beer – experiment performed at University of Antwerp and KU Leuven Campus Ghent venue

	All respondents (191p)	Foreigners (121p)	Belgians (70p)
	Percentage of the respondents capable to distinguish fresh from aged beer	**Percentage of the respondents capable to distinguish fresh from aged beer**	**Percentage of the respondents capable to distinguish fresh from aged beer**
Beer A [Lager beer] (Number of respondents in category)	47.6% (91/191) => $p < 0.001$	49.6% (60/121) => $p < 0.001$	44.3% (31/70) => $p= 0.052$
Beer B [Blond beer] (Number of respondents in category)	44.0% (84/191) => $p= 0.0018$	43.0% (52/121) => $p= 0.025$	45.7% (32/70) => $p= 0.028$
Beer C [Dark beer] (Number of respondents in category)	61.3% (117/191) => $p < 0.001$	58.7% (71/121) => $p < 0.001$	65.7 % (46/70) => $p < 0.001$

The statistical analysis indicates that both foreigners and Belgians were able to statistically significantly distinguish fresh from aged beer samples in a triangle test. Source: Own content

Additional statistical research was performed by segmenting the respondents group by gender, age, drinking behavior and habits, degree of education and current employed job type (survey in Appendix 6). However, the performed chi-square tests did not produce relevant insights.

3) Conclusions & Recommendations

From the results, it is deduced that the respondents were able to discriminate (with statistical significance) between fresh and aged beer. As a consequence, there is strong evidence that the consumer would notice a difference when the brewery decides to alter the beer recipe or when flavor instability of beer is counteracted by incorporating refrigerated storage and transport

3.2 The preference for fresh over aged beer

1) Methodology

a) Experimental design

In the current experimental test, the potential preference for fresh over aged beer was studied. A duotest was performed to derive this information. The duotest involves offering the respondents two beer samples, demanding if they taste a difference between the beer samples, and asking for the preference. The respondent was informed that beer with two different recipes was offered. Additionally, the willingness to pay of the respondent for the preferred beer sample over the alternative beer sample was asked. Moreover, the contingent valuation method (CVM) was adopted, using a 'payment-card' question, to assess the willingness to pay of the respondent. This economic valuation method is regularly used in practice and described in the literature[48–50]. The respondent was given different options of which the taster was able to choose the monetary amount he/she is willing to pay more for the preferred sample over the other samples.

Prior to the experiment, the respondent filled in a general questionnaire with questions regarding the demographic information and the drinking habits (questionnaire in Appendix 6).

b) Participants - Beer samples - Procedure

The same method of approaching participants, the same beer samples and procedure as in Part 5 Chapter 3 section 3.1 was selected for the current experiment [two different calls were sent out with respect to this experiment and the experiment in Part 5 Chapter 3 section 3.1]. Also, the sample of respondents in this study was not random since the university communication channels were used to gather respondents.

c) Data analysis

Similar to Part 5 Chapter 3 section 3.1, the chi-square test was adopted.

2) Results & Discussion

a) Participants & drinking habits

In total, 95 respondents enrolled in the consumer investigation of which 65 respondents were foreigners and 30 respondents were Belgians. The international participants came from diverse countries (Figure 27a). Furthermore, most foreign participants were only recently in Belgium (85% less than 4 months) and, therefore, were not biased by Belgian drinking habits or used to drinking Belgian beer. While in the triangle tests of Part 5 Chapter 3 section 3.1 most of the respondents had the age between 20 and 30 years old, respondents with a more uniform age segmentation participated in the current experiment (Figure 27b). Furthermore, 73% of the enrolled respondents was male and 27% female. As presented in Table 14, the test population revealed relative moderation in their drinking habits.

Table 14: Drinking habits – duotest

	Beer A (Pilsner)	**Beer B (Blond specialty beer)**	**Beer C (Dark specialty beer)**
≤ 4 beers per month	52%	62%	87%
> 4 beers per month	47%	28%	14%

Source: Own content

Figure 27a: Segmentation of foreign respondents by home country – duotest
Figure 27b: Histogram of the age of the respondents – duotest

Figure 27a

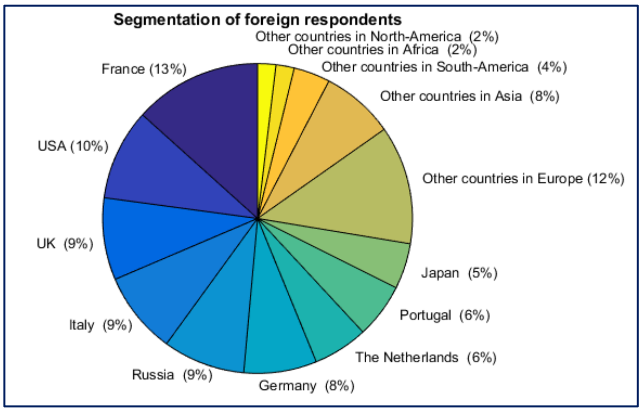
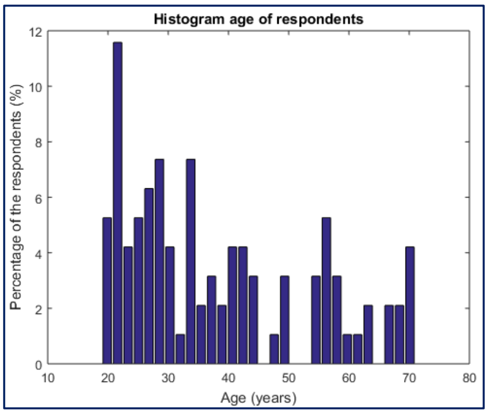


Figure 27b



Source: Own content

b) Non-expert panel evaluation of the beer samples

In Table 15, the results of the executed duotests are presented. From this table, one may conclude that a statistically significant majority of the respondents taste a difference between the fresh and aged beer samples. However, the percentage of respondents that prefer fresh over aged beer remains moderately close to 50%, i.e. the fresh beer is not statistically significantly preferred over the aged beer (on a significance level of 5%). The fresh lager beer [Beer A] is preferred by 50.5% of the respondents over the aged beer. The fresh blond specialty beer [Beer B] is favored by 54.1% of the respondents over the aged equivalent. The fresh dark specialty beer [Beer C] is preferred by 60.0% of the respondents over the aged beer. The preference for fresh over aged beer is higher with respect to the dark specialty beer than the lager and blond beer. The researcher attributes the latter finding to the more pronounced taste characteristics of the beer (also picked up by the triangle test in Part 5 Chapter 3 section 3.1).

Table 15: Results of the performed duo tests – fresh and aged (3 to 4 months at 30°C) beer – experiment performed at University of Antwerp and KU Leuven Campus Ghent venue

All respondents (95p)	**Percentage of the respondents that indicate to be capable to distinguish fresh from aged beer**	**Percentage of the respondents that prefer fresh over aged beer**
Beer A [Lager beer] (Number of respondents in category)	90.5% (86/95*) => $p < 0.001$	50.0% (43/86) => $p = 1.000$
Beer B [Blond beer] (Number of respondents in category)	67.0% (61/91*) => $p < 0.001$	54.1% (33/61) => $p = 0.522$
Beer C [Dark beer] (Number of respondents in category)	76.9% (70/91*) => $p < 0.001$	60.0% (42/70) => $p = 0.094$

* 4 respondents only took part in the tasting of Beer A (the lager beer), and not of Beer B and C

While a considerable number of respondents indicated to taste a difference between the fresh and aged beer samples, the fresh beer was not statistically significantly preferred over the aged beer. Source: Own content

While additional segmentations were performed based on the drinking pattern, age[XXVIII], gender, and nationality, similar results were found as presented in Table 15 (no relevant insights). Furthermore, the willingness to pay for fresh over aged beer was determined for the three beer types. However, since there was no clear preference for fresh beer, a perfect bell shaped curve with respect to the willingness to pay[XXIX] was identified, which indicates the indifference or equal preference for fresh and aged beer.

The current findings were benchmarked with the existing literature. Stephenson and Bamforth (2002)[51] also indicated the indifference of the consumer towards fresh versus aged beer. However, the objectives of the experiment and the experimental design of Stephenson and Bamforth diverged from the current study (i.e. stale character of beer in relation to branded and unbranded products were researched). Moreover, other studies revealed that marketing, branding and market positioning is of major importance to consumer's buying behavior. Galizzi and Garavaglia (2012)[52] stated that the decision of a consumer to purchase beer is more affected by the perceived brand evaluation than by the intrinsic characteristics of the beer. The latter also proves the success of European beers, and Belgian beer brands in particular, in foreign countries, which are commonly positioned as premium brands. The consumer generally perceives a product of higher price as better quality or status, while beer of lower price might signify mass-produced drinks[53]. In Hong Kong and the USA, for instance, European beer resembles a richer style of beer and a product of top quality for which the consumer is willing to pay a high premium[54,55].

<u>3) Conclusions & Recommendations</u>

Within the limitations of the experimental set-up, it can be concluded that the surveyed respondents did not statistically significantly prefer fresh over aged beer with respect to the three selected beers (Beer A, B and C). As a consequence, there are three additional remarks (hypotheses) that might be deduced from this study:

- The aroma and taste characteristics of fresh and aged beer differ and an equal number of respondents might favor fresh and aged beers.
- The respondents might be insensitive to the change of taste and aroma since the difference between the two samples is perceived to be minimal.
- The respondents might prefer fresh over aged beer, but the difference might not be picked up by the duotest. This might be attributed to stress of the respondents participating in a beer experiment, or the small beer sample sizes. The small beer samples might be insufficient to respondents in order to frame an opinion on the preference of the tasted samples. Furthermore, when beer is consumed in reality the beer temperature in the glass rises over time. The rising beer temperature increases the presence of off-flavors in beer, and, therefore, the preference for fresh beer might be more pronounced in larger sample sizes.

In order to further study the potential preference of fresh over aged beer and the above mentioned considerations, an additional experiment was designed in Part 5 Chapter 3 section 3.3.

[XXVIII] Due to the results of Part 5 Chapter 3 section 3.3 on the drinkability of fresh/aged beer, the results of the preference test of Belgians older than 27 years was analyzed. The results (presented in Appendix 8) are not statistically significant due to the small number of samples but indicate the preference for fresh beer.
[XXIX] A histogram was made of the willingness to pay for fresh over aged beer. The preference and increased willingness to pay for aged over fresh beer, respectively fresh over aged beer, is identified by a negative percentage, respectively a positive percentage. A bell curve with average at 0% observed (no increased willingness to pay for fresh nor aged beer).

3.3 The drinkability of fresh and aged beer

1) Methodology

a) Experimental design

In the current experimental study, a multi-objective experiment was designed with respect to the preference and the drinkability of fresh and aged beer. The drinkability of beer is defined as:

"*When speaking of drinkability most brewers take it to refer to the quality of beer which motivates a consumer to have another one – i.e. to have two pints when they intended to have one, or have three when they intended to have two. What motivates a consumer to do this is a complex mixture of situation, psychology, physiology, beer chemistry and beer physics*."[56]

Therefore, by studying the drinkability, the effect of multiple 25cl. beer consumptions with respect to fresh and aged beer is researched. Fresh beer is assumed to be more drinkable than an aged beer since the taste and aroma should be more balanced in fresh beer. The experimental design is identified as the 'paired comparison test' described by Cejka et al. (2011)[57]. In the executed experiment, respondents first drink small test samples of the two studied beers prior to the general test. Afterwards, the respondents can freely decide to consume the beer they prefer. The volume and the time between consecutive consumptions should be tracked since a more drinkable beer is defined by a higher consumed volume and faster consumption. Additionally, a proxy for the preference of one of the two samples can be derived by the identification of the first consumption after the duotest (prior to the experiment).

In the current experiment, the drinkability of beer was studied, and, therefore, a pub-like environment was simulated. Nevertheless, the researcher made sure that during the experiment responsible drinking was always high on the agenda.

b) Participants

In the current research, the objective was to study the drinking behavior of respondents from both foreign countries and Belgium of diverse age groups with respect to fresh and aged beer. Diverse communication channels were utilized to distribute information concerning the experiment and to gather respondents. Moreover, a general call from the researcher's profile and targeted messages in the group 'expats in Antwerp' and 'PhD researchers in Antwerp' were generated by using Facebook. Furthermore, an email was distributed through the university network to inform employees and students from the University of Antwerp. The tasters participated out of their own free will and without a preceding selection process. Prior to the experiment, the respondent had to ensure to be of legal drinking age or older. Since the university communication channels were used to gather respondents, the author of the study would like to emphasize that the respondents sample was not random.

c) Beer samples

Since the drinkability of fresh and aged beer was studied, a lager beer brewed by a Belgian brewery was selected. Half of the beer samples were aged for 120 days (4 months) at 30°C in climate room (still air) and half the samples were stored in a climate room (still air) in 5°C over the same time period in order to keep the beer fresh. The same ageing period and temperature was used as was performed in the taste experiments of Chapter 3 section 3.1 and 3.2. The chemical parameters characterizing the beer samples are presented in Appendix 9.

d) Procedure

While the drinkability of fresh and aged beer was assessed in the current experiment, this information was not communicated to the respondents. Moreover, the participants assumed that two types of lager beer were tested (Beer X and Y) that were brewed by different beer recipes. Participants were required to register in an online tool prior to the experiment. In the online tool, questions were asked in order to identify the general information (e.g. age, gender, etc.) and the consumption profile of the participant (questionnaire in Appendix 6). Before the start of the experiment, every participant was assigned a random respondent number by the researcher. The respondent number was printed on 6 consumption tickets that was used by the participant to order their preferred beer (Beer X or Y). The consumption tickets were handed over to the respondent at the beginning of the experiment (after executing the duotest). A maximum number of 6 consumptions (25cl.) were offered in order to prevent irresponsible drinking but also to induce the natural consumption pattern of the respondent. Respondents had to order a consumption of their preferred beer (X or Y) at the counter by handing over a consumption ticket (that is linked to their registered profile). A software program (that was built in Matlab especially for the current experiment) registered the time, the type of the sample (X or Y) and the respondent number. It was made sure that there were no queues at the counter and that respondents were not able to see the type of beer the other respondents were served. Furthermore, the beer brand was not visible to the respondent. While the beers (25cl.) in the drinkability experiment were served in glasses as is in a normal pub, the glasses of the duotest (prior to the drinkability experiment) were served in black opaque plastic cups (10cl.). The reasoning of using the plastic cups was to design the experiment similar to the duotest in Chapter 3 section 3.2. Before and during the experiment sandwiches and crackers were served in order to allow the respondents perform the experiment without an empty stomach. The room of the experiment was filled with tables of variable sizes in order to simulate a normal pub experience. Before the actual test, a pre-test was organized with 17 respondents (17 out of 91 respondents) in order to dry-run the experiment. The duration of the experiment was 2 hours (informed to the respondents before the experiment), although the respondents did not enter simultaneous. Therefore, the total duration of the experiment was 3.5 hours.

e) Data analysis

The data generated by this experiment was analyzed by variable methods:

- The Wilcoxon's signed rank sum test (e.g. in order to identify the beer type X or Y with the highest drinkability, i.e. the median or mean of the difference between the number of fresh and aged samples should be significantly different from zero)
- The Chi-square test [Likelihood, Pearson and Fischer] (e.g. identifying the significance of the segmentation of data, i.e. by building a contingency table and comparing the expected and observed frequency of success between different variables)
- The Chi-square test [Randomness test] (e.g. identifying the significance of success within one variable, i.e. comparing the expected and observed frequency of success for a specific variable)

The statistical analysis of the current research was performed within JMP Pro13.

2) Results & Discussion

a) Participants & drinking habits

In total, 91 respondents enrolled in the consumer investigation of which 35 respondents (38%) were foreigners and 56 respondents (62%) were Belgians. The international participants came from diverse countries (Figure 28a). In the current experiment, respondents with the age between 20 and 30 predominantly participated in the experiment (Figure 28b). Furthermore, 56% of the enrolled respondents was male and 44% female. As presented in Table 16, the test population revealed relative moderation in their drinking habits.

Figure 28a: Segmentation of foreign respondents by home country – drinkability test
Figure 28b: Histogram of the age of the respondents – drinkability test

Figure 28a

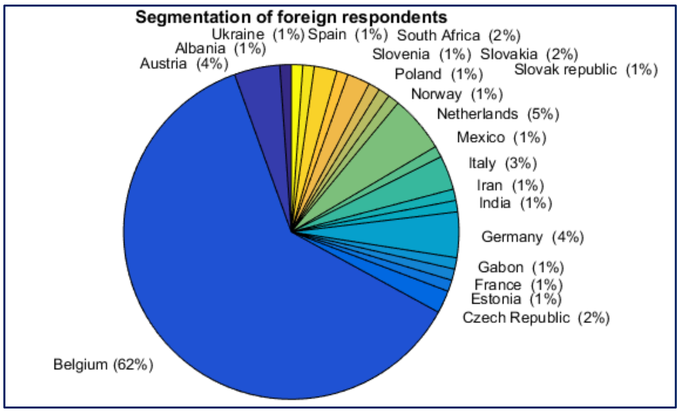
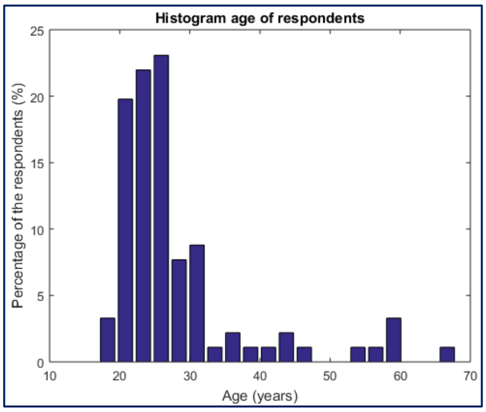


Figure 28b



Source: Own content

Table 16: Drinking habits – drinkability test

	Lager beers	Specialty beers
≤ 4 beers per month	48%	58%
> 4 beers per month	52%	42%

Source: Own content

b) Drinkability results

The consumption pattern of all respondents consuming fresh and aged beer was tracked throughout the experiment. In Figure 29a and 29b, the results of the drinkability experiment are presented in which the respondents are ranked by table and age. In total, 376 beers of 25cl. were consumed of which 160 were aged and 216 were fresh lager beers (statistically significant by the chi-square randomness test on a 5% significance level). The first consumption after performing the duo test was in 65% of the cases a fresh beer (59 out of 91 respondents – statistically significant by the chi-square randomness test on a 5% significance level). Between 77 and 89% of the respondents that consumed fresh, respectively aged beer, as a first consumption continued within the same type of beer with respect to their second consumption. Some respondents kept on drinking the fresh and aged beer for six consumptions in a row. From the figures, one may derive that some respondents consumed the two beer types, although they performed the duo test prior to the experiment. This may be attributed to curiosity in the other beer type, the influence of the other respondents (sitting at their table), or indifference towards the two offered beer types. Figure 29a indicates that there are strong indications that the table at which the respondent is sitting influences the consumption of the two beer types. Moreover, the tables can be segmented in fresh and aged tables (strong preference per table) while it is expected that the larger the table size the more the consumption volume per table would approach the overall preference of 58% fresh beer. A descriptive analysis of the nominal homogeneity index[58] (nHi), presented in Appendix 10 indicates the same finding. The analysis of the age of the respondents and their consumption profile (Figure 29b) indicates that older respondents might be more inclined to prefer fresh over aged beer.

Figure 29a: Results of the performed drinkability test (respondents ranked by table)

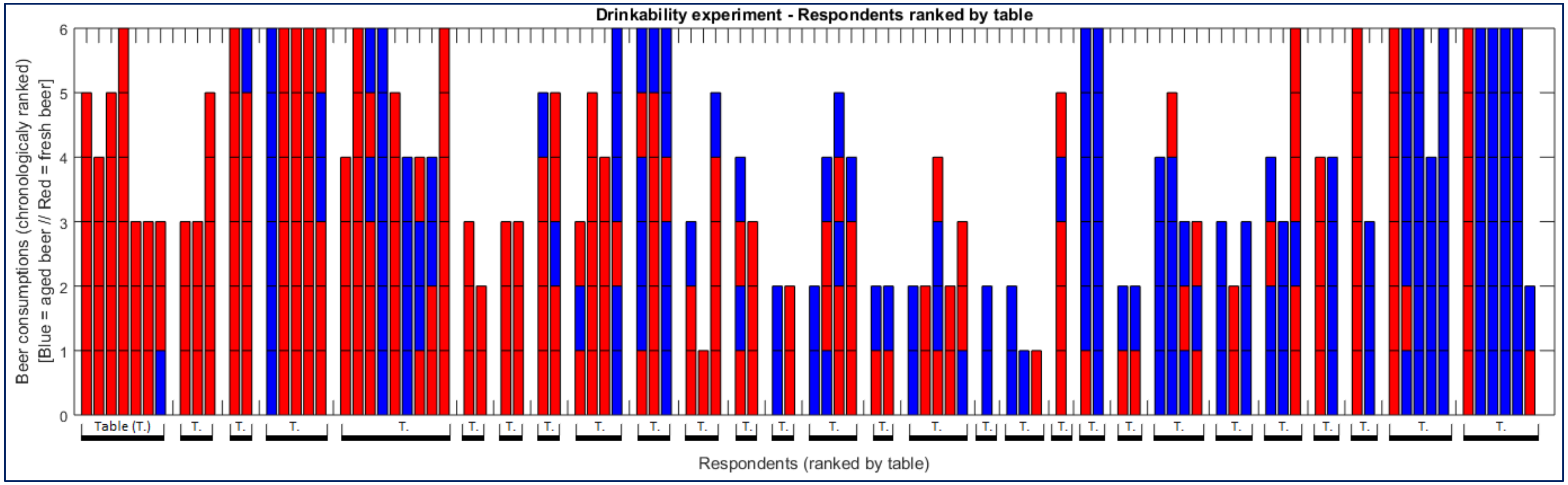
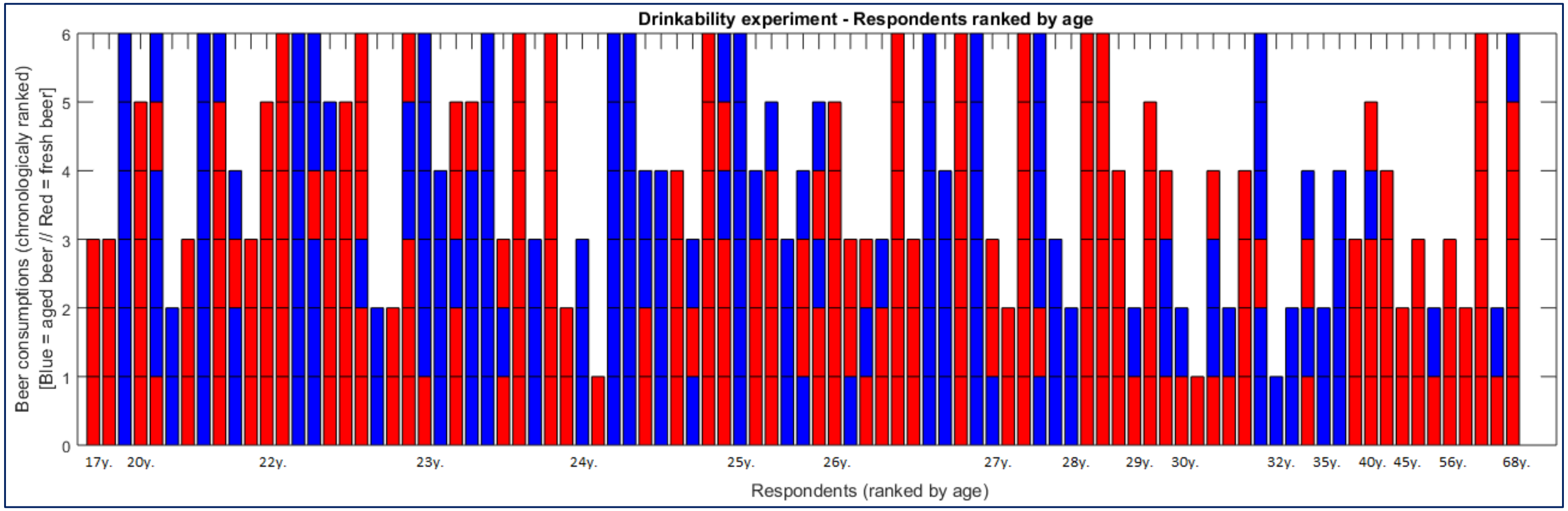


Figure 29b: Results of the performed drinkability test (respondents ranked by age)



There is strong evidence that the table setting (Fig. 29a) and the age of the respondents (Fig. 29b) are explanatory variables for the consumption behavior. Source: Own content

The data that was generated by the experiment was also studied by statistical analysis. Moreover, the Wilcoxon's signed rank sum test was executed in order to test the overall drinkability for fresh and aged beer (with H_0: The drinkability of fresh beer is identical to the drinkability of aged beer – the volume of fresh beer is identical to the volume of aged beer). Since 57.5% of the total consumed volume of beer was fresh beer (216 out of 376 consumptions), the statistical analysis also indicated that the null-hypothesis (H_0) should be rejected on a 10% significance level (p-value of 0.056). Nevertheless, while the preference for fresh over aged beer is manifest, which contributes to the higher consumption volumes of fresh beer, the study also indicates that several respondents are capable of drinking multiple aged beer consumptions (max. 6 consumptions). Therefore, consumers that drink aged beer do not necessarily consume less of the aged beer compared to the respondents drinking fresh beer. Furthermore, the Wilcoxon's signed rank sum test was also executed on the time interval of the respondents drinking their first fresh respectively aged beer (with H_0: The drinkability of fresh beer is identical to the drinkability of aged beer – the volume of fresh beer is identical to the volume of aged beer). There was no statistical significant difference observed between the time of consumption of a fresh or an aged beer, and, therefore, the null-hypothesis (H_0) is not rejected (p-value of 0.731).

Additionally, an explorative analysis was performed on the parameters that may contribute to the increased drinkability and preference of fresh over aged beer. Therefore, contingency tables were built that present a segmentation of the total consumed volume of fresh and aged beer among the nationality, the age and the table size of the table at which they performed the experiment (Table 17a - 17c). The contingency tables enable to perform statistical Chi-square tests [Likelihood, Pearson and Fischer, Randomness]. The following null-hypothesizes (H_0) were formed:

- H_0: The segmentation between Belgians and non-Belgians is not relevant with respect to the results of the drinkability experiment. [Likelihood, Pearson and Fischer]
- H_0: Within the category of the Belgian respondents, the consumed volume of fresh and aged beer is not significantly different from each other. [Randomness test].

Table 17a: Contingency table – influence of Belgians and Non-Belgians – fresh and aged (4 months at 30°C) beer – drinkability experiment performed at University of Antwerp and KU Leuven Ghent venue

NATIONALITY	Belgians (56p.)	Non-Belgians (35p.)	Total
Fresh	152 (= 64%)	64 (= 47%)	216 (= 57%)
Aged	87	73	160
TOTAL	239	137	376

The segmentation between Belgians and non-Belgians is relevant (p-value < 0.001). Belgians significantly consumed more fresh than aged beer (p-value < 0.001).

Source: Own content

Table 17b: Contingency table – influence of Age – fresh and aged (4 months at 30°C) beer – drinkability experiment performed at University of Antwerp and KU Leuven Ghent venue

AGE	Age (≤ 27y.) (62p.)	Age (> 27y.) (29p.)	Total
Fresh	146 (= 53%)	70 (= 71%)	216 (= 57%)
Aged	131	29	160
TOTAL	277	99	376

The segmentation between respondents younger than 27 years and older than 27 years is relevant (p-value < 0.001). Respondents younger than 27 years significantly consumed more fresh than aged beer (p-value < 0.001).

Source: Own content

Table 17c: Contingency table – influence of table size – fresh and aged (4 months at 30°C) beer – drinkability experiment performed at University of Antwerp and KU Leuven Ghent venue

TABLE SIZE	Tables (≤ 2p. per table) (24p.)	Tables (> 2p. per table) (67p.)	Total
Fresh	56 (=64%)	160 (= 56%)	216 (= 57%)
Aged	32	128	160
TOTAL	88	288	376

The segmentation between respondents at tables less than 2 people and more than 2 people is not relevant, although a low p-value was observed (p-value = 0.11). Respondents at tables less than 2 people significantly consumed more fresh than aged beer (p-value < 0.001).

Source: Own content

From the contingency table of Table 17a and the performed statistical analysis, one may derive that the segmentation between Belgians and non-Belgians is relevant (rejection of H_0 with p-value < 0.001). Furthermore, Belgians significantly consumed more fresh than aged beer (rejection of H_0 with p-value < 0.05). The consumed volume of fresh and aged beer of non-Belgians is not significantly different from each other. With respect to the age of the respondents (Table 17b), the segmentation of the respondents younger and older than 27 years is relevant (rejection of H_0 with p-value < 0.001). A sensitivity analysis was performed on the age of the respondents (with respect to the same analysis). The same but less substantial results were found when the segmented cut-off age was lowered at 26, 25 and 24 years (but not at 23 years old). Furthermore, the respondents older than 27 years significantly consumed more fresh than aged beer (on a significance level of 5%) while this finding was not observed for the younger respondents. The results of the drinkability experiment (Figure 29a) suggest that there are strong indications that the table size has an influence on the consumption pattern of the respondents. Therefore, a segmentation was performed on tables smaller and larger than 2 respondents per table (Table 17c). However, the statistical analysis indicates that the segmentation of the data is not relevant (acceptance of H_0 with p-value = 0.11). Nevertheless, the data indicates that respondents at tables smaller than or equal to 2 persons per table significantly consume more fresh beer. The same finding is not observed for tables larger than 2 persons. A similar analysis was performed in order to identify the impact of the gender of the respondents, and the consumption pattern (≤ and > 4 consumed lager beers per month) but no statistically significant findings were observed.

Further segmentations were performed in order to understand the findings of the drinkability experiment. Moreover, the respondents were segmented by nationality, consumption pattern and age (Table 18). However, the results are predominantly indicative due to the relative small sample sizes. Nevertheless, from Table 18, it can be deduced that Belgians older than 27 years significantly prefer fresh over aged beer irrespective of the consumption habits of the respondent (sensitivity analysis indicates the cut-off at 25 years). Furthermore, Belgians younger than 27 years and non-Belgians of all age categories that participated in this experiment did not significantly consume more fresh than aged beer. Additional analysis of the Belgian respondents older than 27 years was executed with respect to the table sizes (Table 19). The results of Table 19 indicate that the higher consumed volume of fresh over aged beer (at different table sizes) is predominantly attributed to the Belgians that are older than 27 years. This finding also indicates that the opinion of these respondents on the perceived flavor quality of the beer is less influenced by the other respondents at their table compared to the other age groups and nationalities.

Table 18: Contingency table – influence of a segmentation by nationality, consumption pattern and age – fresh and aged (4 months at 30°C) beer – drinkability experiment performed at University of Antwerp and KU Leuven Ghent venue

	(Belgian) + (≤ 4 consumed lager beers per month) + (Age ≤ 27y.) (16p.)	(Belgian) + (≤ 4 consumed lager beers per month) + (Age > 27y.) (8p.)	(Belgian) + (> 4 consumed lager beers per month) + (Age ≤ 27y.) (24p.)	(Belgian) + (> 4 consumed lager beers per month) + (Age > 27y.) (8p.)	Total (56p.)
Fresh	35 (= 57%)	**22 (= 85%)**	67 (= 55%)	**28 (= 87%)**	152 (= 64%)
Aged	26	**4**	53	**4**	87
TOTAL	61	**26**	120	**32**	239
	(non-Belgian) + (≤ 4 consumed lager beers per month) + (Age ≤ 27y.) (13p.)	(non-Belgian) + (≤ 4 consumed lager beers per month) + (Age > 27y.) (7p.)	(non-Belgian) + (> 4 consumed lager beers per month) + (Age ≤ 27y.) (9p.)	(non-Belgian) + (> 4 consumed lager beers per month) + (Age > 27y.) (6p.)	Total (35p.)
Fresh	26 (= 50%)	8 (= 53%)	18 (= 41%)	12 (= 46%)	64 (= 47%)
Aged	26	7	26	14	73
TOTAL	52	15	44	26	137

From Table 18, it can be derived that predominantly Belgians older than 27 years explain the observed results with respect to the consumed volume of fresh beer.

Source: Own content

Table 19: Contingency table – influence of a segmentation by age and table size (Belgian respondents) – fresh and aged (4 months at 30°C) beer – drinkability experiment performed at University of Antwerp and KU Leuven Ghent venue

	(Belgian) + (Age > 27y.) + (Tables with ≤ 2p. per table) (9p.)	(Belgian) + (Age > 27y.) + (Tables with > 2p. per table) (7p.)	OTHER RESPONDENTS at tables with ≤ 2p. per table (15p.)	OTHER RESPONDENTS at tables with > 2p. per table (60p.)
Fresh	**28 (= 85%)**	**22 (= 88%)**	28 (= 51%)	138 (= 52%)
Aged	**5**	**3**	27	125
TOTAL	**33**	**25**	55	263

From Table 19, it can be derived that predominantly Belgians older than 27 years explain the observed results with respect to the consumed volume of fresh beer. Furthermore, the table setting is irrelevant regarding the consumption of fresh beer for this particular group of respondents.

Source: Own content

In addition to the current analysis, the preference data of the current experiment (first beer consumption after the duo test) was compared to the results of the duo test of Chapter 3 section 3.2 in Appendix 8. The results presented in Appendix 8 validates the formerly described findings with respect to Belgians older than 27 years.

3) Conclusions & Recommendations

Within the limitations of the experimental set-up of the drinkability experiment, the following conclusions are developed:

- The drinkability of fresh beer is statistically significantly higher for fresh than for aged beer (216 consumptions fresh beer and 160 consumptions aged beer)
- The higher preference for fresh over aged beer is statically significant (65% fresh beer as a first consumption)
- The consumption of aged beer does not discourage the respondent to stop further drinking of aged beer (there are respondents with 6 aged beer consumptions)
- Belgians that are older than 27 years (sensitivity analysis indicates the cut-off at 25 years) have a strong preference for fresh beer (and perceive to be less influenced by other respondents (at their table))
- Foreign respondents and Belgians younger than 27 years (sensitivity analysis indicates the cut-off at 25 years) have no statistically significant preference for fresh beer
- The tables respondents are sitting at and table sizes significantly influence the type of beer consumed (since respondents influence each other)

As a consequence, and taking into consideration the prior conclusions, targeting the consumer group of Belgians older than 25 years is crucial for breweries with respect to the beer flavor quality. Furthermore, additional research is recommended in order to identify the reasons why this consumer group is more sensitive to the differences between fresh and aged beer. Nevertheless, it is relevant to improve product quality since in an ever digital world it is essential to not underestimate the influence of other people's opinions (e.g. groups of people in a pub or (online) expert reviews) on the mimicking behavior of consumers[59].

Furthermore, since this study is the first to explore the drinkability between fresh and aged beer, it is recommended to repeat the current experiment in order to improve the statistical significance of the results. Additionally, it is recommended to study the drinkability by using the 'Monadic test' as described by Cejka et al. (2011)[57], which will make able to develop more insights on the drinkability that cannot be found when using the current 'paired comparison test'. In this experimental design, the respondents are split up in two groups and are forced to drink one of the two beer types, i.e. fresh or aged beer. The advantage over the 'paired comparison test' is that respondents cannot mix consumptions of the fresh and aged beer, and, therefore, the interpretation of the results is more straightforward. Ideally, the experiment is repeated and the same respondents drink the other beer type they drank in the first experiment.

Part 6: Economic implications

Chapter 1: Economic feasibility of refrigerated transports

The use of refrigerated ('reefer') containers to transport beer can result in an improved chemical and sensorial quality of the beer since the heat to which beer is exposed is controlled[3]. In order to explore the feasibility of cooled transport, a comparative study of the dry container and refrigerated container transport costs was performed. Furthermore, the mechanisms that contribute to the pricing and freight rates of container traffic will be elaborated. The distinction between maritime (section 2a) and truck transport (section 2b) was made to evaluate the brewer's transport costs. The results indicate that refrigerated shipping containers are approximately € 1,500 more expensive than the dry equivalent (although volatile and quickly changing over time). Refrigerated truck transport in Belgium and its neighboring countries is approximately € 50 more expensive, while to other countries an additional price increase of 60% to 150% on top of the normal dry container freight price is charged.

In addition, the impact of adapting reefer temperature to optimize beer quality and economic feasibility was studied (section 2c). With respect to beer flavor quality, it is crucial to protect beer from elevated temperatures (e.g. 30°C-45°C), however there are limited problems in exposing beer to temperatures between 5°C-15°C. Therefore, by increasing the reefer temperature fuel costs can be saved and a better negotiation position of the brewery in decreasing reefer transport costs can be achieved. Finally, the economic feasibility of refrigerated transports by breweries is discussed (section 2d). Simulations were performed in which the feasibility of refrigerated transport was assessed by mapping the theoretical change in total profits and the increase of volume of beer sold due to refrigeration and increased beer flavor stability.

1) Methodology

Apart from the findings in literature, the current study (Section 2a and b) was developed based on the information coming from the personal correspondence with six logistics providers.

- Logistics providers A, B and C: multinational shipping companies
- Logistics providers D and E: small and medium enterprise truck transport companies located in Belgium
- Logistics provider F: International transport carrier (predominantly truck transport) with subsidiary in Belgium

With respect to Section 2c, adapting reefer temperature during refrigerated transport, personal correspondence with a supplier of the cooling equipment of reefer containers was a major source of information. The last Section 2d is composed based on the information of previous sections.

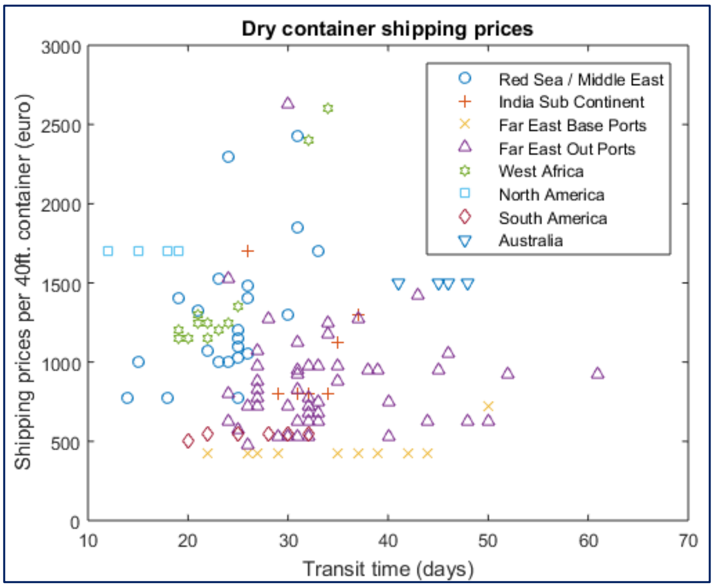
2) Results & Discussion

a) Maritime transport prices

Dry container shipping rates/prices

The dry bulk market shipping freight rates are considered difficult to interpret, volatile and quickly changing over time[60]. The dependence on gasoline for the vessels, the influence of port infrastructure and regional logistic and fiscal regulations are aspects contributing to maritime container transport prices. In Figure 30, an overview of the dry container shipping rates in March 2016, with Antwerp as the port of origin and destination ports in different continents, is presented[61]. The figure also indicates that transit time (x-axis) is not the main driver contributing to the shipping price (excl. port charges, import charges, and other charges) (y-axis). These findings were also highlighted in the work of Wilsmeier (2014)[62]. Furthermore, competitive freight rates and maritime transport prices contribute to the competing strength of a port environment and, as a consequence, the economic power of an entire region[60]. The information concerning transport prices can indicate the need for reforms (e.g. customs administrations) or potential investments that should be induced by the policy makers[60]. For instance, Wilsmeier (2014)[62] indicated that it is on average 40% to 70% more expensive for the international transport of imported goods for developing countries, particularly in Africa and Oceania, than it is for developed countries. The region's trade imbalances, lower trade volumes and shipping connectivity, and pending port and trade facilitation reforms are indicated as the main drivers.

Figure 30: Dry container (40 ft.) shipping prices relative to transit time*



*The information of the figure was provided by an international shipping agency company (with subsidiary in Belgium). Analysis in this section is limited to 40 ft. containers (2 TEUs – 'Twenty Foot Equivalent Unit'), the most commonly used type of containers in the international container traffic.
There is no particular relation between the transit time and the shipping prices per 40ft. container since multiple other parameters explain the maritime transport prices e.g. availability of a container, trade volumes, shipping connectivity.
Source: Logistics provider A, 2017[61]

Reefer container shipping rates/prices

Reefer containers or refrigerated containers are used to transport food products under cooled transport conditions. Large seaborne perishable cargoes transport these products (e.g. exotic fruit, meat and dairy products) predominantly from the developing countries, which have a warmer climate, to the developed countries, the consumers of the products. Apart from food products, shipments in refrigerated containers could also be beneficial for transporting beer. Since beer quality is sensitive to temperature, refrigerated shipments could increase the chemical and sensorial beer quality. In Appendix 11, an overview of the ISO-norms regarding size and dimensions of 40 ft. containers are presented. The table illustrates the additional loss of weight, size, and dimensions of reefer containers compared to dry containers. By using a reefer container, the volume or cubic capacity decreases by 10%.

Since dry container freight rates are to a high degree dependent on the specific port of origin and destination, refrigerated container freight rates will behave the same way (i.e. difficult to interpret, volatile and quickly changing over time). Additionally, the reefer market is seasonal with high demand between late November until July and a peak between February and April[63]. Furthermore, the global reefer capacity (40 ft. containers), with 1.4 million TEUs, exceeds 16% of the total TEU capacity and grows rapidly by 3% to 4% per year[63]. However, reefer freight rates were temporarily in an imbalance in recent years. The reefer business was less profitable up to 2013 since competitive pressure caused the rates to be extremely low while investment costs for a new reefer container are high. While the cost for a new reefer container is up to three to four times higher compared to dry containers, reefer container freight rates were only 30 to 40% higher than dry container freight rates[62,64]. In 2013, the multinational Maersk, one of the large players in the industry with a global market share of 20%, decided to increase the prices for reefer containers by an additional 1500 dollar (on average) to make their reefer operations profitable[64]. Competitive players adapted their freight pricing which induced reefer rates to be considerably higher than dry container freight rates. In Table 20a, the transport costs between a dry and reefer container transport are compared.

Table 20a: Comparison dry vs. reefer container transport costs (quote 19th of May 2016)

	40 ft. Dry container (€) (Belgium – Japan)	**40 ft. Reefer container (€)** (Belgium – Japan)
Ocean freight charges	650	2050
Origin charges		
Container Haulage (per container)	285	285
THC (Terminal Handling Charges) (per container)	/	270
Export Customs Clearance (per document)	50	50
Handling Charges (per B/L)	75	75
AMS Charges (per B/L)	30	30
Total	**1090**	**2760**
DIFFERENCE		*+ 1670*

Source: price quote of a Belgian brewery from Logistics provider B, 2017[65]

Apart from the ocean freight rates, additional charges as container haulage (per container), export customs clearance (per document), handling charges (per B/L) and AMS charges (per B/L) are present when performing ship transport. The abbreviation 'AMS' stands for 'Automated Manifest System', which is a multi-modular cargo inventory control and release notification system. The 'bill of loading' (B/L) is related to the shipment documents used in international trade.

In Table 20b, a comparison between dry and reefer freight charges to different destinations is presented. The provider of the data, an employee of a large multinational shipping company, indicated that port infrastructure, the availability of reefer containers at the port of origin, and the need for reefer containers in the destination port are important parameters that explain the cost values. In other words, supply and demand of refrigerated containers are important determinants of international reefer freight charges. Furthermore, direct shipment or transshipment, i.e. stops in different ports, also cause the significant different freight rates between destination ports.

Table 20b: Comparison dry vs. reefer container ocean freight charges (quote 17th of June 2016)

Ocean freight charges from Antwerp harbor to destination port	40 ft. Dry container (€)	40 ft. Reefer container (€)
Shanghai (China)	160	1100
Kobe (Japan)	440	1700
Jebel Ali (Dubai)	300	1200
Melbourne (Australia)	1600	1800
New York (USA)	1200	2100

*USD amounts converted in euros (exchange rate of 17th of June 2016: 1 EUR = 1.1275 USD)

Source: Logistics provider C, 2017[66]

b) Truck transport prices

<u>Dry container truck transport rates/prices</u>

Truck transport is the most frequently used mode of transport by breweries to transfer beer within the European main land. In literature, cost considerations and flexibility (e.g. location of origin and destination, and responsiveness to changes in the economic cycle) are identified as major advantages of truck transport over other modes of transport[67].

Contact with several truck logistics providers indicated the costs related to truck transport are predominantly dependent on the labor cost of the driver[68–70]. As a consequence, the price charged for small distance transport is linked to the hourly wage of the truck driver (roughly 55 €/hrs.)[68]. Small distance transport is defined as transport within Belgium and its neighboring countries: the Netherlands, France, Luxembourg, and Germany. For long distance transport, which is offered by a limited amount of logistics providers, the charged price is linked to the kilometer-distance (and to the weight of the transported container). Afterwards, additional diesel charges are imposed, i.e. the charges are ought to increase the total freight price by 15%[68]. One of the contacted logistics providers identified the price to be € 0.95 per km when executing a round trip, and € 1.05 per km for a one-way transport[69]. The latter price rates were benchmarked with diverse logistics providers[68–70].

In Appendix 12, a map of a logistics provider portraying the transport lead times throughout Europe is presented. The information was used in vibration and temperature experiments during the research presented in this study. In Appendix 12, the corresponding dry container freight rates are identified. Since countries consist of many areas or provinces (distinguished by postal code), the average and the standard error transport rate with Belgium/the Netherlands as country of origin was calculated and presented in the table. Additional charges (e.g. vignettes, toll charges) were not included in the table.

<u>Reefer container truck transport rates/prices</u>

Information on the transport rates for dry and reefer containers was obtained from personal correspondence with three transport carriers. All three companies make a distinction between the prices or rates of transports to locations close by (e.g. Belgium, the Netherlands, France, and Germany) and locations that are further away in distance.

Apart from the higher investment cost, reefer containers also make use of gasoline in order to generate electricity and cool the container. As a consequence, the latter mechanism raises the cost per transport. Two transport carriers indicated that approximately € 5 per hour are charged for gasoline expenses, as well as “a small amount of money” for the depreciation of the investment in the reefer container[68,69]. In general, the small carriers charge a surplus of € 75 to 100 to locations in Belgium and the surrounding countries of Belgium. The large transport carrier surveyed in the current study, on the contrary, disclosed that no additional charges are imposed for reefer transports in comparison with dry transports to locations within Belgium or in the surrounding countries of Belgium[70]. This statement indicates and emphasizes the significant difference between the costs and the rates/prices, which are subject to market dynamics. When cargo is transported to countries further than Belgians neighboring countries, a substantially higher rate is charged for cooled transport by the transport carrier. Table 21, which presents the comparison between dry and reefer transport rates, indicates that there is a 60% to 150% surplus in transport price of a reefer container compared to a dry container for large distance transport.

Table 21: Comparison market price dry container vs. reefer container transport

City of origin	City of destination	Distance (km)	Dry 40 ft. container transport price (€)	Reefer 40 ft. container transport price (€)
SMALL DISTANCE TRANSPORT				
Antwerp (Belgium)	Ghent (Belgium)	60	225 (excl. VAT)	250 (excl. VAT)
	Dinant (Belgium)	137	325 (excl. VAT)	350-420 (excl. VAT)
	Lens (France)	160	350 (excl. VAT)	385-450 (excl. VAT)
	Magdeburg (Germany)	581	825 (excl. VAT)	900-1600 (excl. VAT)
	Lyon (France)	768	1375 (excl. VAT)	1450-2500 (excl. VAT)
LARGE DISTANCE TRANSPORT				
	Bologna (Italy)	1155	2000 (excl. VAT)	3400 (excl. VAT)
	Madrid (Spain)	1609	1880 (excl. VAT)	4600 (excl. VAT)
	Lisboa (Portugal)	2086	2150 (excl. VAT)	4900 (excl. VAT)
	Sofia (Bulgaria)	2112	2600 (excl. VAT)	4900 (excl. VAT)
	Athens (Greece)	2828	3500 (excl. VAT)	5700 (excl. VAT)

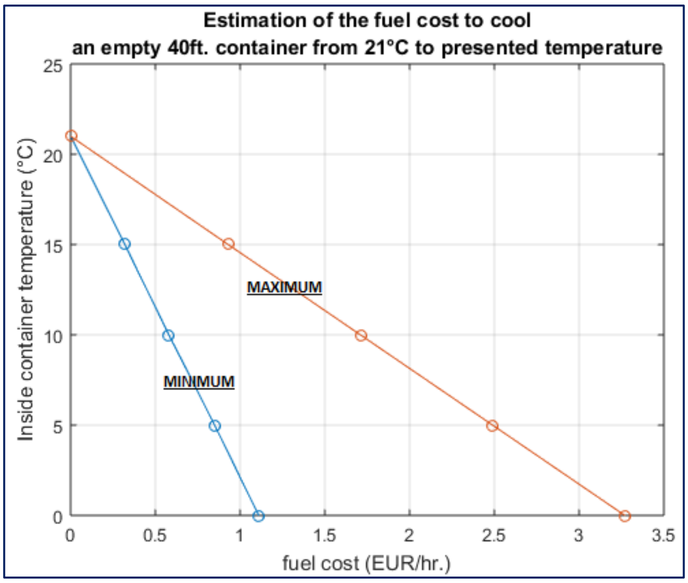
Source: Logistics providers D, E and F, 2017[68–70]

c) Adapting reefer temperature to optimize beer quality and economic feasibility

The optimal temperature to transport and store beer is identified between 0 and 5°C. Exposure to higher temperature results in an exponential decrease in beer quality[20]. As a consequence, breweries should transport their beer in temperatures close to 0°C from a beer flavor quality point of view. However, the increased cost needs to be justified by the possible gains, i.e. consumers willing to pay or consume more for/of the beer or increased brand loyalty. Since beer can be transported and stored at different temperatures, the analysis was performed on the effect of decreasing container temperature to control beer quality to optimal and economically feasible levels.

However, correspondence with the contacted transport carriers indicated that customers receive a fixed price quote irrespective of the requested container temperature during transport. Moreover, the total fuel expenses of reefer containers are equally allocated over all transports[61,65,66,68–70]. As a consequence, brewers will not directly benefit of improved price quotes by increasing the container temperature of the reefer container. However, information and a better understanding of the fuel costs of reefer containers can result in a better negotiation position and better price quotes for the breweries. While logistics providers were reluctant to share information, a supplier of the cooling equipment of reefer containers was able to offer information on the fuel efficiency of reefers.

Figure 31: Estimation of the fuel cost to cool an empty container*



When the fuel cost of refrigerating a container is estimated, breweries might transport beer at higher (controlled temperatures between 0°C and 21°C) while at the same time controlling the flavor quality of the beer and reducing the cost to cool the container. The estimation of the fuel cost might help breweries in the negotiation for lower price quotes of the transport providers.

* The estimations of the fuel cost are based on the fuel consumption and efficiency of diverse cool installations used for refrigerating transport containers. Furthermore, variability is included in the model taking into consideration fuel prices 0.4 €/liter (MIN) and 0.9 €/liter (MAX). The estimations are calculated on maintaining a constant temperature inside an empty container (with an ambient temperature of 21°C). In order to frame the possible beer flavor quality decrease and the suggested reefer temperature, the overall aging scores are estimated.

- No refrigeration – inside container temperature 21°C: 0 €/hr. (MIN) - 0 €/hr. (MAX)
  - ⇨ Calculated fuel cost of 30 days container temperature at 21°C (empty container): € 0
- Cooling 6°C – inside container temperature 15°C: 0.32 €/hr. (MIN) - 0.93 €/hr. (MAX)
  - ⇨ Calculated fuel cost of 30 days container temperature at 15°C (empty container): € 230 - 670
- Cooling 11°C – inside container temperature 10°C: 0.58 €/hr. (MIN) - 1.71 €/hr. (MAX)
  - ⇨ Calculated fuel cost of 30 days container temperature at 10°C (empty container): € 420 - 1230
- Cooling 16°C – inside container temperature 5°C: 0.85 €/hr. (MIN) - 2.49 €/hr. (MAX)
  - ⇨ Calculated fuel cost of 30 days container temperature at 5°C (empty container): € 600 - 1800
- Cooling 21°C – inside container temperature 0°C: 1.11 €/hr. (MIN) - 3.27 €/hr. (MAX)
  - ⇨ Calculated fuel cost of 30 days container temperature at 0°C (empty container): € 800 - 2400

Overall Aging Score (OAS) estimates:**

30 days at 0°C: 0 (+/-1.25) // 30 days at 5°C: 0.29 (+/-1.25)
30 days at 10°C: 0.56 (+/-1.25) // 30 days at 15°C: 0.87 (+/-1.25)
30 days at 20°C: 1.23 (+/-1.25) // 30 days at 25°C: 1.41 (+/-1.25)
30 days at 30°C: 1.88 (+/-1.25) // 30 days at 35°C: 3.19 (+/-1.25)
30 days at 40°C: 7.93 (+/-1.25) // 30 days at 45°C: 8 (+/-1.25)

** Estimates are based on the temperature – OAS model of Part 6 Chapter 3 section 3.1.

Source: Supplier of cooling equipment of reefer containers[99]

In Figure 31, an analysis of the fuel cost of cooling the inside temperature of a container up to 0°C is presented (with an ambient temperature of 21°C). Moreover, the graph displays the minimum and maximum hourly fuel cost related to maintaining container temperature lower than the ambient temperature of 21°C. The variability of the cost estimations (minimum and maximum) can be attributed to the fuel prices and the efficiency of diverse cool installations. Since the fuel cost per hour is displayed in Figure 31, the cost of cooling the container over a period of 30 days was also calculated. The cost calculations were based on maintaining the temperature in an empty container. Since a container filled with air has a lower total heat capacity in comparison with a container filled with pallets of beer, the container will heat up faster in the absence of power. Therefore, a container filled with pallets of beer (that is conditioned at the specified container temperature before loading in the container) will have a slightly lower energy consumption when maintaining a certain temperature in comparison with an empty container.

Additionally, the overall aging score (OAS) of beer that is stored at different temperatures over a period of 30 days is presented in Figure 31. The values were identified to benchmark and validate managerial decisions in cooling transport. As the aging scores indicate, it is fruitful to prevent beer from exposure to elevated temperatures (e.g. 30°C – 45°C). However, the aging scores of beer samples exposed to low temperatures 0°C-15°C remain stable, and, therefore, lower temperatures are recommended with respect to beer flavor stability. The optimal temperature to transport beer cannot be calculated based on the latter research but should be attributed during managerial decision-making.

d) Discussion on the economic feasibility of refrigerated transports

When refrigerating transport, the influence of both temperature and vibrations on the beer flavor quality is reduced, as indicated in Part 5 Chapter 2. Since temperature can rise to 55°C in a transported container due to solar radiation[33], refrigerated transport can be crucial in order to inhibit or, at least, limit the beer flavor degradation. In the current study, the economic feasibility of refrigerated transports for exported beer is analyzed and discussed.

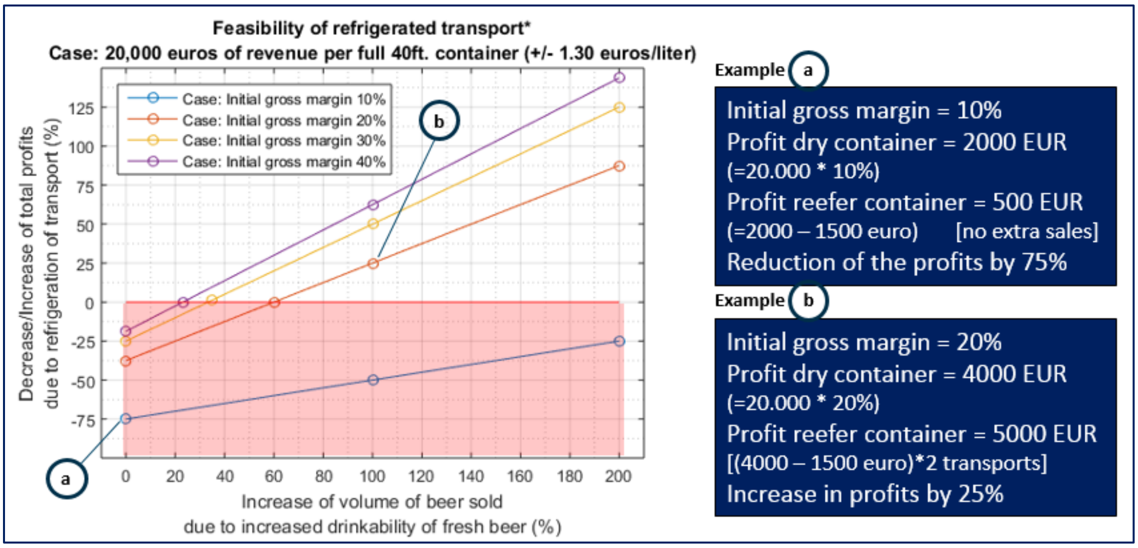
The export of beer is predominantly executed on an ex-works basis[71], which means the wholesaler or distributor organizes and pays the transport to its warehouse facilities. Since it is not realistic that the wholesaler/distributor will take the initiative to organize and finance refrigerated transports (beyond the possibility that a brewery might force the wholesaler to do so), we can assume that a brewery is required to finance the additional investment of a refrigerated transport over a normal dry container transport. Nevertheless, the decision of executing refrigerated transport should also be influenced by other parameters:

- The storage temperature in the warehouses of the distributors, wholesalers and retailers (after transport)
- The tolerance of the consumers for aged beer (as well as the brand rejection and brand loyalty)
- The awareness of the consumers to appropriately store beer (storage in cooled environments)
- The additional expected revenues caused by the investments in the beer flavor quality

When taking into consideration the profit equation, the additional cost in refrigerated transports should be (at least) balanced by an increase in the overall revenues of the brewery. This increase in revenues can be attributed to an increase in the selling price or an increase of the volume of beer sold (or a combination of the two). However, requesting a higher beer price as a brewery is not evident, since there is dependency on the market dynamics of the country of import (competitive forces), but also the exchange rate and standard of living (e.g. beer exported to Norway vs. Thailand). Moreover, selling beer at a higher price can particularly be justified when the product can be sold as a premium product, when consumers are price insensitive. Due to this complexity, the effect of increasing the beer price is not considered and, therefore, the increased revenues are required to be attributed to an increased volume of beer sold. When increasing the beer quality (by investing in a refrigerated supply chain), the researcher assumes that the drinkability and consumer preference for the beer may increase that might result in improved brand loyalty and rising consumption of the beer.

Therefore, simulations were executed to investigate the feasibility of the investment decision in cooled transports under the assumption of resulting in increased volume of beer sold due to an increased drinkability. The parameters involved in the simulation are the initial gross margin (company-specific and, therefore, fixed to 10%, 20%, 30% and 40%) and the current revenue for a 40ft. container transport (€ 20,000 and 30,000 of revenue or the equivalent of approximately 1.30 €/liter and 1.95 €/liter). From the literature, it can be derived that the gross margin of a brewery should be approximately 20%[72]. In a 40ft. container, approximately 24 pallets of beer can be stored of which one pallet of beer is approximately 670 liters of beer and the value of beer on average is equal to 1.30 €/liter (i.e. ratio between the total revenues of the Belgian brewers and their total production volume of beer in 2015[1]). Since a major share of the produced beer is lager beer[1], we assume the price for specialty beer to be 50% higher at approximately 1.95 €/liter. The simulations are based on the additional investment of refrigerated transport (fixed to € 1500 per transported container) and the increased volume of beer that is required to be sold to balance the investment.

Figure 32a: Estimation of the feasibility of refrigerated transports
(Case: € 20,000 of revenue per full 40ft. container (+/- 1.30 €/liter))



The feasibility of refrigerated transport was estimated based on the current gross margin of the brewery and the required increase of volume of beer sold (due to increased quality/drinkability of the beer) to compensate for the additional cost of refrigerating the transport.

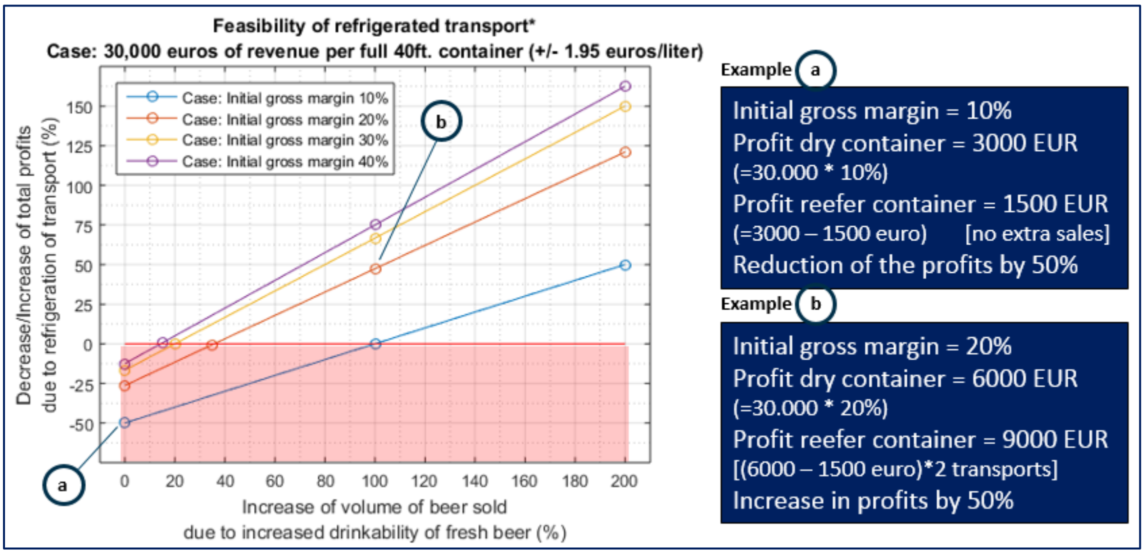
* Assumptions: Since the export of beer is predominantly executed on an ex-works basis, the wholesaler/distributor is assumed to finance the costs related to the transport of beer and the brewery for the additional cost of the refrigerated container. The additional cost of a refrigerated 40ft. container over a dry container is assumed to be fixed to € 1500. Furthermore, the assumption was made that the cost of an additional container is equally spread over all container products (therefore, straight lines are observed).

- Initial gross margin of 10% (without refrigerated transport) => new gross margin of **2.5%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **> 200%**
- Initial gross margin of 20% (without refrigerated transport) => new gross margin of **12.5%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **+60%**
- Initial gross margin of 30% (without refrigerated transport) => new gross margin of **22.5%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **+33%**
- Initial gross margin of 40% (without refrigerated transport) => new gross margin of **32.5%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **+23%**

Source: Own calculations

The simulations are presented in Figures 32a and 32b. The results indicate that for breweries with low profit margins (e.g. initial profit margin of 10%) an additional investment in refrigerated transports might not be recommended since the volume of beer sold should increase by more than 200% (lager beer ≈ 1.30 €/liter), respectively 100% (specialty beer ≈ 1.95 €/liter). In comparison, a brewery with a profit margin of 20% should sell 60% (lager beer ≈ 1.30 €/liter), respectively 33% (specialty beer ≈ 1.95 €/liter) more beer to balance the investment in refrigerated transports. Furthermore, the results indicate that refrigerating transports of beer with a higher initial price (i.e. specialty beer) is more feasible.

Figure 32b: Estimation of the feasibility of refrigerated transports
(Case: € 30,000 of revenue per full 40ft. container (+/- 1.95 €/liter))



The feasibility of refrigerated transport was estimated based on the current gross margin of the brewery and the required increase of volume of beer sold (due to increased quality/drinkability of the beer) to compensate for the additional cost of refrigerating the transport.

* Assumptions: Since the export of beer is predominantly executed on an ex-works basis, the wholesaler/distributor is assumed to finance the costs related to the transport of beer and the brewery for the additional cost of the refrigerated container. The additional cost of a refrigerated 40ft. container over a dry container is assumed to be fixed to € 1500. Furthermore, the assumption was made that the cost of an additional container is equally spread over all container products (therefore, straight lines are observed).

- Initial gross margin of 10% (without refrigerated transport) => new gross margin of **5%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **+100%**
- Initial gross margin of 20% (without refrigerated transport) => new gross margin of **15%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **+33%**
- Initial gross margin of 30% (without refrigerated transport) => new gross margin of **25%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **+20%**
- Initial gross margin of 40% (without refrigerated transport) => new gross margin of **35%** (with refrigerated transport) // break-even point refrigerated transports = increase of volume of beer required to be sold: **+15%**

Source: Own calculations

These results should be compared with the findings of the drinkability experiments in Part 5 Chapter 3. The drinkability experiments indicated that fresh beer was 35% more consumed than aged beer[XXX]. As a consequence, from the current study (and a theoretical perspective), it can be recommended that it is economically feasible to invest in refrigerated transports (depending on an increased volume of

[XXX] The reader should take into considerations the limitations and assumptions of the drinkability experiment (e.g. fresh vs. aged beer [4 months at 30°C], no random respondents sample).

beer sold) if the initial gross margin of the brewery is approximately 29% (lager beer) or 19% (specialty beer).

When increasing the revenues by raising the sales price in order to fully cover the investment cost of refrigerated transport (no increase of sales volumes expected), a price increase of approximately 10 eurocent per liter is required. The latter price increase corresponds to 3.33 eurocent per 33 cl consumption or 2.5 eurocent per 25 cl consumption for both lager and specialty beers. As a consequence, only an incremental price increase can contribute to a refrigerated transport chain. Therefore, the author of this study induces that both marginally raising the price and relying on a sales volume increase will make cooled transports feasible. However, a brewery-specific and country-specific (location-specific) risk assessment of the beer flavor degradation is required to further complement the managerial decision-making (e.g. usefulness of refrigerated transport in summer vs. winter, to Ireland vs. Brazil).

4) Conclusions & Recommendations

The analysis suggests that maritime dry and refrigerated container transport rates are volatile and quickly changing over time. The substantial influence of the interplay between container supply and demand, as well as port infrastructure, cause the pricing to be difficult to interpret. With respect to truck transport, the cost is predominantly dependent on the salary costs of the driver and, as a consequence is linked to the duration of the transport. From the comparative study of dry and refrigerated (40 ft.) maritime container prices, it can be concluded that reefer containers are approximately € 1500 more expensive per transport when compared with dry containers. Truck transport of refrigerated goods over small distances (Belgium, the Netherlands, France, Luxemburg, and Germany) is approximately € 50 more expensive than dry container freight. Refrigerated long distance transport results in an additional price increase of 60% to 150% on top of the normal dry container freight price. From the latter analysis can be concluded that market dynamics predominantly determine the pricing for both dry and reefer container transport.

The fuel cost of cooling an empty container at different temperatures was estimated in order to lower the brewer's price quotes of refrigerated transport. Moreover, container temperature could be controlled to optimal levels for both beer quality and economic feasibility. From the analysis, it can be concluded that is worthwhile to protect beer from elevated temperatures (e.g. 30°C – 45°C). However, the exact temperature to execute refrigerated transport should be the managerial decision of the breweries and is, therefore, not discussed.

Furthermore, the researcher believes that the economic feasibility of refrigerated transport is dependent on the market dynamics of the country of import. In markets in which the exchange rate and the standard of living allow beer to be sold at premium prices, additional investments and costs of cooled containers can be incorporated in the price (only 3.33 eurocent per 33 cl consumption or 2.5 eurocent per 25 cl consumption for both lager and specialty beers). Furthermore, additional parameters, e.g. the tolerance of the consumers for aged beer, the brand loyalty, and the additional expected revenues caused by the investments, make the economic feasibility of refrigerated transport and storage a country-specific (location-specific) and brewery-specific decision. However, maintaining a refrigerated supply chain demands investments and efforts from all actors from brewer to consumer (i.e. personal behavior, local storage conditions e.g. in the harbor, malls, households etc.).

Chapter 2: Economic feasibility of horizontal collaboration in logistics between breweries

In the current Chapter 2, the objective is to assess the economic feasibility of collaboration activities between the (Belgian) breweries with respect to logistics. Therefore, a deeper analysis on the distribution chain of the Belgian brewers was performed (Section 2a). Afterwards, a qualitative analysis was performed on the feasibility of horizontal collaboration in logistics between brewers (Section 2b). Moreover, the aim was to identify the attitude of the brewers towards working together and their liking or disliking of the concept. Consecutively, a theoretical economic simulation of collaboration activities in logistics between the brewers was executed (Section 2c). Furthermore, an analysis of the optimal transport frequency and cargo quantity of beer exports taking into consideration beer quality is performed. Also, the feasibility of incorporating refrigerated containers together with horizontal collaboration in logistics is investigated (Section 2d). The rationale is that the benefits of horizontal collaboration in logistics should be equal to or larger than the additional investment in refrigerated transport.

1) Introduction

Since global competition is becoming fierce, horizontal cooperation in logistics is gaining momentum[73]. Horizontal cooperation, defined by the European Union (2001)[74] as 'concerted practices between companies operating at the same level(s) in the market', is beneficial to bundle and synchronize the flow of goods (e.g. limiting unfilled containers) but also to increase the frequency of transports[75]. The Logistics service provider (LSP), an independent third party, combines and optimizes the logistics chain for the two or more parties that execute transport together (e.g. collaboration between companies in the food sector with respect to chocolate, beer, etc.). There are multiple advantages and disadvantages of horizontal cooperation, also presented in Table 22. Cost and productivity considerations are the main advantages, but there are also difficulties in working together, i.e. reliable partners, allocation of costs and profits, etc.[73].

Table 22: Advantages and disadvantages of horizontal cooperation in transport

Advantages of horizontal cooperation in logistics	Disadvantages of horizontal cooperation in logistics
Increase in the company's productivity for core activities (e.g. decrease in empty hauling, better usage of storage facilities, etc.) and reduction in the costs of non-core activities (e.g. organizing safety trainings, joint fuel facilities, etc.)	Difficulty in finding a reliable party that can coordinate the cooperation in such a way that all participants are satisfied
Reduction in purchasing costs (e.g. vehicles, onboard computers, fuel, etc.)	Difficulty to ensure a fair allocation of the shared workload in advance among partners
LSPs can offer better quality of service at lower costs (e.g. in terms of speed, frequency of deliveries, geographical coverage, reliability of delivery times, etc.)	Difficulty to ensure a fair allocation of the benefits among partners
Geographical expansion, due to an increased customer reach, and a better market position for all partners	Difficulty in communication among partners and with the LSP

Source: Cruijssen et al., 2007[73] and Van Cappellen & Paternoster, 2016[71]

2) Methodology

Data was aggregated from different sources in order to analyze horizontal collaboration between brewers. Moreover, personal correspondence and two online surveys that were sent to the brewers enabled to execute an in-depth analysis.

The research commenced with outlining the distribution chain from brewer to consumer (a) with attention to the inventory models of breweries and wholesalers. Insights came from personal correspondence with brewers, further complemented with findings from a first online survey (Survey Van Cappellen & Paternoster[71]). The survey was filled in by 24 of the 33 Belgian breweries in the VIS-project to which the online questionnaire was sent[71]. The objective of the survey was to identify the size and market structure of the Belgian breweries, the exported volume of beer, the logistics practices of the breweries and the perceived feasibility of horizontal collaboration in logistics between breweries. The information and the findings coming from the survey was described in the second section of the study (b) entitled: "the qualitative analysis on the feasibility of collaboration activities in logistics."

Additionally, a second online survey was effectuated and was filled in by 17 breweries (out of a respondents group of 33 Belgian breweries of the VIS-project) (Survey Paternoster[76]). The main aim of the survey was to identify and estimate the need of and the demand for a transport and storage simulation environment to identify beer quality and stability of Belgian beers in foreign markets. However, the survey also entailed a question on the frequency and quantity of beer pallets that are exported to foreign beer distributors. While the question was filled in by only 5 Belgian breweries (5/17 filled in the question), sufficient information was provided to execute theoretical simulations of collaboration activities in logistics (c). Furthermore, the available information on the brewers export quantity and frequency was employed to define the optimal strategy in performing transports (transport frequency and cargo quantity), reducing storage lead time and maintaining increased beer quality (d).

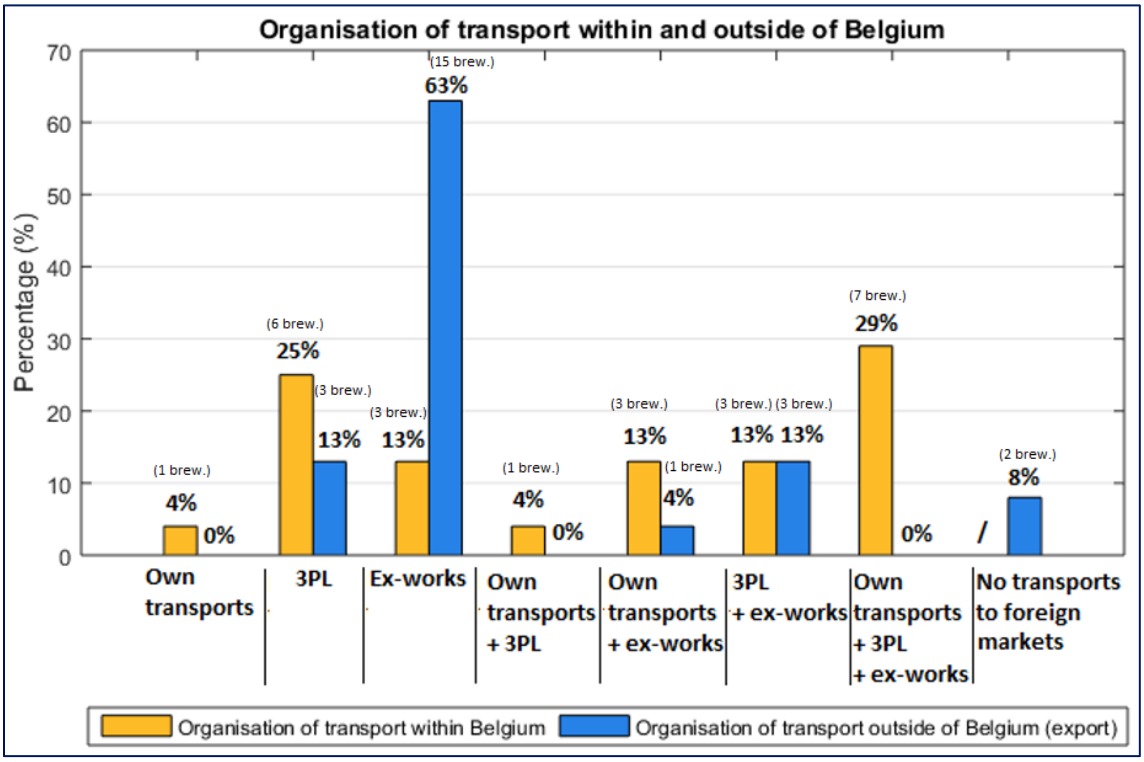
3) Results

a) Deeper analysis of the Belgian brewer's distribution chain & transport processes

In order to further study the possible impact of horizontal cooperation between breweries with respect to logistics, a deeper analysis of the distribution chain of the breweries is recommended. Moreover, the production, stock and order strategies of both the breweries and the distributors interact and shape the industry.

When the raw materials are in stock, i.e. malt, bottles and other packaging materials, beer can be produced and bottled in a few days. Therefore, brewing beer is characterized by a short lead time and, as a consequence, breweries operate according to a 'make-to-order' production and stock strategy[77]. The latter implies that breweries only produce beer when orders are placed by the customer and, as a consequence, the stock of bottled beer is limited. Furthermore, breweries can adapt or adjust the production process resulting in intermediate products in order to optimally meet demand. Moreover, keeping beer in tanks or containers before bottling results in a better-maintained beer quality and reduced stock costs (e.g. bottled beer should be stored inside and is difficult to prevent from heating up). Distributors and wholesalers order beer from the breweries and further distribute the beverage to pubs, bars, restaurants, and supermarkets. Their stock strategy is identified as 'deliver-from-stock' and comprises the minimization of transport and storage costs, and the risk of stock outs.

Figure 33: Organization of the transports of Belgian breweries (Survey filled in by 24 of the 33 Belgian brewers, including the 4 largest breweries of Belgium)



* Legend: 'brew.': brewery // 3PL (Third Party Logistics): a third party organizes the transport that is paid by the brewery // Ex-works: the client is responsible for the transport of the bought goods

Export to foreign countries is predominantly performed by ex-works distribution. Transport within Belgium is performed by different methods. Source: Van Cappellen & Paternoster, 2016[71]

In Figure 33, an overview of the organization of the transports of Belgian breweries is presented (Survey Van Cappellen & Paternoster[71]). The figure indicates that the distribution of beer outside of Belgium diverges from the methods used in Belgium. Moreover, the organization of transport within Belgium is more complex than transport outside of Belgium due to the recycling logistics of beer bottles and plastic crates. Most of the large and midsize breweries have facilities to bottle beer on-site. As a consequence, when bottled beer is transported to the customer, plastic crates with empty bottles are loaded and sent back to the brewery. Small breweries, on the contrary, outsource the process and make use of bottling plants. Beer that is transported outside of Belgium is frequently bottled in one-way bottles and packaged in cardboard crates that cause no need for a recycling process. When exporting beer, close to all breweries make use of ex-works logistics. In an ex-works transport strategy, the customer organizes and finances the transport of the bought goods. The distributor approaches a logistics provider (possibly advised by the brewery) that transports the beer to its destination. Since the logistics provider is addressed by multiple companies, all sorts of cargo are bundled. Transport within Belgium is organized by diverse methods depending on the size of the brewery. The large breweries predominantly transport beer within Belgium by using their own transport infrastructure and possibly in combination with third party logistics providers (3PL) and ex-works distribution. The distribution of beer by 3PLs is mainly organized by mid-size breweries since beer is sent to different distribution centers or clients. Small breweries make use of different combinations of transport methods. A larger part of the brewed beer is transported on an ex-works basis, and, as a consequence, demonstrates the willingness of clients to buy high-quality specialty beer made by small breweries. A schematically overview of the beer export distribution process is presented in Figure 34.

Figure 34: The current beer export distribution process

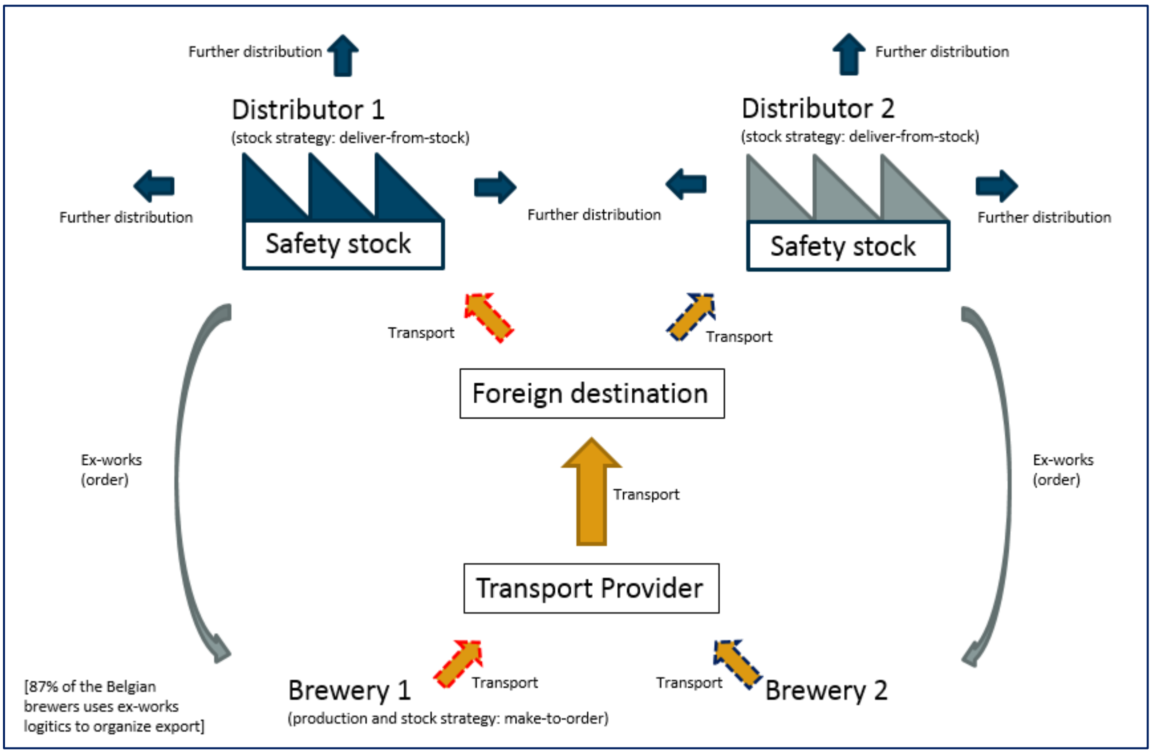


Figure 34 depicts the export distribution process of beer: beer coming from the breweries is transported to the transport provider. The transport providers bundle the pallets and transport the pallets to the foreign destination. Afterwards, the beer is transported to the different storage facilities of the distributors. Source: Own content

b) Qualitative analysis of the feasibility of collaboration activities in logistics

The study performed by Van Cappellen & Paternoster (2016)[71] indicated that 42% (10/24) of the brewers already cooperated (with other brewers) and tried to bundle cargo[XXXI]. Moreover, out of the 10 respondents that had experience with cooperating with other breweries (with respect to logistics), 7 were mid-size and 3 were small breweries. The respondents indicated that working together does not happen on a regular basis, however collaboration in a friendly manner is not unheard of. When midsize breweries have free space in their containers, the container is occasionally filled with beer of a befriended small brewer (located in the neighborhood). The advantage is, apart from a small cost benefit, that the brewer has the assurance that the goods are loaded correctly. Furthermore, the survey revealed that 71% (17/24) of the brewers believes that a cooperation in transport will not be beneficial for the brewery. The latter implies that 29% (7/24) of the brewers assumes there are advantages in working together. In total 21% (5/24) of the respondents would consider trying to start a collaboration. As a consequence, a segment of the brewers is open for collaboration between breweries. However, during the VIS/Brewers-project diverse attempts were made to start a pilot

[XXXI] A total of 24 respondents filled in the survey performed by Van Cappellen & Paternoster, 2016[71].

project, but no brewer agreed on beginning it. Therefore, the feasibility of horizontal cooperation in logistics between the Belgian brewers, segmented by size, is analyzed.

Large breweries (> 10,000 hl per year) indicated that there is no need for collaboration with other brewers or suppliers of other goods with respect to the export of beer. The breweries transport containers filled close to full capacity with high frequency. When using transport with 3PLs and when transport is conducted on behalf of the customer (ex-works), there is no further need to bundle cargo. Furthermore, separating shipments in order to optimize cargo weight and volume is not believed to be beneficial for the brewery due to costs allocated per shipment (export customs clearance, handling charges, AMS charges). Additionally, the feasibility of collaborating is rather low due to the aversion of the brewery of sharing company information, losing control and opening the market for (Belgian) competitors. Similar arguments are applicable with respect to transports within Belgium, which is further complicated due to the recycling logistics of the beer bottles, the barrels, and plastic crates. As a consequence, both for transports within and outside of Belgium, horizontal cooperation of logistics is believed to generate no or only a small advantage for the large brewery. Hence, the large breweries demonstrate aversion against horizontal collaboration in logistics between breweries.

Midsize breweries (1000-10,000 hl per year) transporting beer to foreign markets mainly use 3PLs and ex-works distribution. While the containers of the latter breweries are often less loaded to full capacity, 3PLs themselves bundle the goods of their customers. Also when ex-works transports are organized the influence of the brewer is minimal on the logistics and bundling process. Also within Belgium, 3PLs often execute the transports to their customers. However, breweries might also have their own logistics system but the applicability of horizontal collaboration is believed to be rather limited. In Belgium, distances are small, which also inhibits having extensive benefits of collaborating. The excess costs of communicating between the partners, arranging transports (perhaps having a central depot) is believed not to be compensated by the benefits.

Small breweries (< 1000 hl per year) do regularly not transport close to full cargo capacity and, therefore, are most suitable to engage in a logistics collaboration. However, 3PL or ex-works transports are organized when exporting beer, which results in a limited influence of the brewer in bundling the goods. Within Belgium, often ex-works transports are used, which also limits the need to bundle transports for the brewer. However, when transport is needed, small breweries can inform befriended brewers to bundle goods. While the brewers remained skeptical with respect to horizontal collaboration, predominantly small breweries will possibly experience the largest benefits in working together.

c) Theoretical simulation of collaboration activities in logistics

While the qualitative study (b) indicated that collaboration in logistics between breweries is not evident, a theoretical simulation was performed in order to estimate the possible profits of breweries working together with respect to logistics. The theoretical analysis of the current section is limited to transports from Belgian breweries to foreign countries. The researcher assumes that a beneficial collaboration during beer distribution between breweries within Belgium is challenging. Combined logistics can be attractive for small breweries (< 1000 hl per year) located in the proximity of each other that are required to transport small volumes of beer to the same or adjacent locations. Nevertheless, the researcher assumes that benefits of breweries working together with respect to long-distance transport are more substantial than collaborating within Belgium due to the following aspects:

- Transportation costs within Belgium are modest (compared to long-distance transportation costs)
- The recycling logistics of beer bottles within Belgium adds complexity
- (Small) breweries make use of transport vehicles of different sizes and cargo volumes and, therefore, the loading rate is difficult to compare between breweries.

Due to the lack of specific and high-quality data of transports within Belgium the scope of analysis was limited to studying collaborating activities in logistics of breweries during long-distance transport.

Breweries that export beer mainly work on an ex-works basis, as presented in (a). A logistics provider is approached by the distributor or wholesaler (possibly together with the brewery) in order to transport the provided pallets of beer. The price of transport is quantified on a volume basis (per pallet) and depends on the number of pallets provided by the brewery. The more pallets are considered for transport, the higher the load rate of a shipping container, and, thus, the lower the price per pallet. A maximum number of pallets should be transported in order to minimize transport costs per pallet. However, a higher order size of pallets of beer induces a longer time the pallets are kept in storage at the distributor's warehouse, higher storage costs and an increased risk of beer quality deterioration. When cargo is bundled by breweries/distributors, transport can be executed at lower prices, and more frequently (with a smaller number of pallets per brewery). Therefore, real-life export data of five breweries were analyzed in the current study quantifying the optimal order size by which total costs are minimized. Figure 35 presents a schematically overview of the beer export distribution process when distributors and breweries work together to bundle cargo.

Figure 35: The beer export distribution process: bundling cargo

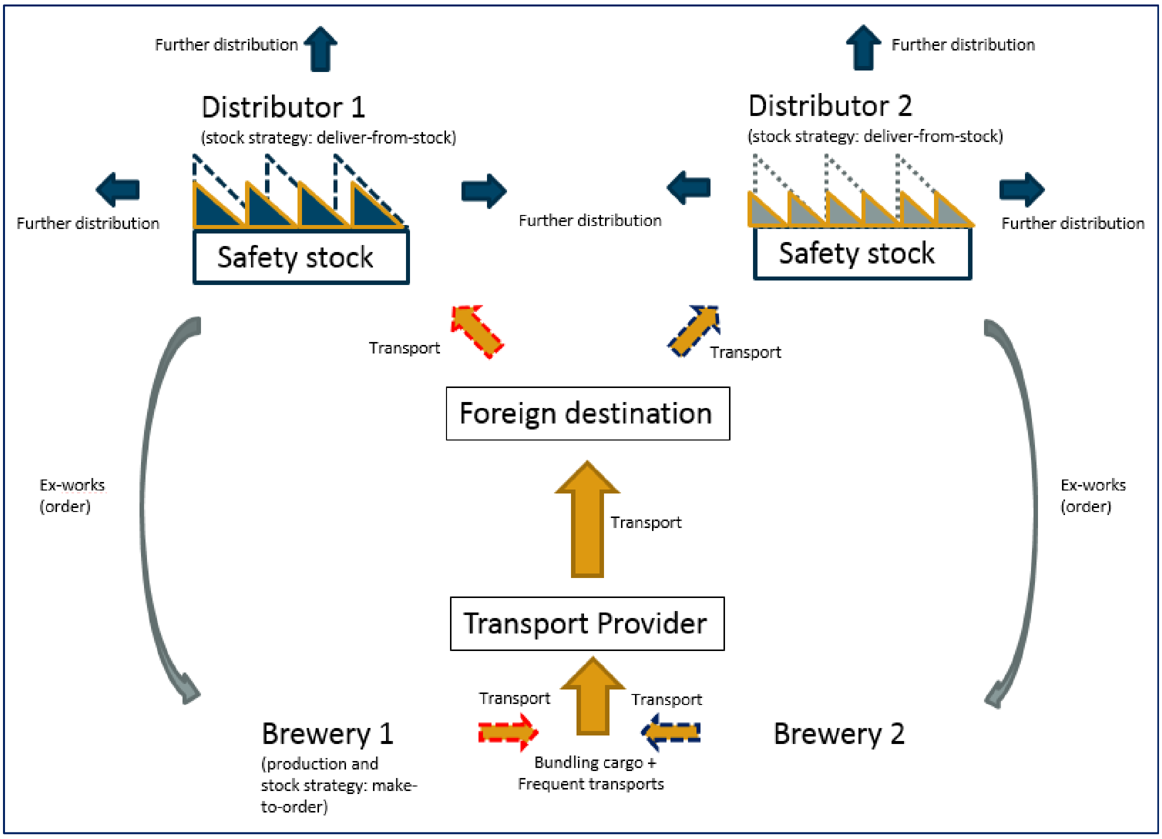


Figure 35 depicts the (possibly new) export distribution process of beer: beer coming from the breweries is bundled by the breweries and transported as a full container to the transport provider. The transport providers transport the pallets to the foreign destination and, afterwards, the beer is transported to the different storage facilities of the distributors. Source: Own content

From the export data of the five breweries, only Italy and the USA are considered as countries that were studied with respect to collaboration in logistics. The latter countries were selected due to their remoteness of Belgium and the availability of data on the exported volumes of the five breweries. In Table 45 (Appendix 15), an estimation of the logistics providers' prices per pallet to Italy and the USA is presented. The price per pallet was calculated based on six logistics providers price quotes for 40ft. and 20ft. dry container transports and assumes that if the transported cargo is reduced by one pallet, the price per pallet increases by 3% (based on the assumption that the price per pallet for 12 pallets in a 20ft. dry container should equal a 40ft. dry container). The distributor's cost related to importing beer from a brewery was calculated in Table 46 (Appendix 15). The transport, order and storage costs were based on the following list of assumptions:

- A 40ft. dry container can contain up to 24 pallets of beer
- 1 pallet of beer is the unit of analysis and corresponds to approximately 670 liters of beer
- The value of beer is equal to € 1,30 per liter (i.e. ratio between the total revenues Belgian brewers and total production of beer in 2015[1])
- The order costs are estimated to lie between € 100 and 200 per transport (equal to the costs related to transportation within Belgium[68–70]). The order costs are defined as the transport and administrative cost to bring cargo from the brewery to the logistics provider and from the logistics provider to the distributor's warehouse.
- The storage costs are estimated to be 25-50% of the products value[78]. Storage costs consist of interest and opportunity costs of capital invested in stock, insurance and risk costs, quality deterioration costs and warehouse costs

The optimal transport frequency and degree of loading

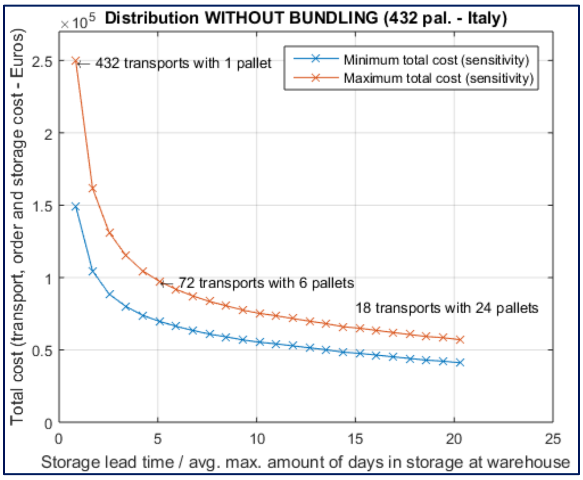
In order to identify the optimal transport frequency and degree of loading, simulations were performed in which the total cost, the sum of the transport, order and storage cost is calculated for transport to Italy and the USA (Figures 36a-f and 37a-f). Three cases were studied with respect to transport to Italy and the USA that differed from each other on the total amount of pallets to be transported over the year (annual demand). The annual demand of the cases relates to the data of the studied breweries (breweries 1-5). Additionally, simulations were performed in which the cost per pallet is fixed at its optimal or minimal level for all transported pallets. The latter scenario relates to bundling cargo or breweries and distributors/wholesalers that collaborate with respect to logistics. For all three cases (different annual demand per country: Italy and the USA) and both scenarios (with and without bundling cargo), the optimal total cost was estimated corresponding to the optimal transport frequency and degree of loading. Furthermore, the figures indicate the following findings:

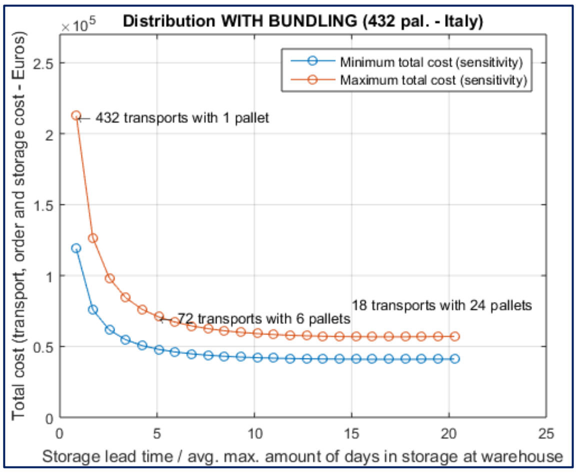
- if the transport cost or the order cost increases or is more substantial than storage costs, it is beneficial to limit the transport frequency and to optimally fill a container
  [e.g. Italy – annual demand: 432 pallets/year (brewery 1) / USA - Annual demand: 288 pallets/year (brewery 3)].
- if storage costs increase or are more substantial than transport and order costs, it is beneficial to transport more frequently (possibly with a lower degree of loading)
  [e.g. Italy - Annual demand: 24 pallets/year (brewery 5) / USA - Annual demand: 36 pallets/year (brewery 5)].
- when goods are bundled and the transport cost per pallet is minimal, the trade-off between the order and the storage cost will determine the transport frequency and quantity.

From the presented graphs in Figures 36a-f the optimal transport frequency and order size corresponding to the lowest total cost (sum of transport, order and storage costs) are calculated. In Table 23, an overview of the optimal transport frequency and quantity with and without bundling cargo for all cases is presented. Furthermore, the expected profits of bundling cargo are calculated as well as the percentage reduction in total costs, which were calculated in order to frame the order of magnitude of the expected profits. The results indicate that when annual demand is sufficient (Italy - 432 pallets/year; USA – 288 pallets/year) the optimal transport quantity will be close to full capacity for both with and without bundling cargo. As a consequence, the benefits in collaborating and bundling cargo are negligible. When few pallets per year are required to be transported over long distances (Italy - 24 pallets/year; USA – 36 pallets/year), bundling cargo can result in a decrease in total costs up to 25%. Since both transport frequency and transport quantity with and without bundling remain stable, only transport costs reduce due to bundling. In the two remaining cases (Italy - 144 pallets/year; USA – 88 pallets/year) the optimal transport frequency doubles after bundling cargo or the optimal transport quantity halves due to bundling. As a consequence, due to bundling cargo resulting in a constant transport cost per pallet, the trade-off between the order and storage costs benefits more frequent transports with lower order sizes. Total costs reduce between 8 and 20% in the latter studied cases.

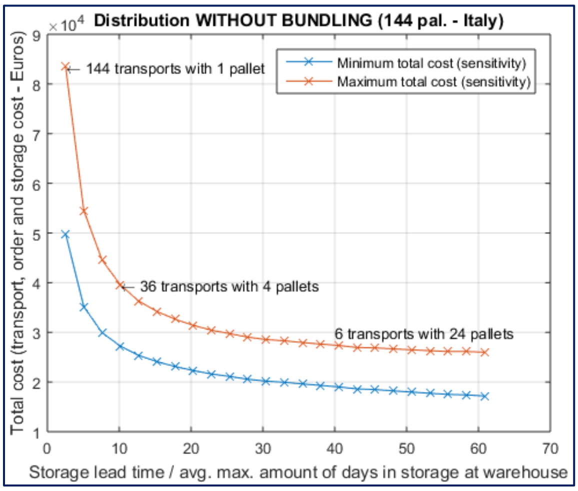
Figures 36a-f: Total cost vs. storage lead time (with and without bundling) – Italy

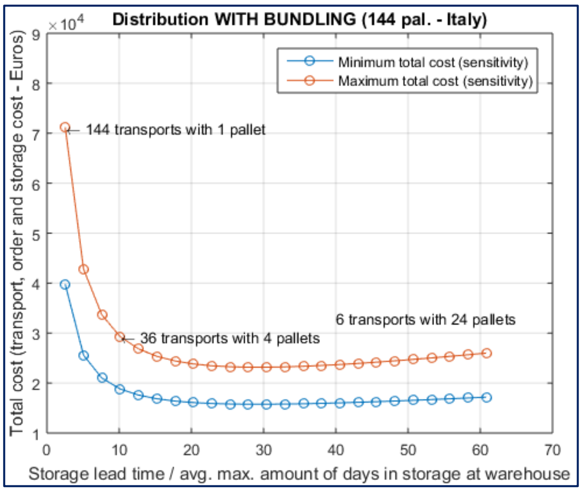
Annual demand: 432 pallets/year (brewery 1)



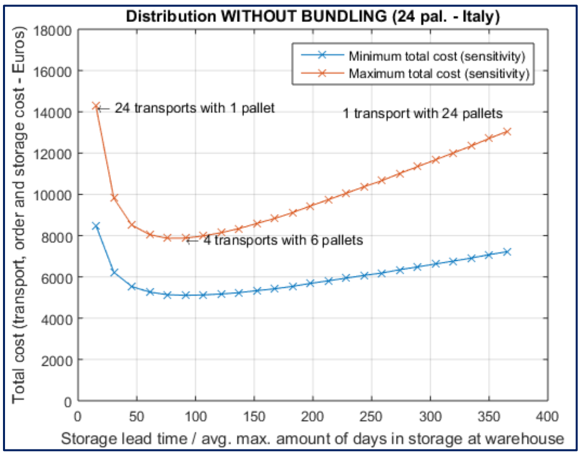


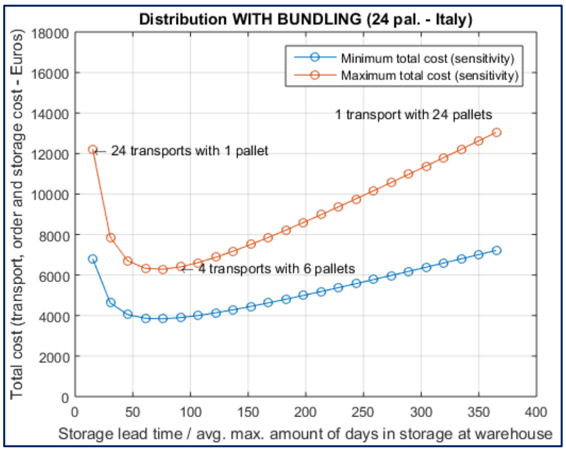
Annual demand: 144 pallets/year (brewery 2/3/4)





Annual demand: 24 pallets/year (brewery 5)



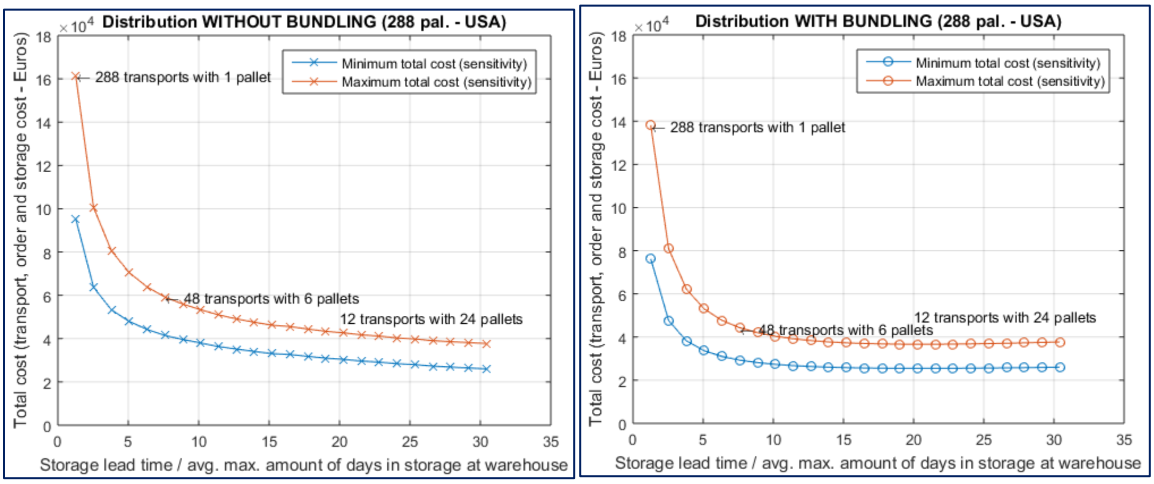


Simulations were made in which the annual demand of beer pallets is distributed with a variable transport frequency and degree of loading per transport (# pallets). The minimum and maximum total cost was calculated by summing the transport, order and storage costs. The calculation of the three categories of costs is identical to Table 46 (Appendix 15). In the distribution of beer WITH bundling the transport price per pallet equals the minimum price of 83 €/pal., in distribution of beer WITHOUT bundling the price per pallet can be found in Table 45 (Appendix 15).

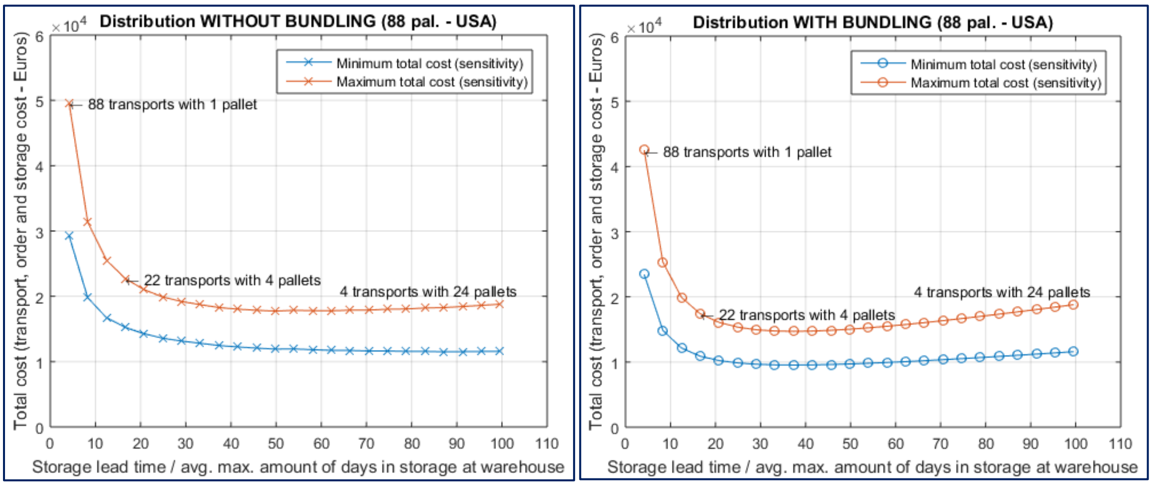
Source: Own calculations

Figures 37a-f: Total cost vs. storage lead time (with and without bundling) – USA

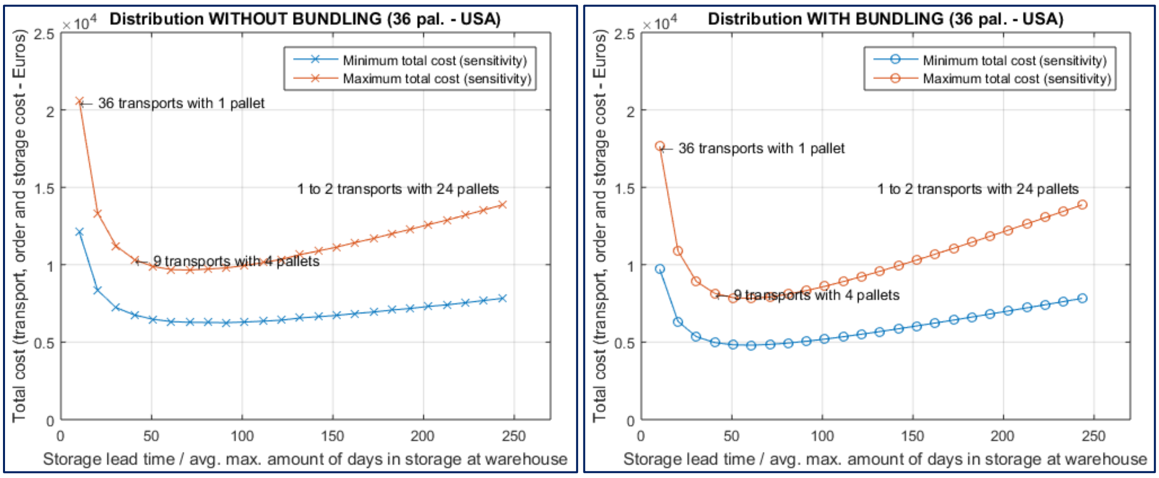
Annual demand: 288 pallets/year (brewery 3)



Annual demand: 88 pallets/year (brewery 4)



Annual demand: 36 pallets/year (brewery 5)



Simulations were made in which the annual demand of beer pallets is distributed with a variable transport frequency and degree of loading per transport (# pallets). The minimum and maximum total cost was calculated by summing the transport, order and storage costs. The calculation of the three categories of costs is identical to Table 46 (Appendix 15). In the distribution of beer WITH bundling the transport price per pallet equals the minimum price of 71 €/pal., in distribution of beer WITHOUT bundling the price per pallet can be found in Table 45 (Appendix 15).

Source: Own calculations

Table 23: Overview of results on optimal transport frequency and quantity for export to Italy and the USA with fixed annual demand

Italy - Annual demand: 432 pallets/year (brewery 1)	Transport per year	Number of pallets per transport
Optimal transport frequency and quantity WITHOUT bundling:	18	24
Optimal transport frequency and quantity WITH bundling:	22	20
⇨ Profit from bundling:	€ 200 +/-100 (reduction of 0.4-0.5% in total costs)	
Italy - Annual demand: 144 pallets/year (brewery 2/3/4)	**Transport per year**	**Number of pallets per transport**
Optimal transport frequency and quantity WITHOUT bundling:	6	24
Optimal transport frequency and quantity WITH bundling:	12/13	12/11
⇨ Profit from bundling:	€ 2,100 +/-700 (reduction of 8-11% in total costs)	
Italy - Annual demand: 24 pallets/year (brewery 5)	**Transport per year**	**Number of pallets per transport**
Optimal transport frequency and quantity WITHOUT bundling:	5	5
Optimal transport frequency and quantity WITH bundling:	5	5
⇨ Profit from bundling:	€ 1,400 +/-100 (reduction of 20-25% in total costs)	
USA - Annual demand: 288 pallets/year (brewery 3)	**Transport per year**	**Number of pallets per transport**
Optimal transport frequency and quantity WITHOUT bundling:	12	24
Optimal transport frequency and quantity WITH bundling:	10	9
⇨ Profit from bundling:	€ 800 +/-300 (reduction of 2.0-2.8% in total costs)	
USA - Annual demand: 88 pallets/year (brewery 4)	**Transport per year**	**Number of pallets per transport**
Optimal transport frequency and quantity WITHOUT bundling:	4	21
Optimal transport frequency and quantity WITH bundling:	10	9
⇨ Profit from bundling:	€ 2,700 +/-800 (reduction of 17-20% in total costs)	
USA - Annual demand: 36 pallets/year (brewery 5)	**Transport per year**	**Number of pallets per transport**
Optimal transport frequency and quantity WITHOUT bundling:	5	7/8
Optimal transport frequency and quantity WITH bundling:	6	6
⇨ Profit from bundling:	€ 1,700 +/-200 (reduction of 19-23% in total costs)	

Based on the Figures 36a-f and 37a-f, the optimal transport frequency and degree of loading (# pallets per transport) can be calculated by minimizing the total (transport, order and storage) cost. For every brewery (with respective annual demand), the combination transport frequency and quantity with the lowest cost with and without bundling is presented. Furthermore, the possible gains by bundling cargo are presented.

Source: Own calculations

Collaboration in logistics with respect to the studied data of the breweries

In the current section, a theoretical simulation of bundling cargo is performed based on the reported transport volumes of the breweries. In addition to the previously described assumptions, current analysis also builds on the assumption that the required new transportation frequency with bundling cargo should be at least higher than the original transport frequency without bundling cargo. For both Italy and the USA, two possible scenarios are studied:

- Scenario 1: Bundling cargo of the selected breweries without changing the transport frequency
- Scenario 2: Bundling cargo and optimizing the transport frequency of the transported pallets of beer

In Table 47 (Appendix 15), an overview is presented of the results of the selected breweries theoretically collaborating in logistics. The simulation of the two scenarios of Italy indicates that significant profits of € 3,500 – 4,500 (bundling cargo) and € 6,500 – 11,000 (bundling cargo and optimizing the transportation frequency) are possible. With respect to transport to the USA, profits are lower: € 800 – 1,000 (bundling cargo) and € 2,300 – 3,100 (bundling cargo and optimizing transportation frequency). Profits can be more substantial with optimal partner selection and when the group of possible partners is broad. The division of the profits is not considered in this study.

d) Beer quality and logistics practices (transport load and frequency)

Due to the negative impact of transport and storage conditions on the beer quality, the lead time between bottling beer and consumption should be minimal. The shorter the lead time, the lesser negative conditions (e.g. time and temperature) can cause beer flavor instability or quality degradation. In previous analysis, the feasibility of collaboration in logistics between breweries/distributors is explored. In current section, the objective is to investigate the relation between the logistics and storage practices, and the beer quality.

Currently, 80% of all breweries indicated that maximum 20% of the transports are executed in refrigerated containers at cooled temperatures[71]. In a first explorative analysis, the feasibility of performing transport in cooled conditions by only employing the profits of collaboration in logistics is identified. In Part 6 Chapter 1, the additional logistics providers price of transport with a refrigerated container is characterized as approximately € 1,500 (compared to transport with a dry 40ft. container). However, the optimal maximum individual gains of breweries/wholesalers that collaborate are identified as approximately € 3,000 per annum (approx. maximum € 250 per transport). Therefore, continuously refrigerated containers in combination with collaboration activities in logistics are not feasible from a cost perspective only. When transport (and storage) are cooled, beer flavor quality will be more stable, which is believed to also influence the revenues (increased consumption and brand equity).

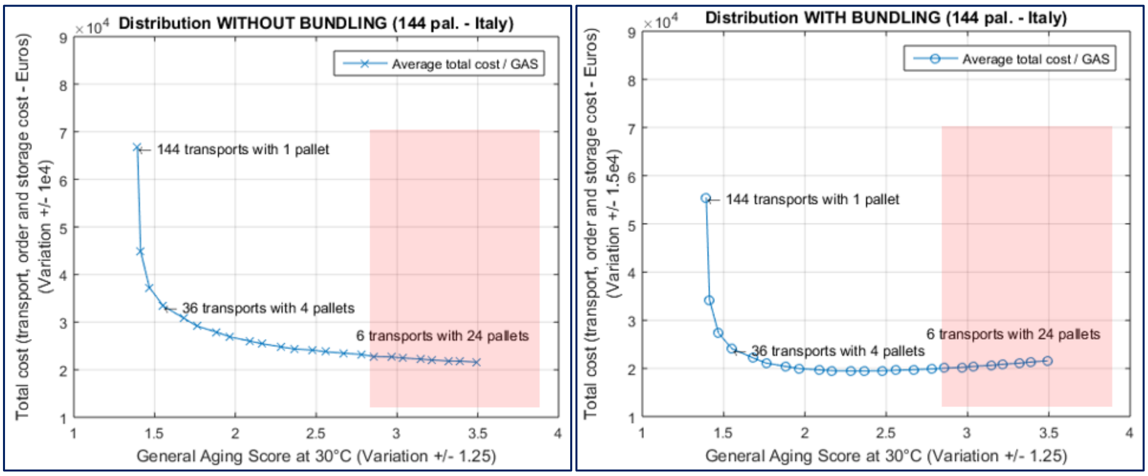
The decision of wholesalers or distributors with respect to the transportation frequency and the quantity of transported/imported beer also influences the beer quality. When the storage lead time is long, the risk increases that the customer at the end of the value chain will consume a degraded beer of low quality. Furthermore, beer quality deteriorates during transport and storage when it is not protected against negative conditions (e.g. temperature). The latter might result in decreasing sales and a rejection of the beer brand, which mainly damages the breweries performance and image (and to a lesser extent sales of the wholesaler/distributor). In the current study, the General Aging Score (GAS) was determined for different storage lead times that correspond to diverse quantities and frequencies (studied in Part 6 Chapter 3 section 3.1). The objective was to identify a conflict of interests between the wholesalers/distributors that aim at minimizing costs and the breweries that aim to offer the consumer the most optimal product quality and sensation (which results in increasing sales).

For instance, with an annual demand of 144 pallets a year (Italy) the wholesaler or distributor can opt to execute 6 transports a year with a full cargo of 24 pallets. This is the most optimal choice from a cost perspective if there is no collaboration with other wholesalers, distributors, and breweries. However, the latter implies that beer may be in storage up to 60 days, which could be too long if not stored at the correct temperature. If the beer is stored at warm temperatures of approximately 30°C the GAS is identified to be 3.5 +/- 1.25 (which is relatively high). As a consequence, the transportation frequency also influences the storage lead time and the risk for beer quality deterioration. In Figure 38a-d, the GAS was calculated for theoretically exposed beer samples to 30°C during the indicated storage lead times. Exposure to the temperature of 30°C is extreme but realistic for warehouses in warm climates.

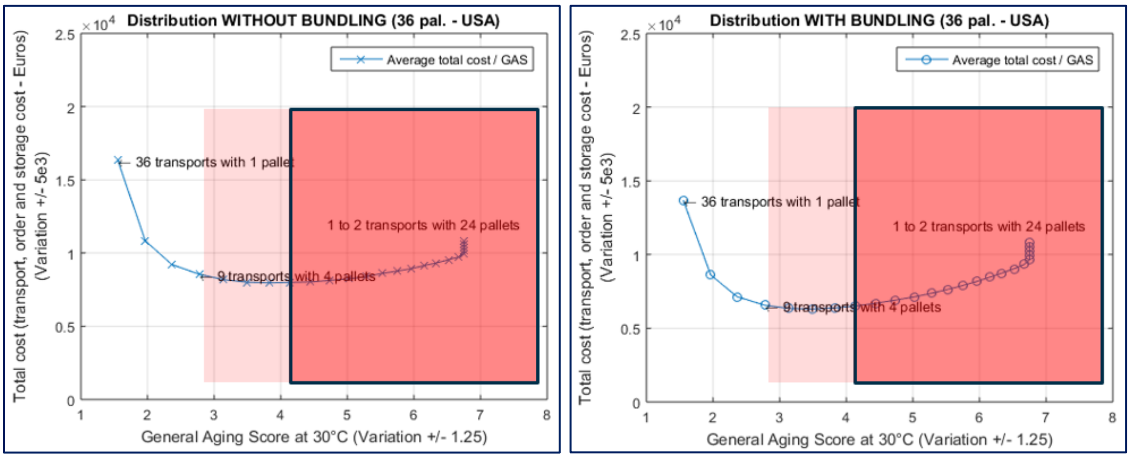
In Figures 38a-d, the example is presented of beer quality during storage corresponding to transport to Italy with annual demand of 144 pallets per year and transport to the USA with annual demand of 36 pallets per year. Analysis indicates that the risk of beer quality degradation is low if the transportation frequency is high and storage lead time is short (corresponding to a high annual demand of approximately more than 250 pallets per year). When the transportation frequency is low, and storage lead time is long, the risk of degraded beer quality is substantial. As a consequence, problems concerning beer quality can predominantly be situated with wholesalers and distributors with a low annual demand of beer (<150 pallets per year). These wholesalers that solely optimize transportation costs will fill containers close to full capacity and will result in offering consumers beer of considerably degraded quality. The latter examples indicate that the examination of beer quality is relevant, especially for small breweries or wholesalers/distributors with a low annual demand and long storage (and transport) lead times.

Figures 38a-d: Total cost vs. Beer quality – General Aging Score (GAS) (with and without bundling) – Case 1: Italy 144 pal./year – Case 2: USA 36 pal./year

Italy - Annual demand: 144 pallets/year (brewery 3)



USA - Annual demand: 36 pallets/year (brewery 4)



Legend:

The General Aging Score (GAS) of the curves is calculated by theoretically exposing beer samples to 30°C during the average time in storage at the distributor's warehouse.

The upper limit of the GAS reaches 4,15 (GAS-scale: 0-8)

The average of the GAS reaches 4,15 (GAS-scale: 0-8)

Belgian beer has an expiration date of one year after bottling (due to flavor stability). The latter implies that the beer can be consumed within the year if stored at normal storage conditions (20°C). The GAS of beer that is stored during 365 days in 20°C corresponds to 4.15 (+/- 1.25). The latter GAS is considered as the minimum required beer quality for selling.

Figures 38a-f are based on the presented Figures 36a-f and 37a-f (annual demand of beer pallets - transport frequency and quantity). The transport frequency impacts the average amount of time the beer is in storage and, therefore, the beer flavor degradation. The GAS score is simulated by assuming the average time in storage is performed at the temperature of 30°C.

Source: Own calculations

4) Conclusions & Recommendations

In the current Part 6 Chapter 2, the feasibility of collaboration between breweries in order to optimize logistics practices is investigated. Based on previous analysis and findings, the following conclusions are formed.

Collaboration between breweries with respect to logistics within Belgium is not opportune due to the modest transportation costs, the recycling logistics, and the large demand volumes resulting in loading transport containers at full capacity. Furthermore, also smaller trucks can transport small volumes of beer at full loading rate. However, collaboration within Belgium might be feasible and profitable by two small breweries located nearby that have to transport beer to the same location.

Collaboration between breweries with respect to logistics outside of Belgium might be more profitable. However, since transport is predominantly organized by the wholesaler/distributor (ex-works), collaboration should be taken care of by the breweries, wholesalers, and distributors together. The latter emphasizes the complexity of the collaboration. Large breweries indicate not to be keen on working together with other breweries, which is a rational attitude validated by the theoretical simulations performed in the current research. This can be attributed due to the large volumes of beer that are transported at optimal capacity. Analysis indicated that only with an annual demand lower than 150 pallets per year, collaboration is fruitful with cost reductions up to 25%. Furthermore, research indicated that the profits coming from the collaboration activities in logistics will not justify the total investment in refrigerated transports. However, an increased transportation frequency will decrease the storage lead time and, thereby, the risk of beer flavor stability problems. The examination of beer quality in the export markets might be particularly relevant for small breweries or wholesalers/distributors with a low annual demand (< 150 pallets per year) and long storage lead times.

Chapter 3: Simulating beer transport and storage

Beer flavor stability is important to breweries due to the increasing importance of export and the lack of beer quality control in foreign markets. Quantitatively testing the beer quality in the foreign markets is not possible since there are no laboratories available that can perform the necessary beer quality analysis. Currently, brewers can only perform sensorial tests on-site or can decide to ship samples back to a beer laboratory in Belgium that can perform the quantitative chemical beer tests. Therefore, in section 3.1 software was developed to predict the General Aging Score (GAS) based on temperature and time data. Also, a setting will be installed to simulate transport and storage, and to investigate the beer flavor stability of the beer samples. In section 3.2, the equipment, tools, and methods to perform transport and storage simulations are described and analyzed. Also, the economic feasibility is assessed of offering the breweries transportation and storage simulations and determining beer quality.

3.1 The simulation of the General Aging Score (GAS)

1) Introduction

In the current research, a first attempt was made to build a theoretical model, in which the sensorial properties of beer are estimated when exposing lager beer to temperature (with variable duration). Moreover, the general or overall aging score (GAS/OAS)[XXXII] is estimated, which is adopted in beer science as a measure for the degree of staling of a beer sample. The objective of the study is to assist breweries in conducting quality control of exported beer, i.e. by measuring the temperature and time pattern exported bottled beer is exposed, inserting the data into the model, and estimating the beer flavor quality, a better informed quality check can be introduced. Since the aged flavors and aromas in beer mostly only gradually develop over time, it is constructive to have an estimation of the beer flavor quality dependent on the (variable) temperature pattern beer is exposed to. Since the modeling of the sensorial acceptance or preference of beer with respect to beer flavor quality and the chemical parameters of beer has not yet been performed in literature, the GAS was adopted in this study.

Further information on the simulation of the General Aging Score and a case-study on estimating the flavor quality of Belgian beer in the export markets is presented in the paper “A first model to simulate the General Aging Score (GAS) - the impact of temperature and time on the sensorial quality of lager beer” in Annex.

2) Methodology

a) Data gathering

In beer research, beer flavor stability is predominantly assessed by exposing beer to an elevated temperature[20]. As a consequence, there is an availability of data with respect to beer quality when being exposed to heat during different times of exposure. For instance, Vanderhaegen et al. (2007)[4] investigated the aging characteristics of different beers and, therefore, exposed beer to the ambient temperature of 20°C, analyzed and profiled the beer on different time instances throughout one year. Malfliet et al. (2008, 2009)[79,80] used similar procedures to estimate beer quality. The data of these articles was used in addition to the internal data of past/performed experiments at the KU Leuven technology campus Ghent. In total, there were 270 cases in which beer was aged over a predefined period of time and sensory evaluated by a panel of minimum five expert tasters. Only the cases

[XXXII] Extra information on the GAS or the OAS is presented in Part 2 section 2.2.2. In this study, the authors assume a linear (equidistant) relation between the scores (0-8) of the GAS-scale. However, this relation has not yet been proved in literature.

consisting of lager beers were considered for this study, excluding 84 of the 270 cases. In the remaining 186 cases, the beer is predominantly aged and stored between 20°C and 30°C, up to 365 days, which emphasizes the accuracy of the model in the defined temperature range. Furthermore, chemical information (concentration of iso-α-acids and aldehydes) is available at different temperatures between 0°C and 45°C, which is only used to further validate the model and was not used in building it[XXXIII]. The chemical data indicates an exponential relation between the temperature of exposure and the decrease in beer quality (also derived from Part 5 Chapter 2 section 2.1). Furthermore, beer flavor quality decays most rapidly during the initial time period when exposed to temperature, but appears to stagnate over time.

b) Building and validating the model

As a *first step*, all available data and its variability was studied. Moreover, the data was compiled into histograms in order to determine the most suitable distribution between temperature, time of exposure and GAS. In Figure 39a, an example of a histogram of the GAS of lager beer samples aged over 120 days at 30°C is presented. The figure (other histograms not shown) indicates that a considerable variability in the GAS is observed for beer samples that experienced the same aging pattern. This can be attributed to the flavor instability of the beer samples (resistance to elevated temperature and duration) and the respondent's perception of taste and flavors. Furthermore, the data of the histograms revealed that a skewed distribution is observed.

In Figure 39b, a theoretical analysis was executed of the predicted variability in the GAS (with constant temperature and changing time of exposure). The researcher of the current study assumes that the variability in the GAS will be largest for beer samples that are not completely fresh nor completely aged ($0 < GAS < 8$), due to the inherent difficulties for a respondent of scoring a beer sample[81]. Furthermore, the researcher believes the variability in the GAS will asymptotically reach 8 the longer the beer samples are exposed to the elevated temperature. However, there is no data available on the natural variation in the GAS for completely fresh (GAS≈0) or aged beer (GAS≈8)[XXXIV]. Therefore, the variation in the GAS of the available data was studied in Table 24. The table indicates the considerable variability in the GAS, and the need for estimating the median, maximum and minimum boundaries of the GAS rather than the average. In the current first model, the median GAS will be estimated and the variability will be demonstrated by indicating a range of +/-1.25 on the median GAS [i.e. spread of 2.5≈75% of the variability in the GAS explained].

[XXXIII] Experiments were executed in KU Leuven, Faculty of Engineering Technology, Department of Microbial and Molecular Systems (M2S), Cluster for Bioengineering Technology (CBeT), Laboratory of Enzyme, Fermentation and Brewing Technology, Technology Campus, Ghent, Belgium.
[XXXIV] When executing a sensorial experiment, the standard procedure is that the respondents are required to taste two beer samples: an aged beer sample and a fresh beer sample that is provided to serve as a point of reference (the GAS of the fresh beer is mostly not expressed). As a consequence, the natural variation in the GAS of completely aged beer samples, respectively fresh beer samples, was never assessed before and requires further study.

Figure 39a: Histogram of data cases – general aging score (GAS) of beer samples aged during 120 days at 30°C
Figure 39b: Theoretical analysis of the predicted variability in the GAS (with constant temperature and changing time of exposure)

Figure 39a

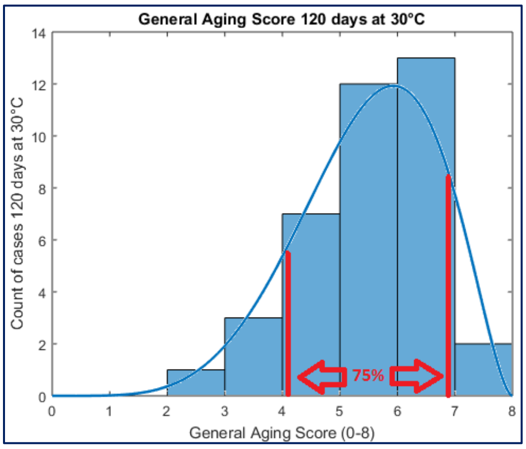


Figure 39b

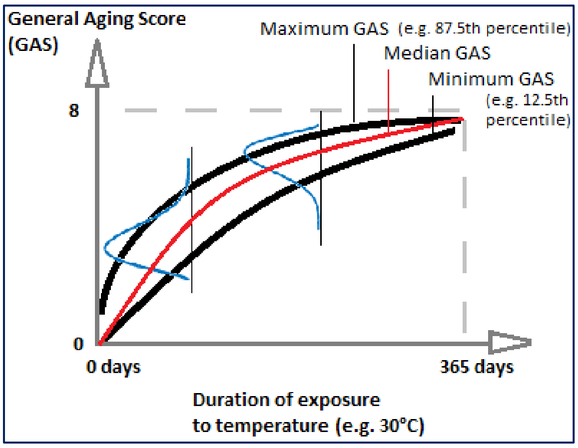


Fig. 39a: A distribution was fitted (current case: Beta-distribution with α= 5.8913 / β= 2.71005) on the responses for the GAS of beer samples aged during 120 days at 30°C (and other temperatures and times of exposure). The variability in the GAS can be explained by the flavor stability of the beer samples (resistance to elevated temperature and duration) and the respondent's perception of taste and flavors.

Fig. 39b: The figure presents the theoretical analysis of the predicted variability in the GAS with the 'median GAS' (50^{th} percentile), 'maximum GAS' and 'minimum GAS' (e.g. 87.5^{th} and 12.5^{th} percentile = 75% of the variability explained). During every time step, the variability of the GAS responses is believed to change. The variability in the GAS for fresh beer (GAS≈0), caused by respondent's perception of taste and flavors, was never assessed before. The researcher also believes the GAS (maximum and minimum) will asymptotically reach 8, i.e. the spread will get smaller and eventually will reach zero, the longer the beer samples are exposed to the elevated temperature. The spread between maximum and minimum GAS is believed to be largest (due to psychometry[81]) when the GAS is not (approximately) equal to 0 nor 8. The current first model estimates the median value of the GAS (GAS between 0-8), but also demonstrates the variability.
Source: Own calculations

Table 24: Analysis of the variation in the GAS of the available data (samples with the same aging pattern - constant temperature and time of exposure) – and validation of the spread between the maximum and minimum boundaries of the GAS-model

	50% of the variability in the GAS explained	75% of the variability in the GAS explained	90% of the variability in the GAS explained
Spread in the GAS of the available data (used to determine the max. and min. of the GAS-model)	1.2 - 1.7	2.0 - 2.8	3.3 - 4.5

The table indicates the variability in the GAS, and the need for estimating the median, maximum and minimum boundaries of the GAS rather than the average. In order to demonstrate the variability of the GAS in the current study, the maximum boundary of the GAS and the minimum boundary of the GAS is presented, which is +/-1.25 compared to the estimated median value [i.e. spread of 2.5≈75% of the variability in the GAS explained].
Source: Own calculations

After the analysis of the available data and the variability in the GAS, in a *second step*, the GAS-model was constructed. Moreover, the median values of the GAS were estimated using all data over the temperature interval between 0°C and 50°C, and the time duration between 0 days and 365 days. Based on the median values of all available data, curves over constant temperature but varying time (and GAS) were fitted by using the Curve Fitting Toolbox in Matlab (Polynomials of degree 3 – due to the exponential nature of the temperature - GAS curves)[XXXV]. As a consequence, the median GAS pattern between 0 and 365 days at the temperatures of 20°C, 30°C and 40°C was accurately derived. Since there was no information available on the GAS over all temperatures, curves were fitted over a constant time but varying temperature (and GAS) using the curve fitting toolbox based on the previously generated data[XXXVI]. Afterwards, curves were fitted again over a constant temperature but varying time (and GAS). The latter fitting induces the GAS to be estimated over a time period of days, hours or even minutes. The result is a three-dimensional model or surface that describes the GAS as a function of temperature and time of exposure.

In a *third and final step*, the model is adapted to allow for estimating the GAS for a beer sample of a certain aging score and subjected to a temperature-time treatment. Since the 3-D model has been fitted to be continuous through interpolation techniques and fittings, any proposed simulation can be done by supplying the parameters of the experiment, i.e. if a timeframe is given at a certain temperature, the resulting path on the 3-D surface can be determined. Moreover, after the surface being adapted to a certain sample frequency, the model can iteratively calculate in each proposed point or timestamp (with corresponding temperature of exposure) what the GAS is. The previous GAS is then used as an input to calculate the next step, resulting in a final GAS determined by the parameters of the experiment.

3) <u>Results & Discussion</u>

In Figure 40, the aging model of lager beer as a function of time and temperature is presented. As can be derived from the figure, the median GAS model starts from the GAS of 0 and ends at 8. The minimum model, respectively maximum model, is 1.25 in GAS lower/higher than the median value and demonstrates the variability in the GAS. Furthermore, the model indicates the exponential effect of temperature on the GAS. For instance, beer samples that are exposed to an elevated temperature of 42°C will reach a GAS score of 8 in approximately 10 days while samples being exposed to 30°C only after approximately 250 days. The saturating effect of temperature over time of exposure can also be derived from the figure. The effect of temperature on the GAS is most substantial in the initial time phases, which can be observed, for instance, from the GAS responses when exposed to the temperatures of 20°C and 30°C.

While the model presented in this dissertation is substantially benchmarked and validated with the available data, the authors suggest further benchmarking with real-life data. The model is predominantly accurate between 20°C and 30°C. However, also the influence of the exposure to temperatures lower than 20°C and higher than 30°C should be further investigated. Currently, the model is based on and validated by chemical data in the afore mentioned temperature ranges. Additional sensorial experiments will generate data that can help in developing an improved and updated model that is more accurate and better in estimating the variability in the GAS. Also the natural variability in the GAS for completely fresh (GAS≈0) or aged beer (GAS≈8) is a topic of future

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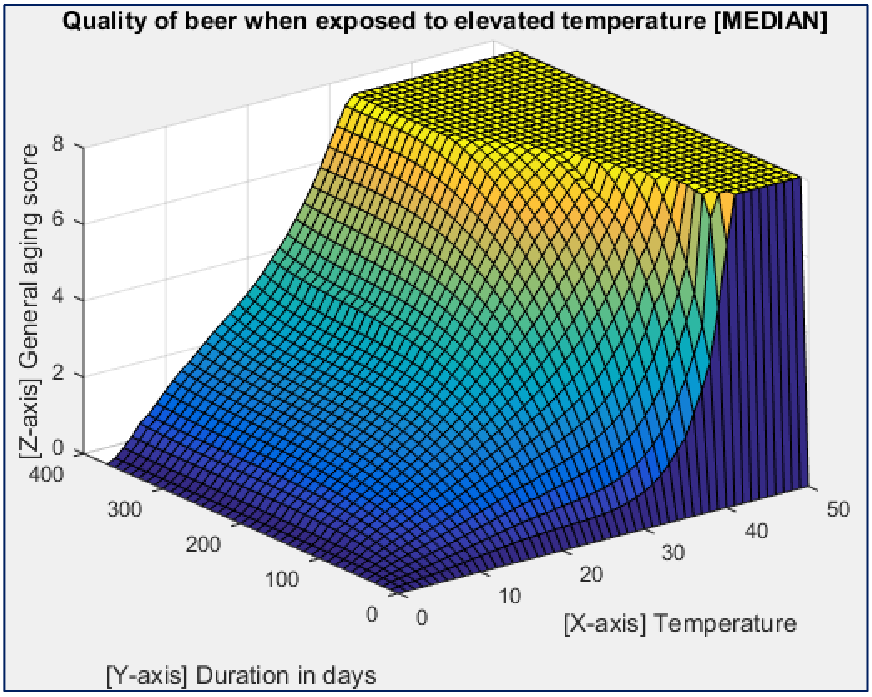
[XXXV] Calculations were performed in MATLAB and Statistics Curve fitting Toolbox Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States.

[XXXVI] In the current study, a first attempt was made to construct a GAS-model through excessive interpolation techniques and fittings based on a sufficient but limited number of data samples. Moreover, the fittings of the GAS-curves at 20°C, 30°C and 40°C and variable time were used to develop the fittings of the GAS-curves over constant time and variable temperature. Therefore, the researchers suggest that an extensive benchmarking study with experimental data is required in order to further reduce the variability and increase the robustness of the GAS-model.

study. Further research is also required on the influence of temperature variations on beer quality, although fluctuations are limited to a large extent due to the secondary cardboard packaging (Chapter 1 section 1.4).

Figure 40: The GAS as a function of temperature and time of exposure (MEDIAN)



Source: Own content

4) Conclusions & Recommendations

From the current research, it can be concluded that it is crucial to protect beer from high temperatures (> 30°C) with respect to the beer flavor stability. As a consequence, it is essential to select the countries and locations beer is exported to and refrigerated transports and storage facilities might be recommended in order to control beer flavor degradation.

Additionally, from the current study, it is also observed that the variability in the GAS, established by expert tasters, is relatively high. Therefore, a more straightforward metric generated by the general beer drinker might be recommended in future research, e.g. the ability to differentiate between fresh and the studied aged beer (by executing a trial test) and the consumer acceptance of the studied aged beer (by executing a preference test).

Finally, while the model presented in the current study will benefit from additional benchmarking and validation of real life data, it is recommended to breweries to adopt the model in order to streamline the beer flavor quality control in the export markets.

3.2 Economic feasibility of offering transport and storage simulations and determining beer quality

1) Introduction

Currently, it is not a common practice to test the beer (flavor) quality after the beer leaves the brewery. The latter might be attributed to the limited reach of the brewer (ex-works distribution results in the wholesaler or distributor to be owner of the beer), the diversity of locations (and distributors/wholesalers) Belgian beer is exported to, and the lack of facilities that can thoroughly and cost-effectively test the flavor quality of the beer. Therefore, a simulation facility will be developed in which beer samples can be exposed to simulated transport and storage and beer quality can be tested. Simulating transport and storage and performing quality tests can be the first step in both better-developed quality control, but also research and development on possible alternative parameters causing beer flavor instability.

a) The application of the simulation facilities

The simulation facilities can be employed in the following affairs:

a) Assessment of the flavor stability parameters after being subjected to a beer aging test (based on simulated transport and storage)
b) Assessment of the flavor stability parameters after being subjected to simulated transport (after measuring the actual transport and storage conditions)
c) Validation of the impact of chemical, process or packaging changes that are aimed to better control flavor stability

Furthermore, the facilities can be used to perform beer quality tests on beer samples sent back to Belgium coming from foreign markets. Also the impact of additional parameters (e.g. temperature and vibrations in interaction with light, etc.) that might influence the beer flavor stability can be tested and assessed in the current simulation environment. All beer quality results will be gathered and stored in order to build a database that will be used to validate and benchmark the flavor quality results of Belgian and non-Belgian beers on foreign and domestic markets.

b) Beer aging methods and machinery

The simulation facility will contain three methods that can be used to age beer samples: temperature, vibration and shock simulations.

The first method of aging beer samples is by controlling ***temperature***. Previous experiments indicated that heat is a major parameter inducing beer flavor instability. Every increase in temperature contributes to an exponential decrease of the beer quality[3], i.e. a change in color (EBC), a decrease of iso-α-acids, and an increase of aldehydes. A climate cabinet can be used to control temperature (in forced air) or a climate room (in still air) in which a multi-parameter experiment can be designed by incorporating vibration or shock simulation equipment.

Beer samples can also be exposed to ***vibrations*** in the current simulation setting. Previous experiments (Chapter 2 section 2.2) indicated the decrease in beer flavor quality (i.e. an increase in aldehydes concentration) due to vibrations of 50 Hz and 15 m/s^2 (0-peak) in combination with elevated temperature of 5°C, 30°C and 45°C during a 90hrs experiment. In another experiment of longer duration (30 days) on a laboratory shaker, beer samples were exposed to horizontal one-dimensional low-frequency vibrations of 1.7 Hz [1.1 m/s^2]. Also in the latter experiment, changes in the chemical components (e.g. color, iso-α-acids, aldehydes, turbidity) were noticed that caused beer flavor quality degradation. Therefore, the simulation facility will be equipped with two shakers:

- Shaker 1: laboratory shaker[82]

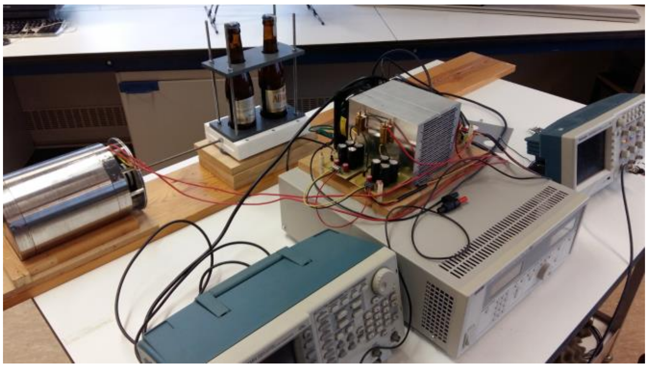
Figure 41: Picture of laboratory shaker

Specifications:
Horizontal vibrations (shaking in 1 or 2 dimensions)
Frequency range: 20 to 250 rpm
Amplitude: Fixed 2mm (peak to peak)

Source: Grant, 2017

- Shaker 2: electrodynamic shaker

Figure 42: Picture of electrodynamic shaker



(Mechanism: a coil is magnetized by an electric current and induces the permanent magnet inside the coil to move back and forth)

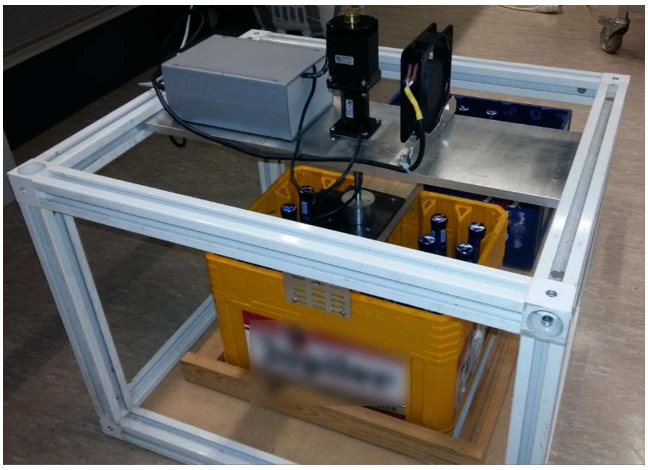
Specifications:
Horizontal vibrations
Frequency range: 5 - 100 Hz
Acceleration range: Max. 15m/s^2 (0-peak)
Amplitude: adaptable (+/- Max. 1.5 cm (0-peak))

Source: Own picture and measurements

Due to the availability of the shakers, beer samples can be exposed to both vibrations of low-frequency content (< 5 Hz) and high-frequency content (> 5 Hz). The laboratory shaker is robust and can perform experiments of long duration (e.g. 30 days), which enables for the simulation of shipments and low-frequency truck vibrations. The electrodynamic shaker needs cooling more frequently and intensely, and, therefore, the shaker can only execute experiments of a shorter duration (e.g. < 4 days). The electrodynamic shaker can be used to simulate high-frequency truck or train vibrations. Furthermore, in the past experiments, beer quality degradation was observed when imposing vertical vibrations of 50 Hz and 15m/s^2 (0-peak). The beer degradation phenomenon is more pronounced when also exposed to elevated temperatures (30°C - 45°C). The impact of horizontal versus vertical vibrations should be explored in future research (i.e. different behavior might be expected due to turbulent fluid flows).

A device to simulate ***shocks (transient vibrations)*** will also be incorporated in the simulation facility since beer bottles are exposed to shocks during transport and handling. The equipment that was manufactured to simulate shocks is a drop device that is able to mechanically and repetitively lift and drop a plastic beer crate (filled with beer bottles). More specifically, by controlling a motor that pulls a rod up and down that is fixed to an electromagnet, a small metal plate anchored to the plastic crate will induce the system to go up and to drop the crate.

Figure 43: Device for simulating shocks



Calibration measurements presented in Appendix 5

Source: Own content

As indicated in the previous analysis, researchers can opt to ***simulate transport and storage*** or to impose a ***standardized beer aging test***. In both options, the objective is not only to subject beer to vibrations, shocks, and temperature during the actual duration of the transport and storage, but also to shorten the experimental duration (while having representative results). Furthermore, in a beer aging test, the beer samples are exposed to a standardized procedure or pattern of temperature and/or vibrations and/or shocks with the aim to validate the flavor stability performance of the beer samples (relative to other beer brands and beer types). In both tests, it is crucial to validate and benchmark the beer quality results with the findings from actual transport and storage.

2) Methodology

The analysis on the feasibility of the simulation facility is predominantly based on the survey performed by Paternoster (2017)[76]. The main objective of the survey was to identify the demand for a transport and storage simulation environment. Furthermore, additional questions were asked that enabled to frame the severity of the flavor stability problem of exported beer for the Belgian breweries. The survey was filled in by the quality manager of 17 Belgian breweries (out of a respondents group of 33 Belgian breweries). The data of the survey in combination with the data available in the literature (Belgian brewing sector data[1], e.g. number of breweries, export data, number of beers) permitted to perform calculations on the expected demand for the transport and storage simulations.

3) Results & Discussion

a) The economic importance of optimizing beer flavor stability: transport and storage simulations

Assessing the economic impact of off-flavors and/or improved beer quality of Belgian beer exported to foreign countries is not an evident task. Already in the 1960s, research highlighted the importance of brand image, beer labels and their associations over product evaluations[83]. Moreover, the beer brand and image has a significant impact on the perceived quality of beer[52]. Therefore, the consumer perception and evaluation of the quality of beer is not an isolated phenomenon and should be seen as a part of the brand experience and brand equity[84]. As a consequence, the researcher should be cautious in estimating the impact of an improved beer quality. The possible impacts of an improved beer flavor stability might be:

- More consumers becoming loyal to the beer brand (which results in increasing sales)
- Lower risk of beer brand rejection
- Lower risk of devaluation of the image of the quality label of Belgian beer in foreign markets

The quality managers of the 13 surveyed Belgian breweries (13/17 filled in the question) indicated that optimizing flavor stability is crucial. Moreover, 10 quality managers indicated that the flavor instability problem is ‘important and a priority’, while three managers indicated the problem is ‘important, but not a priority’. The three quality managers had a different reasoning for the latter response (e.g. “The brewery is expanding and, therefore, priorities have shifted.”, “The consumer is sometimes mild/temperate with respect to the taste of beer; even a sharp beer taste (rated by the professional drinker) appears to have loyal fans.”). Although consumers prefer different beer tastes (sometimes identified as an off-flavor), most of the quality managers indicate that it is fundamental to improve the beer flavor stability. Moreover, the quality managers aim to continuously improve the brews and want to offer the consumer the best possible beer taste, even if not all consumers do taste an improvement in the beer flavor (yet). An additional argument proposed by multiple brew masters is that export and the demand for more beer types rises, which induces people to compare more between brands and which results in increased competition. Therefore, there is an increased need for ‘stable’ beers that can be exported[XXXVII].

While the problem of beer flavor instability is universally known, only 8 out of the 13 questioned quality managers (13/17 filled in the question) have received questions (or complaints) with respect to the beer flavor in the past. However, the frequency of the complaints is mostly less than one per year and the problem of the complaints is frequently related to the hygiene conditions of the tap installation. In addition, most of the complaints come from customers within Belgium or the Netherlands. The researcher of the current study assumes that only a few complaints reach the brewery since export beer distribution predominantly works on an ex-works basis. The wholesalers, distributors, pubs, etc. are intermediaries that prevent or complicate the complaint feedback loops. Furthermore, there are limited visual effects of beer flavor instability (if not compared with fresh beer) and a particular beer taste and flavor is subjective, the price of beer is also limited, and, therefore, the researcher of the current study believes that few consumers will do the effort to complain about beer flavor degradation.

Although there are limited complaints concerning the beer flavor and taste coming from the export markets, the flavor instability problem is manifest to breweries[XXXVIII]. Nevertheless, the Belgian breweries lack a quality control system after the beer leaves the brewery. Only 4 of the 14 surveyed

[XXXVII] An overview of all questions and answers of the survey can be found in Appendix 14.
[XXXVIII] A surveyed quality manager even indicated they only export the beer brands they file as ‘stable’.

breweries (14/17 filled in the question) test the beer quality in foreign markets. Furthermore, all 4 quality managers indicate that beer is sent back to Belgium or the manager physically goes to the distributor to perform a sensorial test (both on an irregular basis, i.e. approx. 1 to 3 times per year). There are no standardized procedures nor quantitative tests that make able to perform objective quality control measurements on a regular basis. The large number of intermediaries during the ex-works beer distribution not only complicates communication, it is also difficult to organize quality control. The latter also induces that the breweries have no information on the demographical characteristics of the clients in foreign markets nor the customer loyalty (results of the survey[76]). Furthermore, the need for a dedicated laboratory that is able to perform the necessary quantitative assessment of the beer flavor quality further complicates the beer quality control.

In conclusion, the previous analysis indicates that there is a need for a simulation facility in which transport and storage can be simulated and the beer quality parameters can be determined. The simulations will enable the brewers to have a clear view on the beer flavor quality after exposure to extreme temperatures, vibrations, and shocks. The simulation facility will also stimulate further research on the parameters influencing the beer flavor instability. If the brewers continuously perform measurements on the external factors transported and stored beer are exposed to (e.g. temperature), a more considered and better informed quality examination can be established[XXXIX]. Furthermore, the information should allow the brewery to negotiate with the wholesaler or distributor about the required transport and storage conditions (e.g. cooled containers or storage).

b) Prediction of the demand for beer transport and storage simulations

In order to estimate the forecasted demand for simulating transport and storage, the usage and application of the simulation services should be segmented in:

1. Validation of flavor stability of the current beers
2. Validation of flavor stability of new beers or product introductions
3. Validation of flavor stability of beers that have experienced chemical or process changes

All these options can be established with a standardized beer aging test in which beer samples are exposed to extreme heat, vibrations, and/or shocks (benchmarked with the measured data during beer transport and storage). Another possibility is to perform a beer transport and storage simulation, adapted to the need of the brewery and the selected country of export. The surveyed breweries indicated to be predominantly interested in the standardized aging test (since the beer is exposed to the most extreme conditions). In Table 25, an overview is presented of the predicted market demand of the breweries for the simulation services. The table indicates that an initial annual market demand between 200 and 530 simulations can be expected from the validation of the flavor stability parameters of the current and new beers.

The researcher of the current study expects that a relatively small number of the total market demand will consider to perform a transport and storage simulation. The expected demand for a transport and storage aging test or simulations at the KU Leuven Campus Ghent is dependent on the following variables:

- The proven or demonstrated economic effect of beer flavor instability and/or improved beer flavor stability

[XXXIX] If the temperature (and time) conditions the beer was exposed to are known, the simulated General Aging Score (GAS) can be calculated (Part 6 Chapter 3 section 3.1).

- The pricing, the difficulty of performing a transport and storage simulation, and the value of the information (e.g. information on the flavor instability of a new beer during the R&D-process and the possible economic benefits of improving beer quality / economic risks of low beer flavor stability)

Table 25: Prediction of demand (market) for simulation facility services

		Source/explanation
Total number of different beers in Belgium (2016):	1500	Belgian brewers annual report[1]
Number of breweries in Belgium (2016):	199	Belgian brewers annual report[1]
Estimated total number of Belgian beer introductions:	between 125 and 180 per year	Based on the results of the survey[76]: 25-30 per year (large breweries), 100-150 per year (other breweries)
Estimated reach of the KU Leuven technology campus Ghent:	between 1/5 and 2/5 of the Belgian breweries	Based on the 40 breweries included in the VIS/Brewers-project and 199 breweries in Belgium
Predicted demand (market) per year Validation of flavor stability of the current beers	180 – 480 beers [≈ simulations] (CURRENT MARKET DEMAND)	(Total number of beers) x (estimated reach KU L) x (percentage of beers exported (60-80%))
Predicted demand (market) per year Validation of flavor stability of new beers or product introductions	15 – 58 beers [≈ simulations] (EXPANSION OF MARKET DEMAND PER YEAR)	(Total beer introductions) x (estimated reach KU L) x (percentage of beers exported (60-80%))
Predicted demand (market) per year Validation of flavor stability of beers that have experienced chemical or process changes	(not defined) Breweries continuously work on an improved beer quality	Results survey Paternoster (2017)[76]

Source: Own calculations

While the quality managers of the breweries are aware of the problem of flavor instability, the exact economic effect of beer flavor instability is not yet fully proven or demonstrated. Since beer export is rising[1] (due to the consumer willing to taste new and 'exotic' beers[5]), the negative (economic) effects of off-flavors in beer are not yet experienced by the breweries. The decrease in beer sales, the destruction of brand equity, and the devaluation of the Belgian beer quality label might be long-term effects the Belgian breweries are not aware of. As a consequence, investments in beer quality and the demand for beer transport and storage simulations will be dependent whether or not the effect of beer flavor instability or increased flavor stability on the consumption behavior and/or customer experience is demonstrated.

Also, the pricing is crucial with respect to a better assessment of the demand for the simulation services. The pricing is related to the difficulty of performing a transport and storage simulation and the value of the information. If the vibrations or shocks experiments are of minor impact (compared to the temperature experiments), breweries might opt to perform a temperature (storage) simulation themselves. This will not only influence the pricing, also the long term feasibility and continuation of simulations in the simulation facility. Therefore, the value of performing a simulation can and should be enhanced by including an extensive benchmarking study with the flavor stability performance of similar beers or beer types that experienced the same standardized aging test.

c) Pricing of the beer transport and storage simulations

Currently, most breweries do not have a fixed research and development budget that is addressed to study the internal beer flavor stability problems (results of the survey[76]). Hence, the willingness to pay and the demand side for transport and storage simulations is difficult to determine. Nevertheless, since beer samples can also be sent back to Belgium by the brewery and tested on its flavor stability parameters in the KU Leuven campus Ghent, the cost of performing a transport and storage simulation should be lower than or equal to sending back a crate of beer from the export markets. As a consequence, a transport (and storage) simulation of truck transport within Europe should be priced lower than or equal to € 150-280, a transport (and storage) simulation of ship transport should be priced lower than or equal to €440-680[XL]. The lower boundary of the price should be based on the operational cost of running the simulations. In Table 26, an overview is presented of the estimated operational (energy) cost of the devices used to perform a simulation of a ship and truck transport, followed by a simulation of storage. The table indicates that the energy cost of the standardized aging test of simulated ship transport and storage approximates € 42-64. The energy cost of the standardized aging test of simulated truck transport and storage equals € 25-35. Therefore, the suggested price for a ship transport and storage simulation should be between € 64 and 680 (the price should be at least higher than the variable cost per simulation), and for a truck transport and storage simulation between € 35 and 280. The research institution should also take into consideration and incorporate a partition of the fixed costs into the price for a simulation. The price for performing a simulation will be further supplemented with the prices charged for the chemical beer tests (displayed in Table 27).

Table 26: Overview of estimated total costs of beer transport and storage simulations
(operational/energy costs – investment costs – maintenance costs) – Total cost of ownership KU Leuven Campus Ghent

VARIABLE COST	**Operational/energy cost of the devices**	**Source/explanation**
Simulation of ship transport and storage	Operational cost: **€ 42-64 per simulation**	shaker[85] climate cabinet[86]
Transport: low-frequency vibrations (shaker 1) during 30 days at 30°C Storage: 90 days at 30°C	Shaker: 70-90W over 30 days = € 13-23 Climate cabinet: 40-60W over 120 days = € 29-41	[24u*30d*70-90/1000kWh*0.25-0.35 €/kWh] [24u*120d*40-60/1000kWh*0.25-0.35 €/kWh]
Simulation of truck transport and storage	Operational cost: **€ 25-35 per simulation**	Shaker/shock device[85] climate cabinet[86]
Transport: high-frequency vibrations (shaker 2) / shocks during 4 days at 30°C Storage: 90 days at 30°C	Shaker/Shocks: 70-90W over 4 days = € 2-3 Climate cabinet: 40-60W over 94 days = € 23-32	[24u*4d*70-90/1000kWh*0.25-0.35 €/kWh] [24u*94d*40-60/1000kWh*0.25-0.35 €/kWh]
FIXED COSTS		
Investment cost	Shaker: € 1000-2000 Shocks: € 1000-2000 Climate cabinet: € 5,000-15,000	(Depreciated over 5 years) Only a fraction of the climate cabinet's capacity & operational hours will be used
Maintenance cost	Shaker: € 50-100 Shocks: € 50-100 Climate cabinet: € 250-750	Assumption: 5% of investment cost per year[87]

Source: Own calculations

[XL] FedEx charges between € 120-230 (excl. VAT) for importing of a 25kg freight into Belgium coming from a European country. The price charge for importing a 25kg freight into Belgium coming from a country outside of Europe is € 360-560 (excl. VAT)[91].

Table 27: Overview of the prices charged for chemical beer tests

Chemical test	**Prices charged by the KU Leuven campus Ghent** (2016) (prices excl. VAT)
Oxygen (TPO, HSO, DO)	€ 50
Color	€ 10
Iso-α-acids UPLC	€ 100
Aldehydes GC-MS	€ 350
Haze	€ 60

Source: Internal information KU Leuven technology campus Ghent, 2017[88]

The researcher expects that the breweries will opt for a simulation of ship transport and storage due to the extreme nature of the experiment, i.e. the beer samples are exposed to both temperature and vibrations during a long (experimental) duration. Since the vibration experiment lasts 30 days and only one to two beer types can be shaken simultaneously, the capacity of performing the simulations is limited. Due to the capacity and occupancy of the simulation devices (related to the duration and the number of samples of the vibration experiments), the researcher of the current study estimates 12-24 simulations to be performed per year. Since the fixed costs per annum were quantified as € 850-2050 (Table 26: shaker and shock device are depreciated over 5 years and climate cabinet is allocated to simulations for 10% and depreciated over 5 years), the price per simulation should be at least increased by € 120 (+/- 10%). This induces the suggested price for a ship transport and storage simulation to be between € 190 and 680, and for a truck transport and storage simulation between € 160 and 280.

4) Conclusions & Recommendations

Quality control of exported beer remains difficult for breweries due to the need for a laboratory, able to execute the necessary chemical tests, and the ex-works distribution. Therefore, the economic feasibility was analyzed of offering the breweries simulations of beer transport and storage in order to study the flavor stability parameters of exported beer.

From the results, it can be concluded that breweries are interested in the simulation services performed by the KU Leuven technology campus Ghent. However, since the export figures are still rising, the demand for the simulation services is to a great extent dependent on the proven or demonstrated economic effect of an improved beer flavor stability. The breweries will be offered the following simulations: a standardized aging test, based on the simulation of ship or truck transport followed by beer storage, or an adapted simulation of transport and storage demanded by the brewery. From the analysis of the current study, it can be recommended that a database of the beer quality results coming from the simulations should be developed. The database will make able to benchmark the beer quality results among different beer types, which increases the value of the offered transport and storage simulations. The database can be built during the VIS/Brewers-project and will support the simulation facility to be operational after ending the project.

While the initial market demand for simulations would be between 200 and 530 simulations, the capacity of the vibration devices will limit the annual performed simulations between 12 and 24. The simulation price should be fixed between € 64 and 680, respectively € 35 and 280, for a ship transport and storage simulation, respectively a truck transport and storage simulation. Based on the simulation prices, the margins and the capacity of the vibration devices, the researcher of the current study indicates that it is economically feasible to perform beer transport and storage simulations.

The expected operational results and the uncertain demand (revenues max. € 15,000 per annum[XLI]) will not yet be sufficient for starting a spin-off of KU Leuven technology campus Ghent, but can be an important additional source of income.

The current study made clear which areas require additional research. Moreover, the results of the survey indicated that the breweries should better identify the consumer profile. This will enable the breweries to react in an agile fashion on consumer trends since the economic impact can be assessed. Furthermore, further research is recommended with respect to performing the vibration simulations and the validation of the results with real-life transport. The impact of imposing the beer samples horizontal versus vertical vibrations should be identified. Additionally, the effect of consecutively imposing vibrations and shocks versus incorporating both at the same time should be assessed. Lastly, the simulation facilities should be used to further study the impact of alternative parameters (e.g. temperature and vibrations in interaction with light) on the flavor stability of beer.

[XLI] Calculation: approx. 24 simulations of € 600 (upper limit).

Part 7: Conclusions, recommendations and implications

7.1 Discussion of the findings (assessment of the methodology, data quality and significance of the results)

In the current Ph.D., diverse research activities were pursued in order to develop results and conclusions of both quantitative and qualitative nature. Moreover, vibrations, shocks and temperature were measured during multiple transports, diverse experiments were designed, surveys were sent out, etc. In the current section, the aim is to reflect on the diverse methods used in this research and to critically analyze the data quality and the significance of the results. The logic and structure of the Ph.D. is followed to discuss the methodologies and findings of all relevant chapters of the research study.

In ***Part 5 Chapter 1***, the aim was to identify the ***temperatures, vibrations and shocks bottled beer is exposed to during the distribution of beer***. Therefore, temperature loggers were sent on beer transports of the breweries going to foreign markets. The temperature measurements produced valuable data and strong evidence on the temperatures packaged beer is exposed to during transport. However, only limited information was acquired on the temperatures during storage (at the wholesaler and/or distributor) and in the last chapter of the value chain before consumption. Furthermore, vibrations and shocks were measured during actual truck and train transport in different case-studies (due to the technicalities and fragile character of the devices). With respect to ship transport, the researcher had to depend on the findings in the literature. However, the measurements made able to derive packaging specific insights with respect to vibrations and shocks and were measured during the most extreme conditions of beer distribution, i.e. truck and train transport. The researcher of the current study believes that a well-developed methodology was established that enabled to gather essential data and comprehensive insights on the external parameters beer is exposed to during distribution. The generated data was an important building block for designing experiments of this research, but will also be of considerable value for future studies.

In the following ***Part 5 Chapter 2, the results of the experiments on the impact of temperature, vibrations and shocks on the beer quality*** were presented. Since industry and academia are well aware of the impact of heat on the flavor stability of beer, the influence of temperature fluctuations was studied in this research. Temperature fluctuations do seldom occur (due to the isolation properties of the beer packaging), but strong evidence is derived from the experiment that temperature variations have limited impact on the beer flavor stability. Furthermore, additional experiments strongly indicated that beer might be vulnerable to vibrations and shocks. However, in the conducted vibrations experiments only vibrations of a single frequency were imposed, which is different from the multiple frequencies beer experiences during transport. Exposing beer samples to vibrations of a single frequency was a conscious decision in order to be consistent with the earlier executed experiments and the technicalities of the devices in the simulation facility. In the vibration experiments, beer samples were exposed to extreme accelerations higher than observed in reality in order to enlarge the effect on beer flavor stability. In the multiple experiments related to vibrations, shocks and temperature the findings were generated with only limited samples mostly due to regulations out of our control (i.e. the availability and occupancy of the devices, the cost and duration of the experiments, the cost of the chemical tests). Therefore, additional experiments are recommended to further develop the significance of the insights from the current study.

In ***Part 5 Chapter 3**, **sensorial tests*** were performed in order to study ***the effect of off-flavors and beer flavor instability on the consumer behavior***. The methodology was to study the differentiating capacity of the general beer drinker between fresh and aged beer with the triangle test, the preference for fresh and aged beer with the duo test, and the recurrent consumption of fresh and aged beer with the drinkability experiment. The latter insights were essential for studying the economic impact of beer flavor instability. Respondents of different age groups, different nationalities, and different beer consumption habits participated in the experiments. As a consequence, the data quality is adequate to gather the first insights on the matter. However, the researcher acknowledges that not all consumer groups were (statistically significantly) assessed, and experiments with alternative beer brands might yield deviating results.

In the subsequent ***Part 6 Chapter 1***, ***the economic feasibility of refrigerated transports*** was assessed. Analysis was performed of different transport carriers' dry and reefer container shipping prices in addition to the findings in the literature. The results made able to identify the additional cost of refrigerated transport to the breweries. Furthermore, a framework was introduced to assess the feasibility of refrigerated transport by benchmarking the expected additional sales volume of beer with the investment in refrigerated transports. However, the researcher indicated that the economic feasibility of refrigerated transport is to a large extent dependent on the market dynamics of the country of import, the customer behavior, and the exported beer brand. Therefore, the study and the significance of the results is predominantly theoretical and the need for further research is necessary.

The economic feasibility of horizontal collaboration in logistics between Belgian breweries was identified in ***Part 6 Chapter 2***. A literature research was performed in order to identify the concept of horizontal collaboration in logistics, and the object of study, the supply chains of the Belgian breweries, was defined by sending out two surveys to the breweries. The available data, generated by the surveys, made able to perform a case-study. The results of the study were significant, i.e. only wholesalers/distributors with small order quantities (and annual demand) will profit from working together. However, the case is hypothetical and theoretical and does not take into consideration the complexities of working together and its practical feasibility.

The last ***Part 6 Chapter 3*** was dedicated to ***simulating beer transport and storage***. A first attempt was performed at estimating a general aging score (GAS) model that is a function of temperature and time of exposure. The tool is valuable for both academic research and industry, but further validation with sensorial data is required. In a last chapter of the section, the demand for transport and storage simulations in combination with a chemical analysis of the beer quality parameters was studied. A survey made able to identify the perceived significance of the flavor instability problem of the breweries. However, due to the limited prior knowledge of the breweries on the objectives and the exact composition of the transport and storage simulations, the demand and willingness to pay should be assessed in future research.

7.2 Relevance and contributions of the research

The current PhD-research is dedicated to the beer flavor instability problem of Belgian exported beer with respect to the impact of vibrations, shocks and temperature. The multidisciplinary nature of the executed research made able to identify several interesting findings that are relevant for both academic research and industry. Therefore, a summary of the contributions of current research is presented.

For the first time, dedicated experiments were designed to measure vibrations, shocks and temperature during beer transport. This made able to assess the impact of the beer packaging with respect to protecting beer bottles from vibrations, shocks and temperature. The benchmarking study proves to be highly relevant for breweries. Furthermore, experiments were performed to investigate the impact of the interaction between transport vibrations, respectively shocks, and temperature on the beer flavor stability. No prior research was executed on the influence of vibrations and shocks on the beer quality, and, therefore, the current research is the first study of its kind. The experimental research also indicated the possibility to further research and develop an accelerated beer aging test that is shorter in duration than currently adopted methods (4 days compared to 2 months).

Furthermore, research was performed on the impact of off-flavors on the taste and flavor perceptions of the general consumer. Not only the ability to distinguish between fresh and aged beer was tested, also the preference and the drinkability were investigated. The latter study is essential for academic research and industry to grasp the significance of the flavor instability problem. Furthermore, this study is a first step in performing additional research in the matter, and will influence managerial decision-making and allow validation of investments in beer quality. Moreover, the theoretical study on the feasibility of refrigerated transports (and horizontal collaboration in logistics) is essential and highly appreciated by breweries.

In the current research, an algorithm was built to simulate the sensorial beer quality (general aging score - GAS) based on the time of exposure and the exposed temperature. When measuring temperature during the export of beer, a brewery can estimate the beer quality without sending back beer samples or performing a sensorial test on-site. As a consequence, the aging score model can become essential to the breweries since it is able to provide important information in a cost-effective fashion. Nevertheless, the researcher suggests to further expand the work on linking the chemical parameters with the sensorial attributes of the beer samples (acceptance - preference), without using the GAS scores, in order to more objectively predict the beer flavor quality of the studied beer samples.

Additionally, contributions were made in the development of a facility in which beer transport and storage can be simulated. For instance, a device was built that is able to automatically and repetitively generate shocks or transient vibrations to bottled beer. The devices can also be utilized for simulations with alternative (food) products, e.g. apples. The main objective of the transport and storage simulations is to enable information gathering on beer flavor instability. This is both crucial and imperative to protect the brands and the image of the Belgian breweries in foreign markets.

Finally, contributions to literature were made by publishing diverse papers (papers in Annex).

7.3 Limitations and Shortcomings

Measurement equipment

Vibrations were measured during beer transport with a self-assembled construction of devices (i.e. data acquisition device, accelerometers, etc.). The researcher is aware that more advanced and sophisticated vibration measurement devices are available on the market. Nevertheless, our measurement equipment was suitable within the scope of this study and the required sensitivity of the results.

Sample sizes of taste experiments

The taste experiments, described in Part 5 Chapter 3, emphasize the importance of researching and improving the beer flavor stability. Nevertheless, the conclusions of this work are highly dependent on the sample sizes and the respondent's profiles. Therefore, the researcher of this study underscores the limitations of the tests: there was no random selection of the respondents, not all socio-demographic groups of society were represented (i.e. age groups, smokers vs. non-smokers, etc.), and the test was performed with a limited number of beer types and respondents.

Quantifying beer flavor and aroma

While research identified the molecules and chemical compounds that contribute to the flavors and aromas of beer, there is no one-on-one relation with the sensorial attributes of the same beer. Currently, beer researchers work in three separate methods to quantify flavor stability of beer samples, i.e. chemical profiling, sensorial profiling (i.e. assigning the characteristics of the beer samples e.g. ribes flavor, notes of toffee, etc.), and selecting a GAS. Also in this research, the same methods were applied, including the GAS, although considered to be a subjective and not-optimal metric to quantify the beer flavor stability (the GAS scores of professional tasters show large variability, demonstrated in this dissertation Chapter 6 section 6.1). The latter is a limitation of the study and this should be emphasized and communicated to all beer researchers, breweries and readers of the current dissertation in general. When building an extensive database, researchers have the ability to link the concentrations of the chemical compounds with the sensorial profile, the GAS and the acceptance and preference of the consumer by using advanced statistics and data mining techniques.

Economic feasibility estimations

In this work, the feasibility of refrigerated transports and horizontal collaboration in logistics were studied. While an accurate view on the complexities was demonstrated, this study was limited to be a theoretical work based on limited (brewery-specific) data. The estimation of the feasibility of offering transport and storage simulations was even more complicated, since it was difficult to assess the importance of beer flavor stability from the breweries perspective. This work limits itself to a high-level approach of the phenomenon and should be developed in further detail. The latter shortcomings are closely related with a better quantification of the beer flavor and aroma. If the consumer's opinion with respect to a beer sample can be estimated (based on limited chemical data), the breweries can be offered more validated and benchmarked recommendations that can lead to better informed managerial decisions.

7.4 Recommendations to the different stakeholders

Recommendations to the breweries

Due to beer flavor instability, the beer flavor and aroma change over time. In the current research, not only the differentiating ability of the general consumer between fresh and aged beer is illustrated. Also, the statistically significant preference of fresh over aged beer is observed. Therefore, I would predominantly recommend the breweries to be ***aware that the beer flavor quality deteriorates*** due to exposure to non-optimal transport and storage conditions. In the current socio-economic context, in which exports are (still) rising, a brewery might overlook or even reject the possible harmful effects of beer flavor instability.

Secondly, from the current research, it is derived that most breweries do not follow-up the beer after it leaves the brewery. Therefore, an ***increased traceability should be recommended*** in which beer batches, and storage conditions (e.g. temperature) are tracked. A better traceability of the exported beer implicitly results in better communication and collaboration with the wholesalers, retailers and other partners in the supply chain. As a consequence, more informed decisions on ***testing the flavor quality of the exported beer***, as well as gathering data on the different consumer groups will be enabled. Currently, the brewery has limited knowledge on the identification of the consumers of their product. A ***better identification of the different consumer groups*** also implies a better estimation of the operational risks (e.g. economic impact of consumer trends).

Finally, the breweries are recommended to take up an active role in solving problems with respect to flavor stability. Belgian breweries should take the initiative to invest in flavor quality in order to maintain the quality image of Belgian beer abroad. ***Close collaboration with research*** (i.e. performing case studies, research projects) can elevate the status of the whole Belgian brewing industry.

Recommendations to the government

The quality of Belgian beer is renowned in foreign countries and, therefore, important with respect to the image of Belgium. As a consequence, ***investing in the sector*** is crucial from an economic point of view. Additional research on beer flavor stability should be recommended, especially on the taste experiments and in better marketing Belgian beer. The research should predominantly represent the interests of SMEs since they do not have the finances and the facilities to conduct the research as can be performed in a large multinational. Additionally, further research should investigate the ***potential economic impact of the performed research*** in order not to underestimate nor overestimate the impact technology and improvements might have.

Recommendations to the distributors, wholesalers, retailers and malls

The distributors, wholesalers, retailers and malls are recommended to better communicate and work together with the breweries. Furthermore, the stakeholders should be ***aware of the negative effects of the transport and storage conditions*** on the beer flavor stability. They should take into consideration that the consumers should be offered the most intense beer taste experience, which for them later on will also result in additional profits and satisfaction.

Recommendations to the consumers

The consumers of beer are recommended to enjoy their beer but also to better taste the beer they are offered. Both aroma and taste should be experienced to the full. Furthermore, the consumers should be aware that for most beers, unlike some wines, aging will not result in better aromas and taste. Therefore, it is also crucial to ***appropriately transport and store the beer*** once it reaches the consumer.

7.5 Avenues for further research

The research described in the current dissertation is in different areas a pioneer in its field, and, therefore, the findings within the current work gave rise to plural avenues for further research.

First and foremost, the ***vibration, shock and temperature experiments*** performed in the current research ***should be repeated*** in order to develop statistical significant insights and holistic conclusions. Moreover, reproducing the experiments with different beer types might infer contrasting results since there is limited knowledge of the effect of vibrations on the chemical pathways of beer aging reactions. Furthermore, the ***complexities of simulating beer transport*** with respect to the different transport modes became clear within the current research. The selection of input vibration and shock pattern most related to real-life transport is challenging, and is further constrained by the availability and specifications of the vibration devices. Therefore, future research should involve assessing the effect of consecutively imposing vibrations and shocks on the beer quality versus incorporating both at the same time, the effect of inducing vibrations of a single frequency (in contrast to the vibrations with multiple frequencies observed in reality) should be studied, as well as the effect of vibrations of single dimension (vertical, lateral or longitudinal) compared to multiple dimensions as observed in reality. In other words, extensive benchmarking and validation are required for the beer quality results coming from real-life transport and the transport simulations.

Furthermore, additional research is recommended on the ***chemical impact of vibrations and the beer flavor stability***. Moreover, the influence of the uptake of oxygen, caused by and in interaction with vibrations, should be explored in the future research. The latter might be prone to consideration of a Ph.D. topic for a chemist and/or physicist due to its complex nature. Furthermore, the impact of the interaction of external conditions on the sensorial quality of beer should be a topic of further research, e.g. temperature and vibrations in interaction with light.

The current research also uncovered the ***limited knowledge and unavailability of data of the breweries on the consumption behavior in the export markets*** (of the consumers of the beer). Breweries are exporting increasingly more volume of beer as a percentage value of total production. The increased appreciation for (unknown and new) Belgian beers in foreign markets causes even the smallest breweries to export beer. However, due to the ex-works distribution and the remoteness of the foreign markets, breweries are unaware of the (possibly changing) consumer perceptions and trends. Therefore, ***research on the consumer behavior*** from a company or academics perspective is highly recommended (e.g. segmentation of the consumer profile, brand loyalty, on-trade vs. off-trade consumption, etc.).

In the current Ph.D. dissertation, an attempt was made to investigate the ***consumer perception of fresh over aged beer***. The ability to distinguish, the preference and the drinkability of fresh over aged beer of the general consumer was studied. These experiments should be repeated with larger consumer groups and different beer types. The researcher of this study believes that further research should be installed on the tolerance and acceptance of the general consumer for aged beer. Statistical and mathematical techniques have the ability to link chemical flavor profiles with the results of sensorial tests, in which the consumer acceptance for aged beer is studied. In a later phase, the chemical parameters can be used as a proxy to accurately estimate sensorial test results of the general consumer. This will be a method that is ***more objective than the currently adopted general aging score (GAS)***, which is only used by the expert tasters and demonstrates considerable variability in the test responses.

7.6 Final conclusions

The current Ph.D. dissertation, devoted to the beer flavor quality and stability of Belgian beer, has brought forth a substantial number of significant insights and results. Therefore, an overview of the most essential conclusions is presented in which the research questions developed in Part 3 section 3.2 are discussed and answered.

RESEARCH QUESTION 1a, 1b:

- **Do fluctuations in temperature, vibrations and shocks during transport cause a decrease in the chemical and sensorial quality of beer?**
- **Does the interplay between temperature, vibrations and shocks (interaction effect) lead to an extra decrease in beer quality?**

Obviously, the answer to the research questions is not straightforward since many experiments were executed that can only generate strong indications and not an all-encompassing answer. However, more experiments with different beer types and beer samples can generate this answer and, therefore, are recommended.

Fluctuations in temperature were not identified as harmful with respect to the beer flavor quality. However, every increase in temperature should be avoided in order to prevent beer aging reactions. Furthermore, ***transport vibrations and shocks are identified as parameters that contribute to beer flavor instability***. Vibrations and shocks induce an uptake of oxygen that later on results in further aging reactions related to the formation of aldehydes and the turbidity in beer. Reducing the initial oxygen content is crucial in limiting the impact of vibrations, shocks and temperature on the beer flavor stability. Additionally, the experiment with respect to the interplay between vibrations and temperature indicates that the impact of vibrations becomes ***more substantial*** (with respect to the aldehydes) ***when temperature is high*** (30°C – 45°C). Furthermore, the individual ***impact of temperature is considered substantially more dominant over the impact of vibrations and shocks*** and, therefore, controlling temperature should be the main focus to breweries.

RESEARCH QUESTION 2:

Are consumers aware of the inferior quality of transported beer (or aged beer) relative to fresh beer and, as a consequence, prefer beer of high quality?

Different taste experiments were designed and executed in order to answer research question 2. From the experiments, it can be concluded (by statistical analysis taking into consideration the limitations of the study) that consumers are ***able to distinguish fresh from aged beer*** (aged for 3 to 4 months at 30°C). Nevertheless, the results of the performed preference tests indicated that consumers equally preferred fresh and aged beer (apart from Belgians older than 27 years that had a clear preference for fresh beer). The ***drinkability experiments***, on the other hand, indicated that there was a ***65% preference of fresh over aged beer*** and that ***fresh beer was 35% more consumed than aged beer***. Predominantly the consumer group of Belgians older than 25 years revealed to favor the fresh beer. In conclusion, we assume that the general consumer is not aware of the beer flavor stability problem but, in general, is able to pick up the difference in flavor and taste. Furthermore, the preference for fresh beer is dependent on the type of beer and also the consumer group (e.g. age, influence of other consumers).

RESEARCH QUESTION 3:

Is the current packaging strategy adequately adapted to protect beer against unfavorable and harmful transport conditions (vibrations, shocks, temperature and light)?

Research question 3 on the beer packaging can be answered by stating that the packaging is adequately adapted to prevent the exposure of harmful transport conditions. Exported beer is transported in ***corrugated boxes that inhibit the exposure to vibrations, shocks and light and isolates the beer from higher ambient temperatures***. In the domestic market, plastic crates are adopted which are less equipped in preventing harmful transport and storage conditions. However, the lead times are shorter and, therefore, adaptations are less recommended.

RESEARCH QUESTION 4a, 4b and 4c:

- **Can the use of refrigerated container transport be economically justified and desirable in order to supply foreign consumers with beer of high quality?**
- **Can co-shipment or horizontal collaboration in transport be implemented for Belgian brewers in an economically feasible way?**
- **Is it economically feasible to offer breweries the possibility to simulate beer transports and to evaluate the chemical and sensorial beer quality?**

The answers to the research questions 4a, b and c are complex and contain many facets. A case-study is built in which the feasibility of refrigerated transports is assessed. From the study, it can be concluded that breweries can invest in the additional cost of refrigerated containers over dry containers since fresh beer will be 35% more consumed over aged beer (result of the drinkability experiment). However, only breweries with a ***profit margin higher than 29%*** (with respect to lager beer) ***and 19%*** (with respect to specialty beer) will be able to perform this investment in a cost feasible fashion. Nevertheless, ***only marginally increasing the sales price 10 eurocent per liter can break-even the cost of refrigerated transports***. The study also indicates that the rest of the supply chain (i.e. storage) should also be performed in a temperature controlled environment in order to reap all benefits and to valorize the investment. Furthermore, breweries may raise prices in foreign countries, although the strategic action is dependent on the market dynamics of the country of import, the exchange rate and the standard of living. Furthermore, additional parameters, e.g. the tolerance of the consumers for aged beer, the brand loyalty, and the additional expected revenues caused by the investments, make the economic feasibility of refrigerated transport and storage a country-specific (location-specific) and brewery-specific decision.

Co-shipment or horizontal collaboration is an innovative and intelligent method in order to reduce transportation cost. However, due to the different actors in the value chain and the ex-works distribution the feasibility of ***implementing the method in the brewery sector is limited***. Nevertheless, theoretical simulations indicate that ***small breweries might benefit*** from working together.

Also the feasibility of offering the breweries transport and storage simulations was assessed. The study indicates that ***simulations can reduce costs of sending back beer crates from foreign countries*** and analyzing the beer in Belgium. However, diverse parameters (e.g. the difficulty of performing a simulation, changes in consumer trends, etc.) determine the demand for the offered simulation. Therefore, the current study can be considered a road map in performing transport and storage simulations and estimating the demand.

Annex

Paper 1:
"The performance of beer packaging: vibration isolation and thermal insulation"
By Paternoster, A., Van Camp, J., Vanlanduit, S., Weeren, A., Springael, J., Braet, J.

Paper 2:
"Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit"
By Paternoster, A., Vanlanduit, S., Springael, J., Braet, J.

Paper 3:
"Vibration and shock analysis of specific events during truck and train transport of food products"
By Paternoster, A., Vanlanduit, S., Springael, J., Braet, J.

Paper 4:
"The influence of the interaction between vibrations and temperature, simulating transport, on the flavor of beer"
By Paternoster, A., Jaskula-Goiris, B., De Causmaecker, B., Vanlanduit, S., Springael, J., Braet, J., De Rouck, G., De Cooman, L.

Paper 5:
"A first model to simulate the Overall Aging Score (OAS) - the impact of temperature and time on the sensorial quality of lager beer"
By Paternoster, A., Jaskula-Goiris, B., Perkisas, T., Springael, J., De Rouck, G., De Cooman, L., Braet, J.

Paper 6:
"The relation between beer flavor instability, the preference & the drinkability of fresh over aged beer"
By Paternoster A, Jaskula-Goiris B, Buyse J, Perkisas T, Springael J, Braet J, De Rouck G, De Cooman L..

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The performance of beer packaging: Vibration damping and thermal insulation

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ABSTRACT

Poor transport conditions can result in an accelerated decay in beer quality. Optimal beer packaging should minimize the impact of temperature changes and vibrations, which occur during (long-haul) transport. In this research, the performance of different beer packagings (BP) regarding vibration damping and thermal insulation was investigated. Three BP's were tested (A: 24 × 33cl cardboard crate/B: 6 × 25cl cardboard crate + plastic foil/C: 24 × 25cl plastic crate).

Cardboard in combination with plastic foil (BP- B) appears to be the best packaging strategy due to the positive thermal insulation properties of cardboard. The plastic foil ties the beer bottles together leaving little space for the bottles to move and therefor reduces the air transfer contributing to better thermal insulation properties. Finally, cardboard in combination with plastic foil exhibits damping characteristics. With a holistic BP strategy, one can control vibrations and temperature biases, which is beneficial for the quality of beer.

1. Introduction

In recent years European beer exports have significantly increased, growing to 78 million hL in 2012 (Brewers of Europe, 2015). Market globalization has induced higher beer production and export volumes. As a result, beer is increasingly more exposed to longer transportation times and variable storage conditions. These transport and storage conditions lead to chemical reactions that cause changes in the chemical composition of beer (Vanderhaegen, Neven, Verachtert, & Derdelinckx, 2006). Chemical reactions, mostly initiated by oxidative reactions, generate chemical compounds that alter the sensorial properties of beer (Jaskula-Goiris, De Causmaecker, De Rouck, De Cooman, & Aerts, 2011; Malfliet et al., 2008). While aging with respect to wines is sometimes perceived as desirable since it enhances certain flavours and aromas, beer ageing results in undesirable flavour changes. As a consequence, the flavour quality and stability of beer change over time. An increase of aldehydes, a decrease in bitterness compounds (iso-α-acids), permanent haze and change of colour are some of the effects related to beer ageing. Ageing characteristics differ between beer types, however, in general, an increase in sweet aromas and a decrease of bitter tastes are mostly observed (Baert, De Clippeleer, Hughes, De Cooman, & Aerts, 2012; Malfliet et al., 2008; Vanderhaegen et al., 2006). Shelf-life problems due to flavour instability have become an important issue to breweries. In order to meet the expectations of the consumer beer should have a constant uniform flavour. When beer has aged and the flavour and aroma diverges from fresh beer, the latter may result in a rejection of the beer brand by the consumer and decreasing sales (Vanderhaegen et al., 2006).

1.1. Beer packaging

A dedicated packaging strategy is essential to maintain a high quality and stable beer flavour. Beer is predominantly stored in kegs, glass bottles, aluminum cans, and PET-bottles (Donoghue, Jackson, Koop, & Heuven, 2012). Since consumer expectations and preferences differ, the type of packaging varies significantly between countries. European countries, for example, use primarily glass bottles, while the consumers in the USA prefer the use of aluminum cans. Marketability and product appeal are important factors when determining the packaging strategy. In recent years, efforts of countries were intensified to reduce the environmental

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impact of the packaging. As a consequence, also the regional legislation regarding packaging taxes and deposit systems influences the packaging decision. The packaging materials used by the European breweries (in 2010) are:

1) Glass bottles (44.2%), of which returnable (24.5%) and non-returnable (19.7%)
2) Metal cans (24.7%)
3) Kegs (20.7%)
4) PET bottles (6.8%), of which returnable (0.7%) and non-returnable (6.1%)
5) Bulk beer tanks (2.8%)
6) Others (0.8%)

Source: (Donoghue, Jackson, Koop, & Heuven, 2012)

The use of the different beer containers can also be segmented by transportation distance. Due to its recycling logistics, kegs are mostly not transported to foreign countries with long transportation distances. Therefore, beer in kegs is predominantly used for domestic consumption. Bottles and metal cans, on the other hand, are used domestically and also exported to foreign countries. Non-returnable glass bottles or 'single-use' bottles are mainly used for export. Returnable or reusable glass bottles are heavier to make them more durable as each bottle can be used multiple times in a recycling process. A secondary packaging is used to transport bottles and metal cans. Glass bottles used for domestic consumption are mostly transported in hard plastic crates to accommodate the recycling logistics. When exporting to other countries, bottles and cans are packaged using cardboard (cardboard crate or holder) and plastic foil (not required when using a cardboard crate) (Donoghue et al., 2012; Euromonitor International, 2014).

1.2. Parameters influencing beer quality

Research of Burns, Heyerick, De Keukeleire, and Forbes (2001) and Jaskula-Goiris et al. (2011) indicated that exposure to light and temperature influence the amount of chemical ageing reactions occurring in beer. Until recently, breweries focused on minimizing the exposure to light and temperature changes in order to maintain the quality of beer when choosing their packaging strategy. However, by limiting the mass and the materials used in the packaging also economic and ecological considerations are incorporated in the packaging decision process. The optimal temperature of beer storage suggested in literature is fixed between 0 and 5 °C. The freshness of beer decreases with higher temperatures, lowering the reaction activation energy and thereby increasing the amount of chemical reactions that take place. Furthermore, every reaction type has a different level of activation energy, which implies that reaction rates are different with increasing temperature. As a result, with increasing temperature different chemical compounds of different reactions are formed in an unequal volume (Jaskula-Goiris et al., 2011). Quality deterioration of beer can also be caused by an exposure to light, a phenomenon referred to as 'lightstruck flavor'. This can be attributed to the absorption of energy, generating an intramolecular energy transfer which causes several chemical reactions (Burns et al., 2001). The vulnerability of iso-α-acids to light can be indicated as the main contributor to photodegradation of beer or its 'lightstruck flavor'. In order to prevent light-induced deterioration, breweries store their beers in light-proof containers (e.g. colored bottles or cans) (Caballero, Blanco, & Porras, 2012).

During transport, beer is also exposed to vibrations and shocks. In rare experiments (Janssen et al., 2014) it was found that vibrations could have an influence on the quality of a food product. Moreover, the authors signaled the emergence of turbidity in beer caused by vibrations. However, limited research has been done on the impact of vibrations on the chemical and sensorial quality of beer. Oxidative reactions initiate a range of different chemical reactions that result in beer ageing. As a consequence, breweries tend to avoid a high level of oxygen when producing and bottling beer. In recent years, the oxygen in beer can be reduced to 0,1 mg/l with modern filling techniques (Caballero et al., 2012). When beer is exposed to vibrations, the oxygen in the upper part of the bottle under the crown will be mixed with the beer. This will enable the beer to have more oxidative reactions and thereby accelerate the beer ageing process. Furthermore, vibrations could increase the collision of molecules, which will lower the reaction activation energy. As a consequence, the generation of ageing compounds will be facilitated. Hence, one can conclude that vibrations can be harmful to the beer quality, and should therefore be avoided.

Beer is commonly transported using trucks, trains, and ships. Depending on the transport carrier, beer is exposed to different vibrations and shocks. Vibrations are periodic in nature while a shock is a single-event or transient phenomenon (Harris & Piersol, 2002). Vibrations generated by a truck, for example, are influenced by the road conditions (roughness), the driving performance (traveling speed) and the specifications of the truck (load, suspension, the number of axles, etc.) (Garcia-Romeu-Martinez, Singh, & Cloquell-Ballester, 2008; Jarimopas, Singh, & Saengnil, 2005; Lu, Ishikawa, Kitazawa, & Satake, 2010). Furthermore, the position inside a container has an influence on the amplitude of the vibrations (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003; Zhou, Su, Yan, & Li, 2007). The vibration spectrum of trucks, trains and ships are characterized in the academic literature (mostly an averaged spectrum to characterize multiple transport vehicles) (Maheras, Lahti, & Ross, 2013). Most of the vibrations of these transport vehicles occur in the frequency range below 100 Hz with accelerations smaller than 10 m/s^2. Based on these findings, boundaries in frequency and acceleration were defined in the experimental design presented in Section 2.1.

1.3. Paper structure and flow

The aim of the current work is twofold: (1) to identify the vibration damping performance of three beer packaging strategies that are commonly used in industry, and (2) to look into the thermal conductivity of the beer packaging. During transport, beer is exposed to vibrations with amplified or attenuated magnitude due the vibration transmissibility performance of the beer packaging. Different packaging strategies have different transmissibility curves and vibration damping performance, making it able to compare and benchmark them. The second objective was to look into the thermal conductivity or thermal insulation of the beer packaging. Increasingly breweries export beer in cooled containers to counteract the influence of temperature on the beer flavor. However, thereafter in next steps in the supply chain, the temperature may rise and can be as high as 50 °C (Weiskircher, 2008). With an experimental set-up, the insulating performance of the beer packaging was tested. To summarize, the objective is to identify the performance of three commonly used beer packaging strategies regarding thermal insulation and vibration damping.

The research performed in current paper can be generalized for other food and beverage products. Diverse academic papers focus on the impact of shocks on the mechanical damage of fresh products (apples, kiwis, tangerines, etc.) (Jarimopas et al., 2005; Tabatabaekoloor, Hashemi, & Taghizade, 2013; Van Zeebroeck et al., 2008). Other research papers (Berardinelli et al., 2003; La Scalia et al., 2015) investigate the influence of vibrations on the microbial growth and change of chemical components of highly perishable products (strawberries, eggs etc.). Besides, the effects of temperature during transport and storage on food and beverage quality (wine, tomatoes, etc.) has been extensively investigated

(Butzke, Vogt, & Chacón-Rodríguez, 2012; Tano, Oulé, Doyon, Lencki, & Arul, 2007). Similar to the study of Eissa, Gamaa, Gomaa, and Azam (2012) this study also evaluates the effect of vibrations on products and their packaging materials, without exploring the modal parameters but rather the transmissibility of vibrations (Eissa et al., 2012). Furthermore, this study focuses on the packaging of beer and adds further insights to literature by also translating vibration and thermal performance into an alternative and recommended packaging strategy.

The remainder of the paper is structured as follows: In Section 2 'Methodology and experimental set-up' the context and definitions of the study and the design of the experiments are described. In Section 3 the results of the experiments are presented. Moreover, the focus is on how to interpret the research findings and translate them into an improved beer packaging strategy. In Section 4 the conclusions of the paper are presented, highlighting key results and limitations of the study.

2. Methodology and experimental – setup

2.1. Vibrations

From a theoretical point of view, an estimate of the resonant frequencies of the beer packaging can be calculated using the Rayleigh-Ritz method (Harris & Piersol, 2002). However, this estimation is complex due to the fact that information is required about the properties of the materials (stiffness coefficients), the geometrical shape of the bottles and the impact of beer bottles interacting with each other. However, an alternative approach in which practical insights can be formulated based on actual data, is to execute an experiment and to calculate the transmissibility function. The acceleration transmissibility function is defined as the function that can be calculated by dividing the Fourier transform of the measured accelerations of the highest accelerometer by the Fourier transform of the accelerations measured on the lowest accelerometer.

For the purpose of this experiment, an electro-dynamic shaker (Brüel & Kjær, type 4802T) was used to generate vibrations. Literature states that the lateral and longitudinal vibration levels are extremely low compared to the vertical vibration levels during truck transport (Garcia-Romeu-Martinez et al., 2008). Therefore, in this experiment vibrations were applied in a single dimension, i.e. vertical relative to the surface area. The vibration table generated a sine sweep rate of vibrations starting at 2 Hz and ending at 100 Hz with an acceleration level of approximately 1 G (duration 200 s). The objective was to artificially replicate vibrations at frequencies and acceleration levels that appear during truck transport.

A first accelerometer was mounted on the base plate, measuring acceleration in the vertical direction. In order to not limit the movement of the bottle and influence the interaction between the bottle and the packaging, a second accelerometer was mounted on the beer bottleneck (also in the vertical direction). Both accelerometers had a sample rate of 100k samples/s. The 'Nyquist frequency' is required to be at least higher than 100 Hz to counteract the aliasing effect (Harris & Piersol, 2002). With the acceleration data of both accelerometers a transmissibility function was calculated.

Three different types of beer packagings A, B, and C were tested:

A: 24 bottles of 33cl in cardboard crate – Longneck (green) – mass bottle: 553 g – mass packaging: 14.76 kg [Fig. 1: Picture 1]

B: 4 packages with 6 bottles of 25cl in cardboard crate with plastic foil per 6 bottles – Vichy (brown) – mass bottle: 494 g – mass: 11.86 kg [Fig. 1: Picture 2]

C: 24 bottles of 25cl hard plastic crate – Vichy (brown) – mass bottle: 494 g – mass: 16.96 kg [Fig. 1: Picture 3]

Packagings A and B are frequently used in international transports and packaging C is mainly used in domestic transports. Due to the scope of the project and the stakeholders involved, the three beer packages, including bottle types, were selected for being most commonly used by Belgian breweries. Although packagings A, B and C are a packaging standard in industry, breweries might add minor changes to their packaging by altering the basic components (cardboard, plastic foil and hard plastic). The findings in this research are a starting point for future research enabling the benchmarking of alternative packaging strategies.

First, a vibration test was performed with no extra load on the bottom plate (without a beer packaging). Afterwards, vibration tests were performed on the three packagings that were strapped on the shaker plate. The amplitude of the shaker was adapted as a function of the mass of the packaged beer to make sure that an acceleration level of approximately 10 m/s^2 was imposed on the base plate.

The data generated by the two transducers have been analyzed using Matlab R2015a. After plotting the two time series a Fourier transform (bandwidth/frequency resolution 1 Hz) was performed. Finally, an estimation of the transmissibility function from the shaker plate to the beer bottleneck was calculated. A low bandpass filter was applied with a moving average filter with a filter length of 10 samples to attenuate the 50 Hz noise component resulting from the shaker.

2.2. Temperature

Brewers want to provide customers with beer of the best possible quality. However, when refrigerated containers reach storage after being transported, the temperature can promptly rise. For the purpose of this research, the container temperature of a ship transport from Antwerp (Belgium) to Tokio (Japan) was monitored (Fig. 2). Fig. 2 shows that a constant low temperature (3 °C) was measured during transport. After transportation a different temperature regime is present, since temperature rose sharply after arrival in its storage facility (27 °C).

Fig. 1. Experimental set-up [vibration damping – packaging performance].

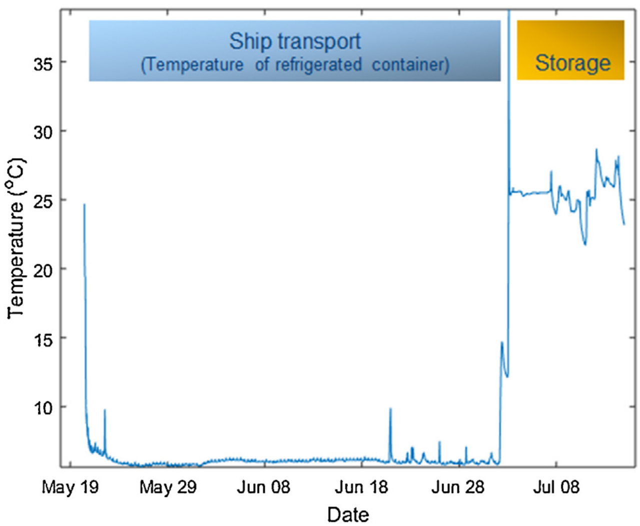

Fig. 2. Container temperature of a ship transport from Belgium to Japan during summer.

In literature, evidence was reported on containers heating up to temperatures up to 50 °C under direct sunlight (Weiskircher, 2008). These findings were used as a starting point when designing and benchmarking the temperature experiment discussed in this section. Since high temperature is harmful to the beer quality, the beer packaging should protect the beer against a rising temperature. In other words, beer packaging with low thermal conductivity or high thermal insulation properties are preferred.

In order to simulate the heating up of a container, an experiment was performed. In this experimental set-up (Fig. 3), the same beer packagings A, B and C as in the vibration experiment (Section 2.1) were tested. First, the beer packagings were stored in a cold storage room with a temperature of 5 °C (in still air). Once the beer had reached the ambient temperature of the environment, the beer packagings were transferred to heating chambers with a temperature of 30 °C and 40 °C (in still air). The objective of the study is to determine the thermal properties of different types of beer packaging in order to protect beer from a higher ambient temperature of 30 °C (respectively 40 °C). The temperature was measured in the fluid using a logger of the brand 'PCsensor', doing a measurement every second. In this experiment beer was substituted by water, because with rising temperature, beer would start foaming. This study focusses on the thermal insulation properties of beer packaging and since beer consists of 90% water (Donoghue et al., 2012), this substitution is acceptable. A small incision in the packaging was made to put the cable connection with the computer, and was afterwards tightly closed with plastic. An exponential function best represented the raw data and, therefore, was fitted to the raw signals.

3. Results & discussion

3.1. Vibrations

The amplitude of the acceleration transmissibility function of packagings A and B is displayed in respectively Figs. 4 and 5. The plot represents the frequency (Hz) and the acceleration transmissibility factor (the division of the Fourier transform of the measured accelerations on the beer bottle by the Fourier transform of the accelerations measured on the shaker plate). When the magnitude of the curve is above one (red line), vibrations of a specific frequency are amplified. A magnitude between zero and one indicates that the vibrations of a specific frequency are attenuated by the packaging. The packaging of the beer will tend to behave as a vibration damper.

The transmissibility functions of beer packaging A and B presented in Figs. 4 and 5 show a completely different transmission behavior. Packaging A transmits vibrations from 2 to 70 Hz while at higher frequencies vibrations are amplified by the beer packaging. From 70 to 100 Hz the increase is exponential up to an acceleration transmissibility factor of four. This particular shape of the curve was similar to the research findings on corrugated cardboard in the academic literature (Huang, 2013). This suggests that with respect to the transmissibility the secondary beer packaging (cardboard crate) of packaging A is of higher significance than other parameters e.g. the particular bottle shape. As a consequence, packaging A underperforms compared to packaging B. Packaging B tends to be a good vibration damper for vibrations higher than 60 Hz. High-frequency vibrations will decrease in magnitude by

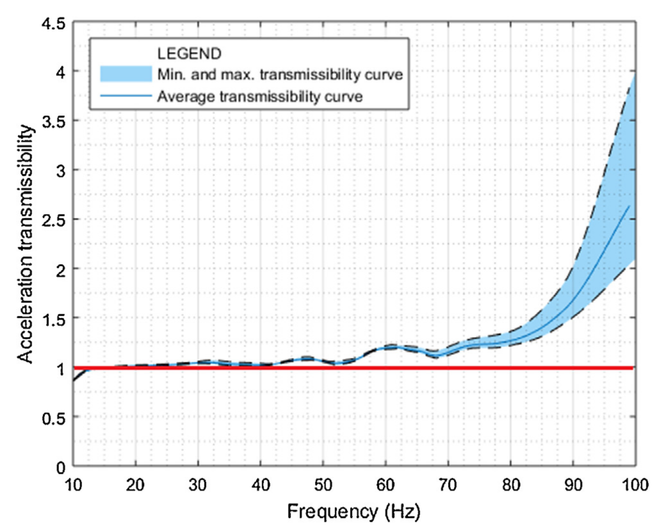

Fig. 4. Transmissibility packaging A.
(Sweep rate from 2 to 100 Hz, acceleration of 10 m/s^2 over 200 s).

Fig. 3. Experimental set-up [thermal insulation – packaging performance].

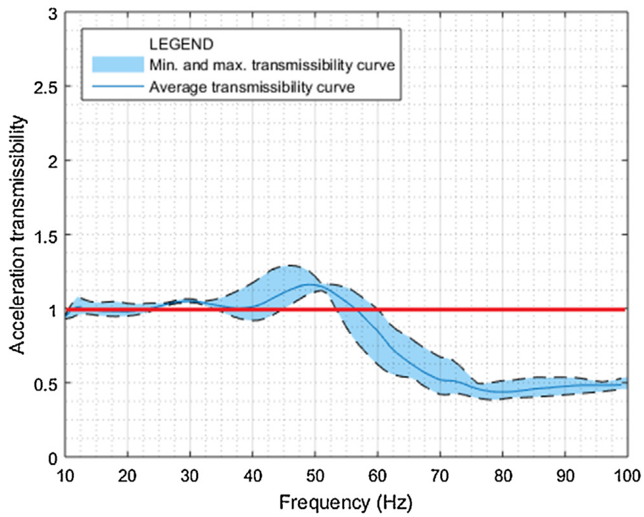

Fig. 5. Transmissibility packaging B.
(Sweep rate from 2 to 100 Hz, acceleration of 10 m/s^2 over 200 s).

50% caused by the packaging material. A possible explanation could be that plastic foil is a decent vibration damper with performance characteristics similar to rubber (Harris & Piersol, 2002).

The transmissibility function of packaging C (Fig. 6) has a magnitude close to one for the whole spectrum. However, the graph should be interpreted with caution because its particular shape is influenced by a 'feedback effect'. The shaker imposes vibrations on the shaker plate (input accelerometer) and subsequently the beer packaging. Since the beer bottles in packaging C, a standard hard plastic crate used for domestic transports, have free space to move within the packaging, the bottles also generate vibrations. These vibrations are measured again by the accelerometer on the shaker plate. The impact of a beer bottle jumping up and down in the crate generates abundant noise in the frequency spectrum. The effect is similar to imposing a shock. When analyzing the time domain plot (Fig. 7), the amplitude level of packaging C is noteworthy. In this particular case, a sweep rate from 2 to 100 Hz is exposed with acceleration level of 20 m/s^2. At a frequency level of approximately 7–13 Hz beer bottles start 'jumping'. When imposing the same sweep rate on packaging

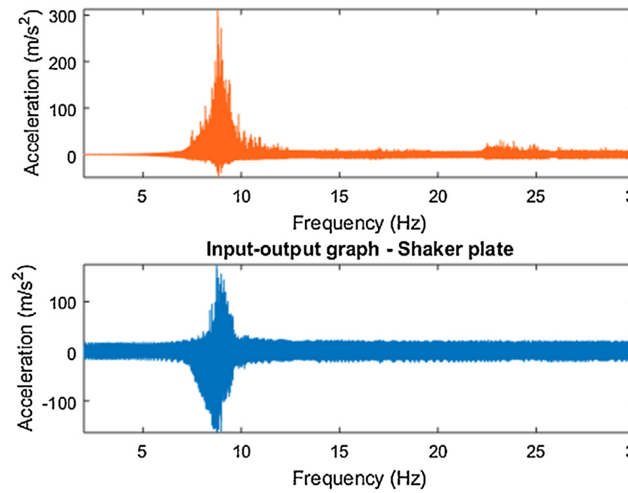

Fig. 7. Time domain plot packaging C.
(Sweep rate from 2 to 100 Hz, acceleration of 20 m/s^2 over 200 s).
(X-axis represents time or number of samples but is related to the frequency in the sweep).

A (Fig. 8), a similar image can be found. Bottles start bumping into each other at frequencies between approximately 7–13 Hz and 19–23 Hz. When imposing sweeps with lower acceleration the phenomenon of bottles bumping into each other cannot be found for packaging A. From this analysis we can conclude that in order to limit the vibrations, the bottles in packaging A should be foreseen with panels separating the bottles from each other. In packaging B, the bottles are packed close to each other what makes it more difficult for the bottles to move individually.

The stiffness and damping coefficient, in the literature defined as the effect of a spring damper system, characterize the vibration damping properties of the beer packaging. However, in reality, multiple packages are stacked upon each other, making the system more complex. Moreover, the mass will be different, there is an effect of multiple layers of products and their packaging materials, the way of stacking will have influence on the vibration characteristics etc. Furthermore, the highest stacked packages will have a larger moment increasing the amplitude of vibrations and shocks, in the case of truck and train transport. Academic literature reports the acceleration of vertical vibrations of the highest stacked boxes of transported peaches to be three to four

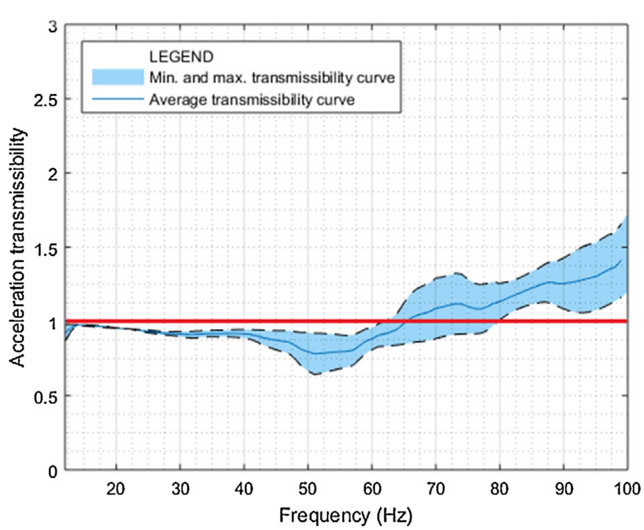

Fig. 6. Transmissibility packaging C.
(Sweep rate from 2 to 100 Hz, acceleration of 20 m/s2 over 200 s).

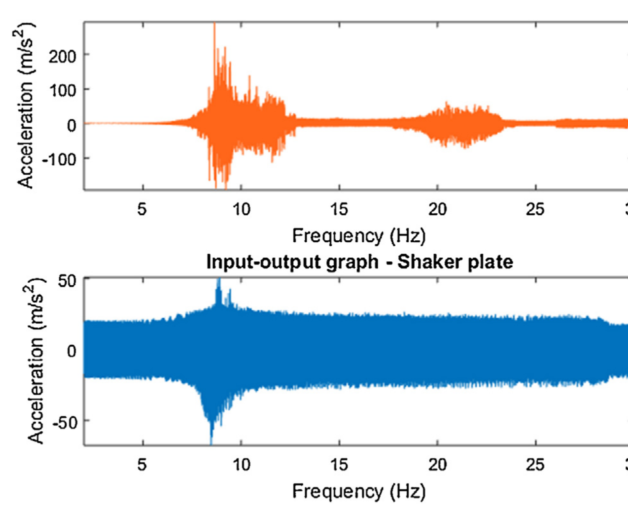

Fig. 8. Time domain plot packaging A.
(Sweep rate from 2 to 100 Hz, acceleration of 20 m/s^2 over 200 s).

times higher than those of the lower stacked boxes (O'Brien, Gentry, & Gibson, 1965).

3.2. Temperature

In practice, beer packages are stacked close to each other, slowing down the beer heating process. In a similar manner, cold beer bottles closely packed together prevent each other from heating up. Furthermore, the packaging material can act as a thermal insulator. The use of plastic can control the airflow, leaving cold air inside and warm air outside. Corrugated cardboard can be characterized as a good thermal insulator, caused by the air in the pores of the material.

In Figs. 9 and 10, the thermal insulation performance of packagings A, B and C can be found. Packaging A has the best insulation properties, however, the curves of beer packagings A and B behave in a similar manner. In packaging A, the cardboard crate, no air movement is possible because the opening on top is covered with plastic tape. Packaging B, the cardboard crate covered in plastic foil, has little air transfer from the sides of the beer packaging. In beer packaging C, the hard plastic crate, bottles are open to the environment hence heating up more rapidly. The temperature of beer bottles in packaging C reaches the ambient temperature after 5 h, whereas the bottles of packagings A and B only reach the same level after 24 h.

4. Conclusions

The packaging of beer has an influence on the exposure of beer to temperature differences and vibrations. All elements need to be taken into account to regulate the shelf life of beer regarding flavor stability. Within the current work different beer packaging types A, B and C are benchmarked with regard to vibrations and temperature.

Packaging B tends to perform best in damping vibrations. The beer packaging attenuates vibrations higher than 60 Hz. Beer packaging A resonates at frequencies higher than 80 Hz and therefore performs weakly. Packaging C performs worst regarding damping of vibrations: beer bottles have free space to move within the beer packaging, which results in an (uncontrollable) amplification of the vibrations. Furthermore, the time domain plots (Figs. 7 and 8) indicate that when bottles are free to move critical resonance frequency areas can be pinpointed from 7 to 13 Hz, and

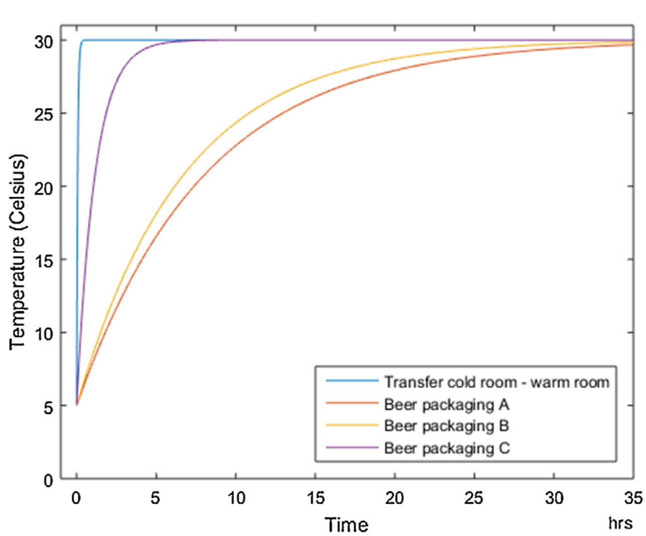

Fig. 9. Results beer temperature (30 °C).
(Experiment: Thermal insulation of the beer packaging; beer temperature reaching the ambient temperature of 30 °C/40 °C).

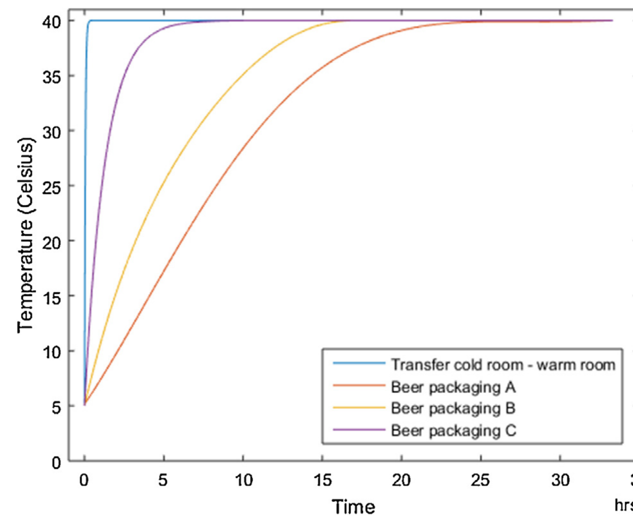

Fig. 10. Results beer temperature (40 °C).

from 19 to 23 Hz. Packaging C, and to a lesser extent packaging A, are sensitive for vibrations within the latter mentioned frequency ranges (and at a considerably high acceleration).

Regarding thermal insulation, beer packagings A and B perform relatively similar. Furthermore, beers from packagings A and B have significantly better thermal insulation properties than beers of packaging C. The use of cardboard, which is an adequate insulator material, combined with plastic tape or foil to reduce the air movement, is the best packaging strategy (of the three used in the study) in terms of thermal insulation.

To conclude, the use of cardboard in combination with plastic foil (packaging B) is the best beer packaging strategy regarding vibration damping and thermal insulation. Cardboard has positive thermal insulation properties. The plastic foil ties the beer bottles together into one solid mass leaving little space for the bottles to move. At the same time, the foil reduces the air movement contributing to better thermal insulation properties. Finally, the use of cardboard in combination with plastic foil shows interesting damping characteristics.

Little is known in literature about the impact of transport vibrations and the interaction with temperature on the chemical and sensorial quality of beer. In future research, this topic should be further investigated. A potential area of future research is to quantify the quality deterioration of beer caused by vibrations. Furthermore building on the latter, a better understanding is essential to detect whether high or low frequency vibrations are most harmful for the beer quality. If the vibrations amplified by the beer packaging (e.g. frequencies above 70 Hz for packaging A) correspond to the frequency ranges where the quality of beer significantly declines, an alternative packing strategy needs to be recommended. Alternative or additional packaging materials can be used to control vibrations.

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Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit

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ABSTRACT

Temperature, vibrations and shocks during transport and storage are believed responsible for beer flavour instability. The aim of current study is twofold: (1) to quantify the vibrations and shocks on packaged bottled beer when travelling on the Belgian road network, (2) quantify the impact of the vibrations and shocks in a preliminary experiment.

The spectral density plots illustrate the importance of low-frequency vibrations and the similarities/discrepancies with international standards (ASTM-D4728 and ISO-13355). With increasing stack height, the amplitude of vibrations (5–25 Hz) intensifies in both corrugated boxes and plastic crates. Vibrations > 25 Hz are amplified up to 9 times the original signal depending on the stack height of plastic crates. Corrugated boxes attenuate vibrations > 25 Hz. Corrugated boxes absorb shocks and are preferred over plastic crates with respect to shocks and vibrations. In an exploratory experiment, vibrations and shocks induce the uptake of oxygen and the change of aldehydes (dependency initial oxygen content).

1. Introduction

Postharvest losses of fruit and vegetables, defined as the losses occurring during transport, handling and storage before the food product reaches the consumer, can be as high as 25% of the initial harvested or produced products (Parfitt, Barthel, & Macnaughton, 2010; Van Zeebroeck et al., 2007; Wasala, Dharmasena, Dissanayake, & Thilakarathne, 2015). In the literature, extensive research was done on fruit losses due to vibrations during truck transport (e.g. losses of apples (Van Zeebroeck et al., 2007), pears (Zhou, Su, Yan, & Li, 2007), tangerines (Jarimopas, Singh, & Saengnil, 2005), etc.). Vibrations and shocks, caused by road unevenness and potholes, can directly induce mechanical damage to the products (Lu, Ishikawa, Shiina, & Satake, 2008). In recent studies, researchers also highlighted that a transport load can deteriorate in quality, i.e. changes in the chemical composition of the product, due to vibrations and shocks. An example of the latter phenomenon can be found in the transport of strawberries (Fischer, Craig, & Ashby, 1990; La Scalia et al., 2015). The decline in the sensorial quality of beer during storage was illustrated by several authors (Vanderhaegen, Neven, Verachtert, & Derdelinckx, 2006; Vanderhaegen, Delvaux, Daenen, Verachtert, & Delvaux, 2007). In this paper, the focus is on the identification of transport vibrations and shocks occurring during beer transports, since literature indicated that a decrease in beer quality might also occur during transport (Janssen et al., 2014). However, also more general findings and recommendations regarding packaging materials can be deduced from the findings of this research and extrapolated for food, beverage and electronic products (which is also susceptible to vibration damage). In this regard, under-packaging or the lack of adequate and sufficient packaging to protect a product from damaging, but also over-packaging products should be avoided. Recent estimates indicate that the total cost of over-packaging for all products, in Europe alone, compasses 130 billion per year (Rouillard & Richmond, 2007).

Since beer is increasingly exported, due to market globalization, more often the beverage is subject to longer transportation times and variable storage conditions that lead to an unfavorable decrease in beer flavor (Vanderhaegen et al., 2007). During transport, bottled beer is being exposed to changing temperatures, vibrations and shocks, which may influence the flavor stability. Janssen et al. (2014) signaled that vibrations during transport influence the development of turbidity in beer. However, the exact influence of vibrations and shocks on the beer quality is a research gap that needs to be explored. A first step to perform this research is to identify the (level of) vibrations that occur during beer transports, and this will be the topic of this paper.

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Table 1
Overview transports − vibrations measurements.

Transport (Recording time)	Type Of Transport	Accelerometers	Experimental set-up
* Beer Transport 1 (Rec.time: 9 h 44 min)	Truck transport (trailer with extra trailer with air-ride suspension) [Specifications Appendix A (1)]	Acc 1: on top of a wooden pallet	Plastic crates stacked on top of each other
* Beer Transport 2 (Rec.time: 2 h 28 min)	Truck transport (trailer with air-ride suspension) [Specifications Appendix A (1)]	Acc 2: bottle neck of a bottle in lowest plastic crate/cardboard crate	Plastic crates and cardboard boxes stacked on top of each other
* Beer Transport 3 (Rec.time: 1 h 50 min)	Truck transport (trailer with air-ride suspension) [Specifications Appendix A (1)]	Acc 3: bottle neck of a bottle in highest plastic crate/cardboard crate	Plastic crates and cardboard boxes stacked on top of each other
* Beer Transport 4 (Rec.time: 3 h 26 min)	Truck transport (trailer with leaf spring suspension) [Specifications Appendix A (1)]	[Specifications Appendix A (2)]	Cardboard boxes stacked on top of each other

Consecutively, with improving the quality of beer, the aim is to contribute to a longer shelf life of the beverage as well as an increased customer experience. Similarly to other food products and beverages, it is desirable to extend the shelf life. On the one hand, direct losses due to mechanical damage can be reduced. On the other hand, the quality of the products will directly induce a longer period in which the product can be consumed or, in other words, a longer shelf life of the product.

In literature, vibration levels during truck transport have been studied worldwide: Japan (Lu et al., 2008), Thailand (Jarimopas et al., 2005), Spain (Garcia-Romeu-Martinez, Singh & Cloquell-Ballester, 2008), and multiple other countries (Chonhenchob, Singh, Singh, Stallings, & Grewal, 2012; Rissi, Singh, Burgess, & Singh, 2008; Singh, Singh, & Joneson, 2006; Singh, Jarimopas, & Saengnil, 2006). These publications present a diverse set of parameters that could indicate the origin or the amplifying effects that influence the generated vibrations. Road roughness and speed of driving during transportation are important vibration parameters (Jarimopas et al., 2005; Lu et al., 2008). Jarimopas et al. (2005), for instance, illustrated vibration performance over a diverse set of pavement surfaces. The truck type, payload, and suspension are also relevant parameters. Garcia-Romeu-Martinez et al. (2008) indicated that root mean square (RMS) and peak vibration can be reduced by 50% by using a truck with an air-ride suspension over a leaf-spring suspension. Other relevant parameters that influence vibration levels are platform location (Zhou et al., 2007), vibration direction (Singh, Antle, & Burgess, 1992) and tires (Jones, Holt, & Schoorl, 1991).

The aim of the current work was to identify the level of vibrations and shocks bottled beer is subjected to when transporting by truck, and using different packaging modalities, and, additionally, to assess the impact of vibrations and shocks on the beer flavor quality (case-study). There are three transport modes that are regularly used to transport beer: trucks, trains, and ships. The scope of this paper was limited to vibration analysis of truck transport (leaf spring and air-ride suspension) in Belgium. Research on truck vibrations is extensive and has expanded considerably in last years. However, the relation between vibrations and shocks during transport with product packaging is often missing or underdeveloped in literature (Eissa, Gamaa, Gomaa, & Azam, 2012). This emphasizes the unique contribution of this paper. The current research was also limited to bottled beer stacked on top of each other in cardboard boxes and plastic crates, the two most commonly used packaging modalities for beer. Plastic crates are frequently used for domestic transportation, due to the recycling logistics of the crates, while cardboard boxes are especially used for transports to foreign countries. Furthermore, the transmissibility of the pallet vibrations to the highest stacked crates is identified and, therefore, the insights of the interaction between vibrations and bottled beer could be extended to other geographical regions by changing the (input) vibration spectra or the amplitude of the vibrations. Bottled beverages that suffer quality deterioration (for instance wine (Chung, Son, Park, Kim, & Lim, 2008)), or other food products (for instance strawberries (Fischer et al., 1990)) could use these findings to further develop their research study.

2. Materials and methods

2.1. Experimental design

For the purpose of this research, vibration measurements were performed on four (beer) transports, three transports with an air-ride suspension truck and one truck transport with a leaf spring suspension. All truck transports were executed over the Belgian road infrastructure. The road typology in Belgium can be categorized as national highways, highways and local or rural roads. Highways are major roads that connect districts and large cities and make able to transport freight over medium and long distances. In current study, the Belgian national highways that were studied are predominantly paved with asphalt. The highways are paved both by asphalt and by concrete, while rural roads are predominantly paved by asphalt but exceptionally by cobblestones. Since attention was given on the validity and significance, the presented results are findings from traveling by truck over all different roads and measured on four different transports.

Table 1 presents an overview of the transports that were attended by the author of this study. The number of transports made able to benchmark and validate the results. As an experimental set-up, plastic crates, as well as cardboard boxes, were stacked on top of each other (5–7 boxes/crates on top of each other). Three accelerometers were used: one accelerometer was mounted on the floor of the container (on top of the wooden pallet), and two accelerometers on the bottleneck of two beer bottles (Fig. 1a) that were located in the stacked crates or boxes (Fig. 1b and c). In order to not influence the interaction between the bottle and the packaging, the accelerometers were mounted on the beer bottleneck. Since food products are transported on wooden pallets, vibrations were measured on the pallet itself and not on the container floor. The aim was to discover the transmissibility of the pallet vibrations to the vibrations beer bottles are exposed to in their beer packaging. During all transports, a camera (GoPro Hero 4) was mounted on the seat of the truck driver to visually capture the road characteristics and the driving speed. Vibrations measurements were performed during transports with full, empty and varying cargo load.

In order to quantify the vibration response during beer transports, vibration measurements were performed with the following experimental set-up. A laptop was connected to a data acquisition board (National Instruments USB-6361), which was connected to different accelerometers. The accelerometers (Sparkfun ADXL 337), mounted on the pallet and on the beer bottlenecks, measured acceleration in three directions. Most research articles on vibrations during transport analyze vibrations up to 100 Hz (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003; Jarimopas et al., 2005), in this study the Nyquist-frequency was fixed sufficiently higher to also evaluate the influence of high-frequency vibrations. The accelerometers, which have a bandwidth of 1600 Hz (X- and Y-axis/noise density: 175 μg/√Hz rms) and 550 Hz (Z-axis/noise density: 300 μg/√Hz rms), had a sample rate of 1e5 samples per second. The total set-up was powered by an external battery and transformed to the necessary voltage using a transformer (Voltcraft SWD-300/12).

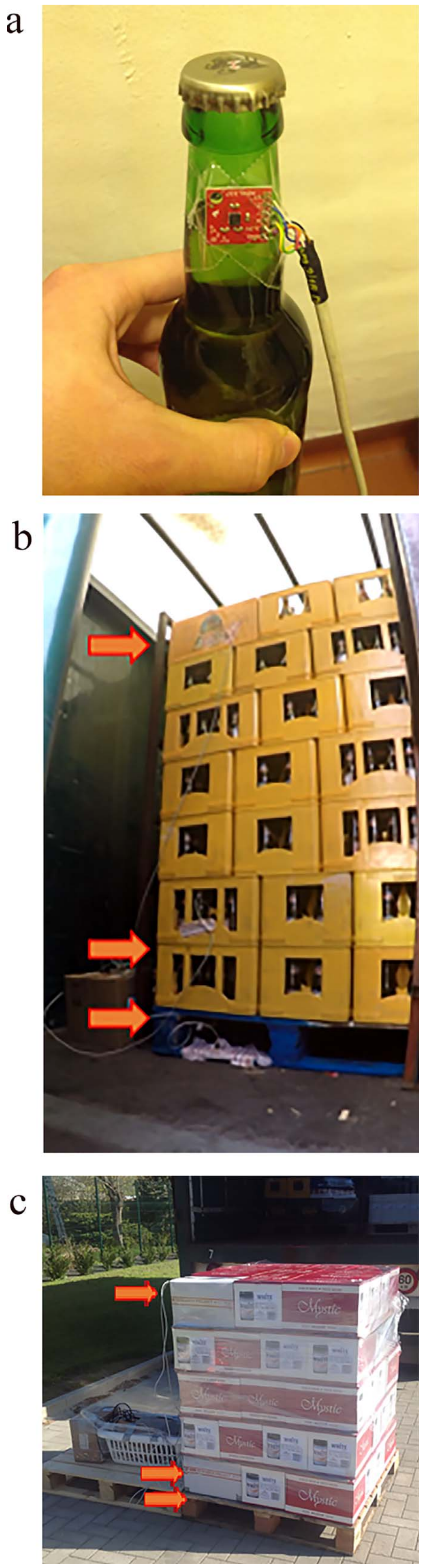

Fig. 1. a) Accelerometer mounted on the beer bottleneck. b) Plastic crates stacked on top of each other. c) Corrugated boxes stacked on top of each other.

2.2. Data analysis

The software Matlab R2015a was used to control the data acquisition board and to save the vibration data. The same software was employed to analyze the vibration signals. The cumulative distribution function (CDF) of the RMS and kurtosis values for different vibration segments over five second intervals were calculated. Kurtosis is a way to indicate the shape or the 'tailedness' of the probability distribution of the measured vibrations compared to the standard normal distribution (Böröcz & Singh, 2016). A kurtosis value of zero can be attributed to the standard normal distribution, while a heavy-tailed distribution is indicated by a positive kurtosis and light-tailed distribution by a negative kurtosis. Furthermore, a Fourier transform was performed and an estimation of the transmissibility function from pallet to the beer bottle neck was calculated. The acceleration transmissibility function is a function that presents the vibration attenuation and vibration amplification between two measured vibration signals in the frequency domain (Harris & Piersol, 2002). The function (g^2/g^2) is calculated by dividing the Fourier transform of the measured accelerations of the first accelerometer by the Fourier transform of the accelerations measured by the second accelerometer. The results of Section 3 indicate average power spectral density (PSD) plots, which are linear averages for PSDs for selected events (bandwidth/frequency resolution 0.2 Hz). There was no filter applied to the signals. The latter technique is frequently used in literature (Garcia-Romeu-Martinez et al., 2008).

Finally, a shock analysis was performed to evaluate both the number and the type of shocks packaged beer is subjected to. In current research, the measured vibration signals (in time-domain) were split into intervals of 20 s. Based on the measured vibrations and shocks in all intervals, a histogram was calculated to depict the amount of vibration samples that were measured above 5 m/s^2 (peak). A histogram of the acceleration samples above 5 m/s^2 was calculated for the signals measured on the pallet floor, as well as the signals measured on the stacked crates and boxes using exactly the same intervals. As a consequence, the different histograms can be compared and an indication of the number of shocks bottled beer is exposed to can be identified. The histograms reveal the average counts of vibrations samples (> 5 m/s^2) measured during transport with confidence boundaries (standard deviation up/down). Furthermore, individual shocks measured on the pallet, bottles in the highest corrugated box and plastic crate (20 shocks per setup) were analyzed in order to identify the type of shocks beer is exposed to. Since the measured shocks are best represented by a decaying sinusoid, the damping ratio (β) was identified. The damping ratio is a function of the logarithmic decrement (λ), the frequency of the damped oscillation (ω_d) and the damped period (T_d) (Thomson, 1993). The damped period is defined by the time between the two highest consecutive peaks. The logarithmic decrement can be calculated by the natural logarithm of the division of the acceleration amplitude of the highest peak ($x(T_1)$) divided by the acceleration amplitude of the second highest peak ($x(T_1 + T_d)$. Furthermore, the natural frequency of the damped oscillation (ω_n) can be computed (Thomson, 1993).

$$\beta = -\frac{\lambda}{\sqrt{\lambda^2 + T_d^2\omega_d^2}} = -\frac{\lambda}{\sqrt{\lambda^2 + (2\pi)^2}}$$

with

$$\begin{cases} \lambda = \frac{1}{d}\ln\left(\frac{x(T_1)}{x(T_1 + T_d)}\right) & \text{with 'd '= integer number of successive peaks} \\ \omega_d = \frac{2\pi}{T_d} & \text{in } \frac{rad}{s} \\ T_d = (T_2 - T_1) & \text{in sec.} \\ \omega_n = \frac{\omega_d}{\sqrt{(1-\beta^2)}} & \text{in } \frac{rad}{s} \end{cases}$$

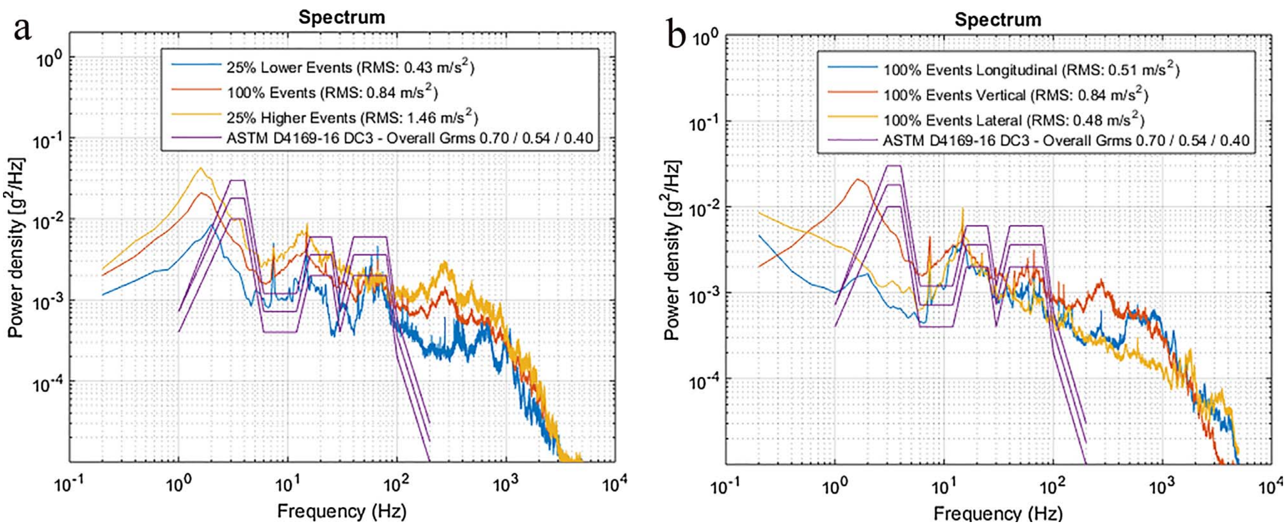

Fig. 2. a) PSD (air-ride) truck transport (Vertical pallet measurements). b) PSD (air-ride) truck transport (Longitudinal, vertical and lateral pallet measurements).

3. Results & discussion

3.1. Pallet vibrations

Both vibrations and shocks of high amplitude are usually present during truck transport. Vibrations during transport mainly come from the engine, and the interplay between the road (road roughness), the tires and type of suspension. In literature, vibrations of low-frequency content are seen as considerably more important than high-frequency vibrations. In a typical PSD plot frequencies between 1 and 5 Hz are attributed to the suspension, 15–20 Hz the tires and 40–55 Hz the structure floor (Singh, Jarimopas et al., 2006; Singh, Singh et al., 2006). The spectral density plots of the truck with air-ride suspension are displayed in Fig. 2a and b. The spectral density plots indicate the importance of low-frequency vibrations. Furthermore, the plots also reveal the higher significance of vertical vibrations in comparison with longitudinal and lateral vibrations.

The PSD results were benchmarked with the in 2016 adapted international standards, i.e. ASTM D4169, and were found to be slightly different. However, similar findings, as the PSD (and RMS) results presented in this research, were found by other authors (e.g. Garcia-Romeu-Martinez et al. (2008), Singh, Singh et al. (2006), Singh, Jarimopas et al. (2006), Soleimani and Ahmadi (2014) and Rissi et al. (2008)). In the research of Soleimani and Ahmadi (2014) the accelerometers were mounted on the lowest crate/pallet (and a stacking of crates) to identify the influence of vibrations on food packages. Therefore, the latter study was used to validate the findings in this experimental study. In the studies of Chonhenchob et al. (2009), Garcia-Romeu-Martinez et al. (2008) and Singh, Singh et al. (2006), Singh, Jarimopas et al. (2006) the vibrations between 0.1 and 10 Hz have a similar amplitude, while the vibrations between 10 and 100 Hz were observed to be smaller. The latter authors, as well as Lu, Ishikawa, Kitazawa, and Satake (2010) have mounted their data recorders on the container floor. The amplitude of the vibrations measured by Lu et al. (2010), on the contrary, is considerably smaller. The findings of Rissi et al. (2008) are similar, although the results should be compared with caution since in this study the data recorders were mounted on the undercarriage of the truck. To conclude, while current experimental study reports highly comparable PSD levels between 0.1 and 10 Hz, PSD levels between 10 and 100 Hz are higher than literature findings. However, PSD levels of vibrations on Belgian roads measured in current study are more comparable to ASTM D4169-16 DC3 than the results reported in literature. As indicated in the diverse plots and by diverse authors, the results suggest the need for further adaptations to the existing international standards (ASTM D4169) in order to develop improved recommended test methods, such as ASTM D4728and ISO 13355.

3.2. Vibrations and beer packaging

Fig. 3a–d present the cumulative distribution function of the RMS and the kurtosis values of the measured acceleration signals (in time-domain) during the different transports. The RMS and kurtosis values of the pallet vibrations, as well as the vibrations beer is exposed to when stacking boxes or cardboard crates, are illustrated. The vibrations were measured in vertical (up-down), lateral (left-right) and longitudinal (back-forth) as displayed in the figures. However, the directions may diverge slightly over the different CDF-plots due to the attachment of the accelerometer to the pallet or slight movement of the beer bottle on which the accelerometer was mounted. Nevertheless, since the experimental design (stacking patterns, the stacking number, the sensors and the crates used) remained the same over all transports, the authors of current research results were able to validate the results. From Fig. 3a and c can be concluded that the vertical vibrations are the most severe or have the highest RMS-values. The vibrations of the leaf spring trailer have a larger amplitude than the air-ride trailer. This was also found by diverse other authors (Garcia-Romeu-Martinez et al., 2008; Rissi et al., 2008). From the kurtosis plots (Fig. 3b and d), can be concluded that predominantly a positive kurtosis is present during the transports. A probability density function with a positive kurtosis has more and more extreme outliers than the normal distribution. As a consequence, positive kurtosis indicates a strong dissociation between the induced vibrations and shocks. The frequent occurrence of shocks of high amplitude causes the heavy-tailed distribution. Due to the frequent occurrence of shocks during leaf spring truck transport, in extreme cases a significantly high kurtosis was measured (Fig. 3d).

Stacking cardboard boxes or plastic crates on top each other results in higher RMS-values of the measured acceleration signals (in time-domain), as indicated in Fig. 3a and c. This finding was also identified in literature (O'Brien, Gentry, & Gibson, 1965; Soleimani & Ahmadi, 2014). There are two effects causing this relation: with stacking boxes or crates on top of each other, the moment (of force) relative to the origin is larger. Additionally, the characteristics of the specific structure come into play (e.g. material properties and shape of the structure). The stiffness components and the damping parameters of the complete structure contribute to vibrations being amplified or attenuated. In order to further analyze the phenomenon, transmissibility curves (g^2/g^2) were calculated (Fig. 4a and b). The authors of the study focused on

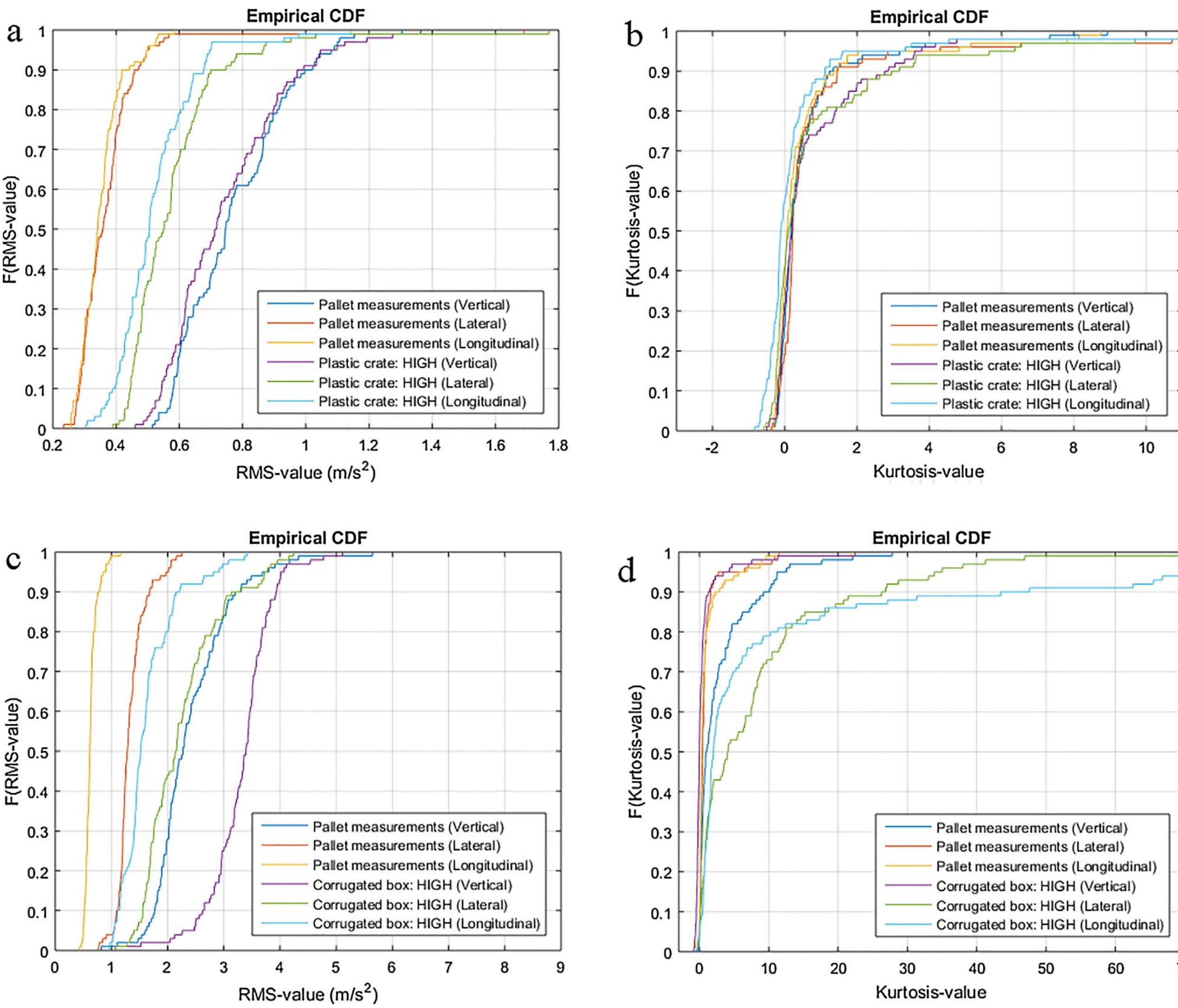

Fig. 3. a) CDF RMS-values of time-domain vibrations, air-ride truck. b) CDF Kurtosis-values of time-domain vibrations, air-ride truck. c) CDF RMS-values of time-domain vibrations, leaf spring truck. d) CDF Kurtosis-values of time-domain vibrations, leaf spring truck.

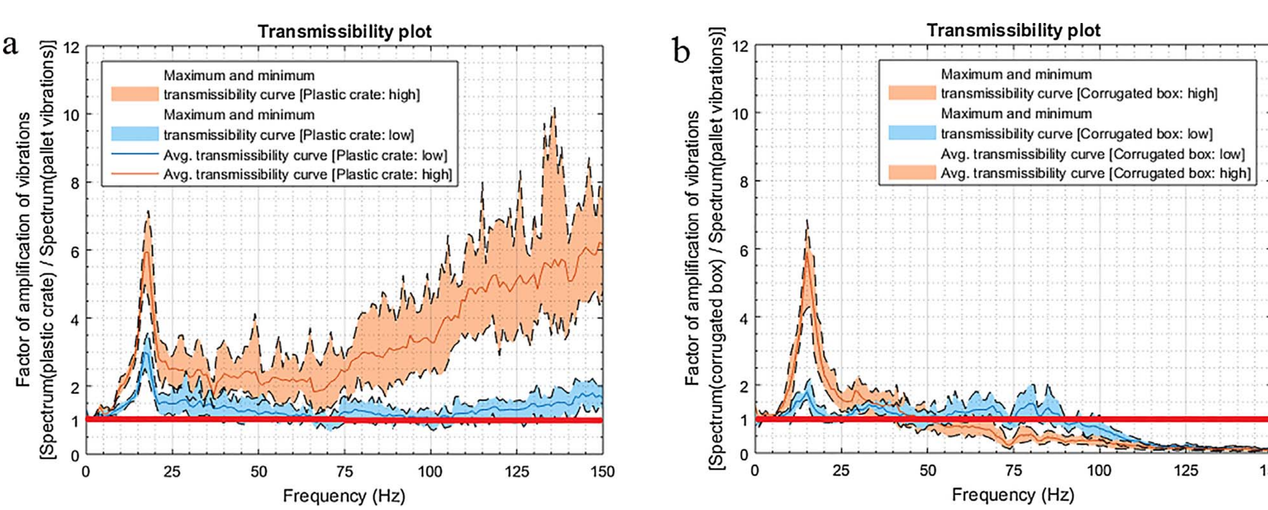

Fig. 4. a) Transmissibility curve, plastic crates stacked on top of each other (Vertical direction). b) Transmissibility curve, corrugated boxes stacked on top of each other (Vertical direction).

the most relevant vibrations regarding frequency and acceleration with respect to future vibration simulation tests and (possible) beer quality degradation. Furthermore, the PSD plots (Fig. 2a and b) confirm that noise was measured at vibrations higher than 150 Hz, and, therefore, were excluded for further analysis. As a consequence, the analyzed range of frequencies of the transmissibility functions of corrugated boxes and plastic crates are studied up to 150 Hz. While displacements at 125–150 Hz are small, the impact of high-frequency vibrations on beer quality are believed to be substantial.

Fig. 4a and b indicate that the particular shape of the transmissibility curve is substantially different between bottles stacked in plastic crates versus cardboard crates. In both figures, vibrations between 1 and 25 Hz are amplified. Vibrations on bottles packaged in plastic crates will also amplify vibrations when frequency rises. The bottles in the highest crates are subject to vibrations between 75 and 150 Hz with up to nine times the amplitude of the pallet vibrations. The authors of the study attribute the measured results to both the configuration (bottles can freely move in the crate), as well as the (damping) characteristics of the crate. Additionally, the bottles move freely and generate vibrations that are picked up by other bottles (Paternoster et al., 2017). Bottles in cardboard crates, on the contrary, will attenuate vibrations higher than 100 Hz. The previously discussed phenomenon is more substantial with increasing the stack height of the cardboard crates. The highest crates attenuate vibrations higher than 50 Hz, although vibrations between 10 and 20 Hz are amplified by a factor of five to seven relative to the amplitude of the pallet vibrations. Results might be clarified by the specific beer packaging. In the plastic crates, beer bottles have free space to move and, as a consequence, are susceptible to increased high-frequency vibrations (75–150 Hz). In cardboard crates, bottles are separated with cardboard panels, which avoids bottles bumping into each other and absorbs vibrations. From the findings of this research can be concluded that food and beverage products packaged in cardboard boxes are subjected and vulnerable to transport vibrations lower than 25 Hz. Researchers often attempt to quantify postharvest losses due to simulated vibrations in a lab scale environment. Moreover, the researcher frequently limits the vibration experiment to imposing vibrations of a single frequency and acceleration. When using cardboard as a packaging material, which is frequently used as a packaging or cushioning material, we suggest focusing solely on vibrations smaller than 25 Hz when performing simulation tests.

3.3. Shocks and beer packaging

During truck transport, cargo is frequently exposed to shocks. The shocks that are measured mainly come from potholes and road unevenness (e.g. concatenation of two roads with different pavement structures). It is the purpose of product packaging to protect the product from shocks and, therefore, product damage. With respect to beer packaging, analysis was performed on the number of vibration samples (in time-domain) that were measured higher than 5 m/s^2 (peak) on the pallet floor (Fig. 5a), on the beer bottle in a cardboard crate (Fig. 5b) and in a plastic crate (Fig. 5c). Only the histograms of measured signals ($> 5 m/s^2$) of the highest stacked crates are presented since the corresponding histograms of peaks of the lower crates were of comparable order of magnitude. As indicated by the figures, the confidence intervals are not centered around the mean value. The latter can be attributed to the skewness of the distribution within every acceleration bin (e.g. 5–7 m/s^2). Furthermore, the results illustrate that when beer is packaged in plastic crates the counts of the measured acceleration samples ($> 5m/s^2$) expands in number, while the cardboard crate completely absorbs all shocks and, as a consequence, diminishes the number of shocks beer is exposed to. As a result, the performance of the cardboard crate in protecting the beer bottles from (response) shocks is significantly better than when using plastic crates [Appendix A (3)].

Furthermore, individual shocks measured on the pallet, and beer bottles in the highest corrugated box and plastic crate were compared. With respect to the shocks that were measured on the pallet, the frequency of the damped oscillation (ω_d) is on average 333 ± 475 Hz. The damping ratio (β) of the analyzed shocks is on average equal to the dimensionless number 0.085 ± 0.024. With respect to the shocks on bottles of the corrugated box, ω_d is on average 115 ± 60 Hz, while ω_d of shocks on bottles in plastic crates is on average 321 ± 287 Hz. The damping ratio of shocks on beer bottles in corrugated boxes equals 0.076 ± 0.023, while in plastic crates is identified at 0.082 ± 0.031. Due to the intrinsic complex nature and the large variety of shocks during transport, the calculated damped oscillation and the damping ratio are large in standard deviation. However, current analysis validates the former results of Sections 3.2 and 3.3. Moreover, the impacts bottles in corrugated boxes are exposed to are damped and, therefore, the frequency of the damped oscillation is lower compared to shocks on the pallet or on bottles in plastic crates. In plastic crates, bottles have free space to move and, as a consequence, shock-impacts generate high-frequency vibrations (also indicated by the transmissibility plot − Fig. 4a). In a simulation environment, shock experiments can be modeled by approximating the frequency of the damped oscillation and the damping ratio.

3.4. Case-study: vibrations, shocks and the beer flavor quality

Two explorative experiments were executed to identify the impact of vibrations and shocks on the beer flavor quality. In order to simulate transient vibrations, a drop device was manufactured that is able to mechanically and repetitively lift and drop a plastic beer crate (Fig. 6a). More specifically, by controlling a motor that pulls a rod up and down that is fixed to an electromagnet, a small metal plate anchored to the plastic crate will induce the system to go up and to drop the crate.[1] A laptop with Matlab 2015a was connected to a data acquisition board (National Instruments USB-6361) to control the device. A large pneumatic shaker of the company Bosal[2] (type MTS 258.05, max. amplitude 50 mm, max. force 50 kn) was used for the vibration experiment (Fig. 6b).

In the shock experiment, beer bottles (25cl. − Vichy) of a selected lager beer were subjected to 8100 shocks (3 days, 10 cycles of 270 shocks) with a drop height of 4 mm and an acceleration peak of 34.69 ± 4.75 m/s^2 (on bottle) in room temperature of 20 °C. The frequency of the damped oscillation and the damping ratio was fixed to 153.74 ± 34.05 Hz and 0.19 ± 0.05. In the vibration experiment, beer samples (33cl. − Vichy) of four beer types (lager beer, blond specialty beer with and without refermentation after bottling, and dark specialty beer with refermentation after bottling) were exposed to vibrations of 15m/s^2 (0-peak) and 5, 15, 30 and 50 Hz during 4 days in room temperature of 20 °C. The beer profiling parameters in this experiment are the oxygen concentrations (HSO −headspace oxygen–, DO −dissolved oxygen–), beer color, iso-α-acids, and aldehydes. Specifications of the performed chemical tests are described in Appendix A (4).

With respect to the shock experiment, oxygen levels decreased slightly, i.e. HSO of 246 ± 29 ppb (ref.) − 188 ± 24 ppb (shocks) and DO of 26 ± 7 ppb (ref.) − 26 ± 4 ppb (shocks). Oxidative reactions are considered the initiator of the flavor aging reactions (Vanderhaegen, Neven, Verachtert, & Derdelinckx, 2006). However, no statistically significant findings were observed for the other parameters. With respect to the vibration experiment, both HSO and DO concentrations of all beer samples decrease due to all exposed vibration

[1] Linear actuator: Nanotec, DC Linear actuator, L5918L3008-T10 × 2-A50, Controller: Nanotec, SMCI35 − Stepper Motor Driver, Positioning Control, 6 A, 24 Vdc to 48 Vdc, Elektromagnet: Stephenson Gobin, 58-0250 24 VDC − Electromagnet, Type 58, 24VDC, 5.4W, 750N, IP51, Spindel: Nanotec, ZST5-5-200-1 − Threaded Screw Spindle, Linear ActuatorsT5 × 5, 200 mm

[2] Bosal subsidiary: Dellestraat 20, 3560 Lummen [Belgium]

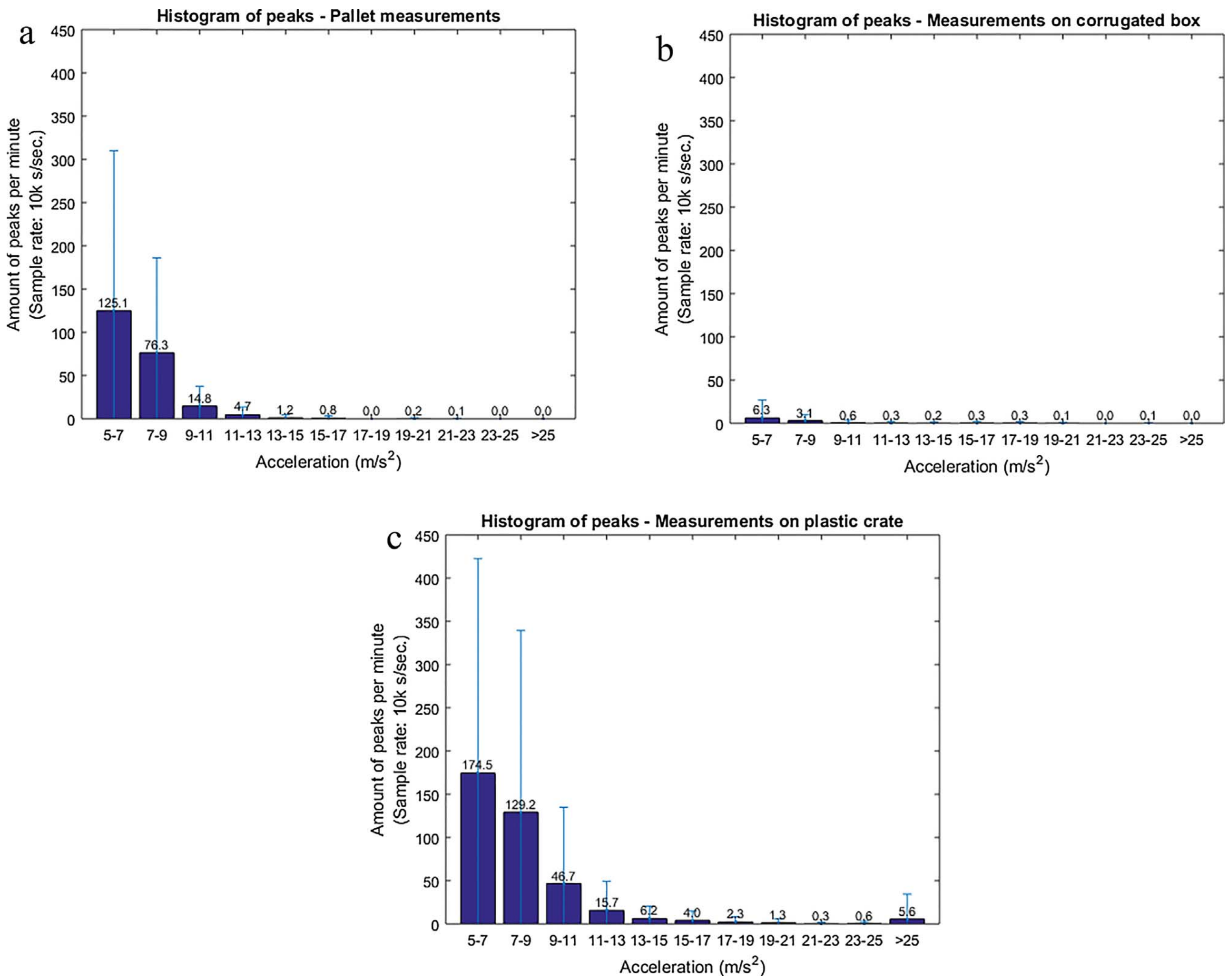

Fig. 5. a) Histogram of time-domain vibrations (> 5 m/s^2), pallet measurements (Vertical vibrations). b) Histogram of time-domain vibrations (> 5 m/s^2), (high) corrugated box measurements (Vertical vibrations). c) Hcistogram of time-domain vibrations (> 5 m/s^2), (high) plastic crate measurements (Vertical vibrations).

patterns (DO-measurements of the dark beer presented in Fig. 7a). This indicates that an uptake of oxygen in the beer and the resulting beer flavor quality degradation might be present. However, no statistically significant findings related to the chemical parameters were observed for the vibrated beer samples except for the dark beer with refermentation after bottling (DSWith). The DSWith-samples had a high initial oxygen content (HSO: 658 ± 235 ppb, DO: 41.5 ± 18.8 ppb) and the aldehydes indicated to be sensitive to the vibrations. The concentration of the individual and total aldehydes of the DSWith-beer samples increased with rising frequency (Fig. 7b, individual aldehydes in 'Data in brief' in Supplementary material). Moreover, the Pearson R and Spearman ρ correlations indicate correlations larger than 0.729 for 8 out of 9 aldehyde components (12 data samples available) and, as a consequence, the hypothesis of having a monotonically increasing aldehyde concentration as a function of the vibration frequency is accepted on a significance level of 10%.

From the prior analysis can be derived that high frequency vibrations (30 Hz, 50 Hz) induce a more severe impact on the beer flavor stability than low-frequency vibrations (5 Hz, 15 Hz). Therefore, the highest stacked crates are more sensitive to transport vibrations compared to the lowest stacked crates (peak around 10–25 Hz in the transmissibility function – Fig. 4a and b). Also, corrugated boxes perform better than plastic crates in protecting beer from vibrations since the high-frequency vibrations (> 25 Hz) are attenuated.

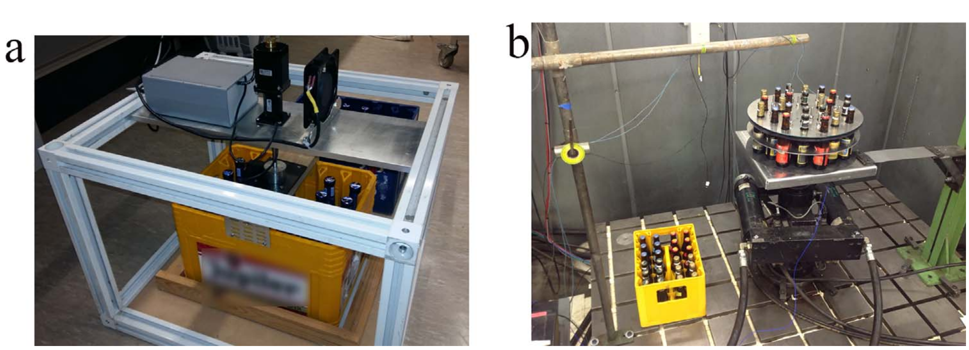

Fig. 6. a) Eaxperimental setup shocks and beer flavor quality. b) Ebxperimental setup vibrations and beer flavor quality (Vertical vibrations).

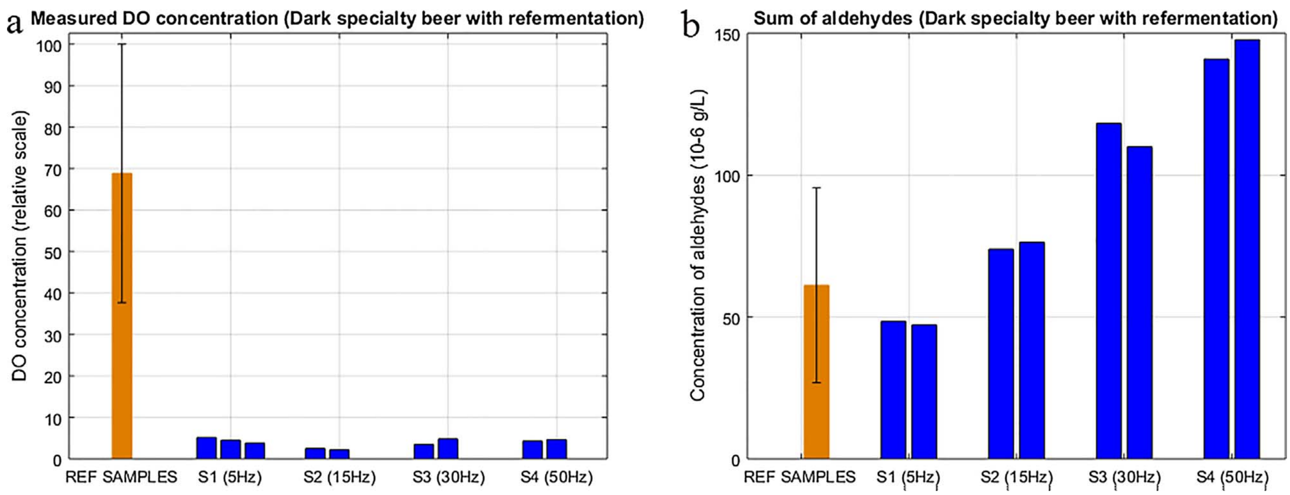

Fig. 7. a) Maeasured DO concentration (relative scale) of DSWith-beer (dark specialty beer with refermentation) after the vibration treatment. b) Mbeasured total aldehyde concentrations of DSWith-samples after the vibration treatment.

Nevertheless, there is an uptake of oxygen at all vibration frequencies and, presumably, a high dependency on the initial oxygen content in the beer. Additional research is recommended on the interaction of vibrations with temperature and the possibility of delayed aging reactions due to the uptake of oxygen. Also, further research is suggested on the interaction between vibrations and shocks on the beer flavor quality.

4. Conclusions and recommendations

From the results of the current paper, the following conclusions are derived:

– Power spectral density plots indicate the important prevalence of vibrations between 0.1 and 10 Hz. Spectral density results of vibrations measured on the Belgian road infrastructure are similar to the results described in literature between 0.1 and 10 Hz, and higher between 10 and 100 Hz (but comparable to ASTM D4169-16 DC3).
– With increasing the stack height of plastic crates or corrugated boxes, RMS-values of the vibrations in time-domain are elevated. Furthermore, the transmissibility curve of plastic crates identifies an amplification over the complete frequency domain with a peak around 5–25 Hz (of maximum a factor seven) and an increase with rising frequency. Vibrations between 75 and 150 Hz are increased up to a factor nine due to the stacking of plastic crates. The transmissibility curve of corrugated boxes identifies an amplification (of maximum a factor seven) between 5 Hz and 25 Hz and attenuation of higher frequencies with increasing stack height. When using cardboard as a packaging or cushioning material, vibration simulation tests should, therefore, focus on vibrations smaller than 25 Hz. Corrugated boxes perform better in attenuating vibrations and protecting beer from vibrations and, as a consequence, are preferred over plastic crates.
– Furthermore, when packaging products, the transporters should take into consideration that shocks of high amplitude are frequently present in transport over Belgian roads. Hence, products that are more sensitive to shocks than vibrations should be cushioned appropriately. Corrugated boxes absorb shocks and, therefore, protect beer bottles. A packaging with cardboard is preferred over plastic crates with respect to shocks.
– A first vibration and shock experiment identified the uptake of oxygen in beer due to vibrations and shocks, the dependency of the initial oxygen content, and the higher effect of high-frequency vibrations over low-frequency vibrations on the aldehydes. Beer in the highest stacked crates and beer in plastic crates are more sensitive beer flavor degradation due to vibrations and shocks compared to beer in the lowest stacked crates and corrugated boxes.

In future research, the effect of vibrations and shocks (in interaction with temperature) on the beer flavor stability of different beer types will be further investigated. This will result in a better assessment of the performance of the beer packaging in protecting beer from vibrations and shocks, and the need for the development of an adapted beer packaging.

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Appendix A

(1) Specifications of bottles, crates and plastic foil:

24 bottles of 25cl in a corrugated box with bottles separated with cardboard panels − Specifications bottle: Vichy (brown) − mass bottle: 494 g − mass crate: 11.86 kg (L x B x H: 36.5 × 24.5 × 24 cm)

24 bottles of 25cl in a hard plastic Polyethylene (PE) crate − bottle type: Vichy (brown) − mass bottle: 494 g − mass crate: 16.96 kg (L x B x H: 39 × 29 × 25 cm)

Transparent plastic polyethylene stretch foil (450 mm)

Beer transport 1: truck + trailer 3 axles (1 + 2) [MAN TGA SH265 FNLC] (length trailer 7.5 m − weight full capacity 26 tons − end of transport [empty beer bottles] 15 tons) − extra trailer 2 axles [Renders RMAC 9.9N] (length trailer 7.5 m − weight full capacity 18 tons − end of transport [empty beer bottles] 13.5 tons)//Beer transport 2: truck + trailer 3 axles (1 + 2) [MAN TGA SH265 FNLC] (length trailer 7.5 m − weight full capacity 26 tons − end of transport [empty beer bottles] 15 tons)//Beer transport 3: truck + trailer 5 axles (2 + 3) [Volvo FH440 + Renders Liftachse ROC 12.27N] (length trailer 13.5 m − weight full capacity 39 tons − end of transport [empty beer bottles] 16 tons)// Beer transport 4: truck + trailer 5 axles (2 + 3) [VOLVO FH440 + Renders Liftachse ROC 12.27N] (length trailer 13.5 m − weight full capacity 39 tons − end of transport [empty beer bottles] 16 tons)

(2) The pallet that was used for current experimental study was loaded on the last part of the extra trailer (beer transport 1), trailer (beer transport 2), trailer (beer transport 3) and trailer (beer transport

4) in order to measure the most extreme vibrations. Moreover, the pallet with the measuring devices was located between one forth and one third of the rear end of the (extra) trailer length (respectively 1.8 m–2.5 m [transport 1], 1.8 m–2.5 m [transport 2], 3 m–4.5 m [transport 3 and 4]). All pallets had 7 layers of plastic crates that are 'clicked' on top of each other. The 'clicking' is possible due to the structure of the plastic crates and ensures safe stacking of crates. All studied pallets have 5 layers of corrugated boxes in which bottles are separated from each other with cardboard panels, which is the industry standard. The corrugated boxes were then stabilized with stretch-wrap.

The authors of current paper indicate that close to all food products are transported in their (secondary) packaging and stacked on pallets. Also beer is stacked on wooden pallets in order to facilitate loading and unloading of beer. Therefore, vibrations were measured on top of the wooden pallet itself (exactly the same spot for all case studies) in order 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.

All bottles were the same for the studied beer transports and contained 33 cl of beer. The bottles with the accelerometers mounted on them stay in the same orientation since the cable hinders them to change direction and balances the bottle. However, the bottles have enough free space to move in order to not affect the normal operation or movement of the bottle.

(3) It is difficult to extract the input versus the responses of the shocks. However, the authors of current research are predominantly interested in the shock response phenomena to identify the conditions bottled beer is subjected to. Post analysis revealed that the frequency of the damped oscillation is predominantly higher than 100 Hz for both shock responses measured on the pallet and the bottles in the plastic crates. Therefore, even with an amplification of the vibrations lower than 50 Hz by a factor seven for the bottles in the highest stacked corrugated boxes, bottled beer in both high and low corrugated boxes will not be exposed to many shocks. The latter can be attributed to the structure of the material (corrugated cardboard) and the cardboard panels between the bottles that absorb the energy of the generated (response) shocks.

(4) Specification of the performed chemical tests:

- Oxygen:

Determination of oxygen concentrations:

Oxygen in bottled beer is determined using the 'Haffmans Inpack TPO/CO_2 meter Type c-TPO'. The measurement is performed in a sealed bottle and the principle is based on O_2 dependent fluorescence of the sensor.

- Beer colour: IOB method: 9.1 (The Institute of Brewing, 1997);

- Iso-α-acids:

UPLC determination of iso-α-acids:

UPLC separations were performed on an Acquity UPLC (Waters, Milford, USA), consisting of a PDA detector, column heater, sample manager, binary solvent delivery system and an Acquity UPLC HSS C18 1.8 μm column (2.1 i.d. × 150 mm; Waters, USA). Data reprocessing: Empower 2 software. Chromatographic conditions: eluent A: milli-Q water adjusted to pH 2.80 with H_3PO_4 (85%, Merck, Darmstadt, Germany); eluent B: HPLC-grade CH_3CN (Novasol, Belgium). Elution: isocratic using 52% (v/v) solvent B and 48% (v/v) solvent A. Analysis time: 12 min. Flow rate: 0.5 mLmin^{-1}. Column temperature: 35 °C. UV detection: 270 nm.

- Aldehydes:

C-MS determination of aldehydes:

Volatile aldehydes in beer were determined according to (Vesely, Lusk, Basarova, Seabrooks, & Ryder, 2003), using headspace-solid phase microextraction (HS-SPME) with on-fibre PFBOA (*o*-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine) derivatization and capillary gas chromatography/mass spectrometry (CGC/MS) (Dual Stage Quadrupole (DSQ™ II) GC/MS system, Interscience Benelux). The DSQ™ II was coupled to a Thermo Trace GC Ultra (Interscience Benelux) equipped with a CTC-PAL autosampler (including SPME sampling), a split/splitless injector with a narrow glass inlet liner (0.5 mL volume), and a RTX-1 fused-silica capillary column (40 m × 0.18 mm i.d. × 0.2 μm film thickness, Restek, Interscience Benelux). Data reprocessing was done by the XCalibur™ data system (Thermo Electron Corporation).

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fpsl.2017.12.007.

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Vibration and shock analysis of specific events during truck and train transport of food products

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ABSTRACT

In international test standards and literature averaged vibration spectra of truck and train transports are reported. However, cargo is exposed to extreme levels of vibrations and shocks for which the averaged vibration data are not representative. The objective of this study is to report evidence of the extreme vibrations and shocks during truck and train transport, and help food scientists design relevant vibration and shock simulation experiments. Results indicate that trains and trucks experience transient phenomena when traveling over train switches, accelerating and stopping the train, respectively road unevenness (e.g. potholes). The damping ratio (β) of shocks measured on the railcar is on average 0.05 ± 0.02, while on the truck 0.08 ± 0.02. Furthermore, the measured spectra of this study diverge from the spectra of international standards. A time-domain analysis indicates that traveling over cobblestones, and concrete pavement generates the most severe vibrations and shocks (dependency on truck velocity).

1. Introduction

Fresh fruit and vegetables, as well as electronic goods, are susceptible to quality losses or failure due to vibrations and shocks. Vibrations and shocks during transport are categorized as an important contributor to the decrease in product quality (Gołacki, Rowiński, & Stropek, 2009; Van Zeebroeck et al., 2007). Since postharvest losses can be quantified between 30 and 50% of all food that is grown (Parfitt, Barthel, & Macnaughton, 2010), increased attention goes to this topic. Postharvest waste is defined as losses arising during transport, handling, and storage of food products before they reach the customer (Parfitt et al., 2010). International test standards (ISO –International Organization for Standardization– and ASTM –American Society for Testing and Materials–) guide researchers and (food) scientists to experimentally test products on transport vibrations. However, there is a mismatch between the vibrations measured in reality and the proposed test methods of the international standards. This study was performed to demonstrate the importance of transient phenomena when doing simulation tests and to further discuss the proposed test methods of international standards and the vibration spectra described in literature.

The international test standards (ASTM D4728 and ISO 13355) suggest the use of averaged vibration data in combination with applying time-compression (i.e. vibrations are artificially amplified to better replicate product damage) to simulate transport. As a consequence, the power spectral density levels (PSD-levels) differ from the ones that are measured in reality (Böröcz & Singh, 2016). An extensive field of literature has been devoted to reporting realistic vibration levels measured on different transport vehicles traveling on a regional transport network (without time-compression). Similar to the international standards, the latter mentioned papers also report averaged vibration data, i.e. root mean square-levels (RMS-levels) and PSD-levels, to characterize vibration measurements (Böröcz & Singh, 2016; Chonhenchob et al., 2009; Lu et al., 2010; Rissi, Singh, Burgess, & Singh, 2008). However, limited evidence was reported in literature on the occurrence of transient phenomena during transport. Furthermore, the averaged vibration patterns to which test items are exposed during (recommended) transport simulations may differ substantially from the extreme levels of vibrations or shocks that are present during transport. Even the use of time compression in combination with averaged vibration data may not replicate damage that is produced by transients (Böröcz & Singh, 2016). Nevertheless, the influence of shocks on food products (for instance apples (Gołacki et al., 2009; Van Zeebroeck et al., 2007)) has been investigated in some papers. Therefore, in this study a thorough time-domain analysis of vibrations and shocks that occur during truck and railway transport was performed. Moreover, by offering additional insights on vibrations and shocks of specific events

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that occur during transport, researchers can simulate transports more realistically. With the information presented in this paper, researchers will be able to optimize experimental designs with better replication of damage to test items due to transport vibrations and shocks.

The literature on vibrations during transport is abundant; two categories of papers can be distinguished. The first category of papers (1) aims to identify the input spectra of different types of transport vehicles traveling on a regional transport network (Chonhenchob et al., 2009; Lu et al., 2008; Rissi et al., 2008; Rouillard & Richmond, 2007). The papers often aim to identify several relevant parameters that influence the magnitude of the vibrations and shocks (Garcia-Romeu-Martinez, Singh, & Cloquell-Ballester, 2008; Lu et al., 2010; Singh, Singh, & Joneson, 2006). In the second category (2), a myriad of papers aims to focus on the impact of vibrations and shocks on a specific food product. The influence of vibrations and shocks on an individual product (Van Zeebroeck et al., 2006), often fruit, or the interaction of products (Pang, Studman, & Ward, 1992) is regularly assessed. Also, the packaging strategy (i.e. damping and cushioning properties (Eissa, Gamaa, Gomaa, & Azam, 2012; Paternoster et al., 2017; Vursavus and Özguven, 2004)) and the configuration in a container (O'Brien, Gentry, & Gibson, 1965) was researched. Since vibrations and shocks have a direct influence on the product integrity and quality, it is essential to gain knowledge on the type and magnitude of the vibrations and shocks that occur during transport. Packaging engineers can adopt these insights to design a better packaging. On the one hand, a lack of knowledge could lead to insufficient packaging or cushioning of the products or, in other words, under-packaging of the products. An excess of protective cushioning, on the other hand, could lead to over-packaging. In the former scenario, under-packaging can easily be identified since the products will exhibit defects. The occurrence of over-packaging, which implies hidden costs, is more difficult to determine. From recent estimates, the total cost of over-packaging in Europe is 130 billion euros per year (Rouillard & Richmond, 2007).

The objective of the current paper is to identify vibration and shock patterns that are present when traveling over the Belgian road and railway network. Moreover, roads were segmented based on road type and speed limit to identify the vibration and shock characteristics. Similar research was performed by Jarimopas, Singh, & Saengnil (2005) indicating the influence of road type (laterite, asphalt, and concrete) with segmentation of the driving speed (20, 40 and 80 km/h) on vibrations and relating the measurements to damage of packaged tangerines. Current research further develops previous insights by also focusing on shock patterns when driving over different road types. While Lu et al. (2008) analyses shocks as individual events (e.g. metal joints, railway crossings), the current study investigates the magnitude and frequency of the shocks attributed to road type in combination with speed of driving. Furthermore, a time-domain analysis was completed to identify vibration and shock patterns that occur during railway transport (e.g. acceleration and stopping of a train, a passing train, etc.). The literature on shocks during railway transport is limited, which to the respect of the authors is remarkable due to the high magnitude of the shocks and the high frequency of occurring. This also emphasizes the unique contribution of this paper. In addition, shock analysis was performed in which the damping factor (β) and the acceleration amplitude (in time-domain) was calculated of diverse shocks measured during truck and railway transport. The last objective of this study was to identify the influence of cargo weight on the magnitude of the vibrations and shocks during transport. More extensive research on the influence of cargo weight on vibration levels was performed by Garcia-Romeu-Martinez et al. (2008), and therefore was used to benchmark research findings.

The scope of the paper is based on the Belgian transport network with specific reference to vibrations and shocks measured on trucks, with air-spring and leaf-spring suspension, and trains with leaf spring suspension within a Belgian context. The findings of this paper can be used by researchers and food scientists to simulate transport and optimize packaging design. The aim of this paper is to confront the simulation tester with the extreme levels of vibrations and shocks that are measured during transport and which are not reflected by the averaged power spectra described in international testing standards and literature.

2. Material & methods

2.1. Experimental design

Vibrations and shocks, defined as periodic or random in nature, respectively a single-event or transient phenomenon, were measured during truck and railway transport. The devices used to measure the vibrations included the following:

1) 3-Axial Accelerometers (SparkFun Triple Axis Accelerometer Breakout – ADXL337–SEN 12786, SparkFun Electronics, Niwot, Colorado, USA)
2) Data acquisition board (National Instruments USB-6361 – Part Number: 782256-01, National Instruments, Austin, Texas, USA)
3) Laptop (Dell 1708FP, Dell, Round Rock, Texas, USA with MATLAB Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States.)
4) External battery (Solar-accu 12 V 60 Ah GNB Sonnenschein – NGSB120060HS0CA, Conrad, Oldenzaal, Netherlands)
5) Transformer (Voltcraft SWD-300/12 Omvormer 300 W 12 V/DC 12 V/DC – 513124 – 8J, Conrad, Oldenzaal, Netherlands)
6) Camera (GoPro Hero 4, GoPro, Paris, France)

The first five elements of the experimental set-up, listed above, are connected to each other. The accelerometers (1) had a sampling rate of 1e5 samples per second in order to also analyze high-frequency vibrations [bandwidth: 1600 Hz (X- and Y-axis/noise density: 175 μg/√Hz rms) and 550 Hz (Z-axis/noise density: 300 μg/√Hz rms)][1]. and were linked by cable with the data acquisition board (2). The latter device transforms the electrical current passed along by the transducers to a digital signal that can be read by the programmable software of the computer (3). The software used in this research is Matlab 2015a. The devices were electrically charged by an external battery (4) connected with a transformer (5). The transformer converts the 12 V DC into a 220 V AC current. While performing measurements, a GoPro-camera (6), mounted over the shoulder of the driver, filmed the events during transport. As a consequence, the filmed events were matched with the corresponding vibration data.

Measurements were performed during seven transports ranging over two different modes of transport, more specifically train and truck transport. The accelerometers used in this study were attached on top of a wooden pallet (between food boxes and the pallet), in the case of the truck transports, and to a metal grill welded to the bogie of the railcar, in the case of the train transport. Since it is the industry standard to transport food products stacked on wooden pallets, for the purpose of this study accelerometers were mounted on top of a wooden pallet rather than on the container floor, as is the standard when doing vibration measurements. Furthermore, the railway vibrations were measured on the structure floor, i.e. fixed to a metal grill welded to the bogie of the railcar. Due to regulations out of our control, stakeholders and industry partners of this project were not able to unseal a container. Therefore, it was not possible to measure vibrations inside a container:

[1] In the current study, no filter was applied to the signal. However, in order to prevent aliasing phenomena and to investigate the measured high-frequency vibrations, the sampling rate was fixed substantially high. The researchers are aware that the current results are predominantly informative within the bandwidth of the sensors.

this may cause limitations when comparing with research findings from the literature. However, this also results into unique insights on the vibration and shock patterns measured during transport. Vibration measurements were executed during the normal operations or activities of the transport vehicle. As a consequence, all transport vehicles were loaded close to full capacity in the beginning of the transport and (completely or nearly) empty at the end of the transport. Therefore, it was possible to compare the difference in vibration patterns between transport vehicles with full or no cargo load. The transports, attended in the context of this research, are presented:

Truck transport [Specifications in Appendix A]:

- Transport 1: 3/02/2016 (rec. time: 9 h. 44mins) [air-ride spring].
- Transport 2: 12/04/2016 (rec. time: 3 h. 26mins) [Leaf spring].
- Transport 3: 23/08/2016 (rec. time: 2 h. 28mins) [air-ride spring].
- Transport 4: 27/09/2016 (rec. time: 1 h 50mins) [air-ride spring].

Train transport

- Transport 1: 27/06/2016 (rec. time: 1 h. 43mins) [Leaf spring with diesel engine].
- Transport 2: 2/08/2016 (rec. time: 2 h. 10mins) [Leaf spring with diesel engine].
- Transport 3: 3/08/2016 (rec. time: 3 h. 55mins) [Leaf spring with diesel engine].

2.2. Data analysis

Complex shock motions, typically a half-sine function, are present during transport (Harris & Piersol, 2002). However, field data revealed that, due to the dynamics of the structure, the shock responses measured during truck and railway transport are best represented by a decaying sinusoid. Shocks occurring during truck transport (due to potholes, metal joints, etc.) or train transport (due to railway switches, etc.) might be represented by impulses that are damped over time due to the vehicle structure (e.g. tires, suspension, etc.). In order to facilitate shock simulation testing, transport shocks were analyzed by calculation of the damping ratio (β). The damping ratio is a function of the logarithmic decrement (λ), the frequency of the damped oscillation (ω_d) and the damped period (T_d), which is the time between the two highest consecutive peaks. The logarithmic decrement is defined as the natural logarithm of the division of the acceleration amplitude of the highest peak ($x(T_1)$) divided by the acceleration amplitude of the second highest peak ($x(T_1 + T_d)$). Also the natural frequency of the damped oscillation (ω_n) can be calculated (Thomson, 1993).

$$\beta = -\frac{\lambda}{\sqrt{\lambda^2 + T_d^2\omega_d^2}} = -\frac{\lambda}{\sqrt{\lambda^2 + (2\pi)^2}}$$

with

Furthermore, a shock analysis was performed to evaluate the number of the measured accelerations (time-domain) above 5 m/s^2 that occur during transport. Moreover, the measured time-domain vibration signals were divided into intervals of 20 s. Afterwards, a histogram of all time-domain vibration data that were measured above 5 m/s^2 was calculated. The presented histograms in Section 3 indicate the average number of peaks during transport and one standard deviation up (respectively down). When dividing the average number of peaks by the sampling rate, the histogram is independent of the sample rate and can be compared with other vibration measurements (with different sample rate). Since a histogram of the measured accelerations (time-domain) above 5 m/s^2 was built for the different pavement types, different road conditions were benchmarked and compared.

Matlab R2015a was used to analyze the vibration signals and to build cumulative distribution functions (CDF) of the RMS and kurtosis values for different time-domain vibration segments. Moreover, the vibration data were partitioned in 1 s intervals, RMS and kurtosis was calculated and, afterwards, the cumulative distribution function was identified. Kurtosis is a statistical concept in which the shape of the measured signal is compared to the standard normal distribution. A positive kurtosis indicates a heavy-tailed distribution and a negative kurtosis a light-tailed distribution. Furthermore, average PSD plots were also calculated by performing multiple fast Fourier transforms and taking the linear average (bandwidth/frequency resolution 0.2 Hz). The technique can be presented by the formula:

$$Average(PSD)_f = \frac{1}{n}\sum_{i=1}^{n} PSD_{f,i}$$

with

$f = given\ frequency\ of\ the\ selected\ event$

$n = the\ amount\ of\ selected\ events$

3. Results & discussion

In this research, the aim is to identify vibration and shock patterns during train and truck transport. Therefore, the effects that come into play with respect to vibrations and shocks of the different transport vehicles are sequentially analyzed and illustrated.

3.1. Vibration analysis – train and truck transport

In Fig. 1a and c, the cumulative distribution functions (CDF) of the RMS-values of the time-domain vibrations measured in the lateral (left-right), longitudinal (front-back) and vertical (up-down) direction of the train and truck transports are presented. The figures indicate that during both train and truck transports vertical vibrations are significantly higher of amplitude than vibrations in any other direction.

$$\beta = -\frac{\lambda}{\sqrt{\lambda^2 + T_d^2\omega_d^2}} = -\frac{\lambda}{\sqrt{\lambda^2 + (2\pi)^2}}$$

with

$$\begin{cases} \lambda = \frac{1}{\mathrm{d}}\ln\left(\frac{x(T_1)}{x(T_1+T_d)}\right) & with\ 'd' = integer\ number\ of\ successive\ peaks \\ \omega_d = \frac{2\pi}{T_d} & in\ \frac{rad}{s} \\ T_d = (T_2 - T_1) & in\ sec. \\ \omega_n = \frac{\omega_d}{\sqrt{(1-\beta^2)}} & in\ \frac{rad}{s} \end{cases}$$

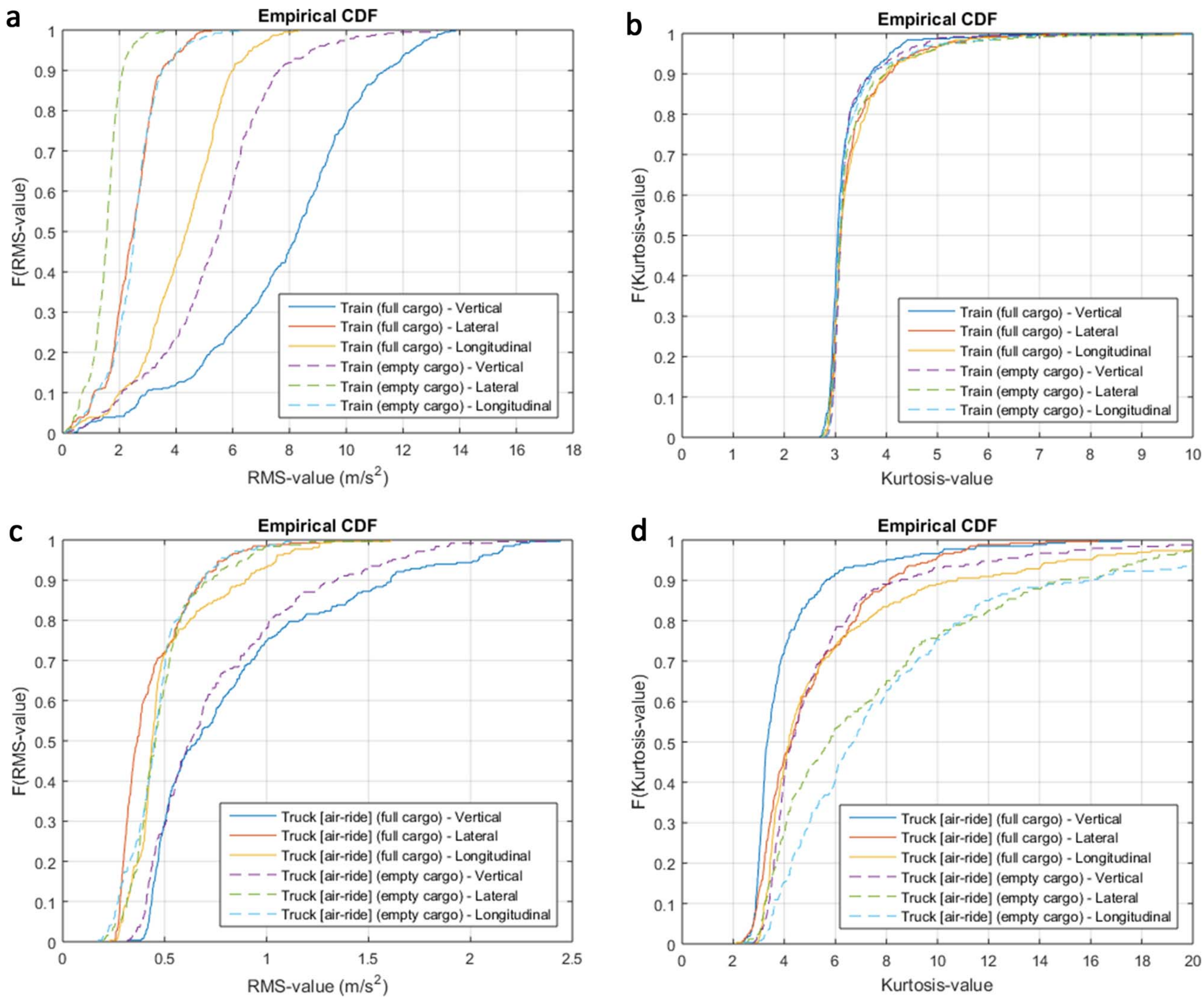


Fig. 1. a: Cumulative distribution function (CDF) of RMS-values of time-domain vibration signals, leaf spring train (full and empty cargo)/. b: CDF kurtosis-values of time-domain vibration signals, leaf spring train (full and empty cargo)/. c: CDF RMS-values of time-domain vibration signals, air-ride truck (full and empty cargo)/. d: CDF kurtosis-values of time-domain vibration signals, air-ride truck (full and empty cargo).

The latter result was found by multiple researchers (Garcia-Romeu-Martinez et al., 2008; Rissi et al., 2008). Furthermore, during train transport, longitudinal vibrations are more pronounced than lateral vibrations, which is attributed to the forces that are build up and transferred along the concatenation of railcars. Since the cargo weight is of high influence on the magnitude of the vibrations (Garcia-Romeu-Martinez et al., 2008), the distinction was also made between vibrations measured in a transport vehicle with full and empty cargo. In the literature, unloaded vehicles are assumed to have on average higher vibration levels than loaded vehicles. In this study, results indicate that the railcar with full cargo had more severe vibrations than without cargo. The latter effect can be attributed to the stiffness of the spring of the leaf spring (suspension) that was not adapted to the cargo weight. In comparison, in truck transport with leaf spring suspension, the driver is ought to adapt the spring stiffness manually to the cargo weight to diminish the number of vibrations the cargo is subjected to. The effect of cargo weight on the vibration levels of truck transport with air-ride suspension is small or cannot be determined (Fig. 1c). In Fig. 1b and d, the CDF-plots of the kurtosis-values of the time-domain vibration signals for the two modes of transport are presented. During railway and truck transport kurtosis is positive, which suggest a heavy-tailed distribution. It is noteworthy that during truck transport lateral and longitudinal time-domain vibrations have higher kurtosis values than vertical vibrations. The latter effect is more pronounced with empty cargo.

The averaged spectral density plots of the truck with air-ride suspension and railcar with leaf-spring suspension, as would be presented in most of the articles in literature and in international standards, are depicted in Fig. 2a–d. With respect to the truck transport, vibrations between 0.1 and 10 Hz are more significant than vibrations higher than 10 Hz. The lowest frequencies are commonly attributed to the road roughness, suspension, and tires (Singh et al., 2006). The PSD plots of the vibrations measured during train transport indicate that also high-frequency vibrations (> 150 Hz) of high magnitude are present. The latter effect can be attributed to the mounting of the accelerometer on the bogie or the structure floor of the railcar. Furthermore, the dynamics interaction of the couplers between the railcars impedes the analysis of the measured vibrations and shocks. Inside a railcar container, vibrations higher than 150 Hz may be damped and significantly reduced in amplitude. However, current research can add insights to the origin and magnitude of the vibrations measured in railcars (leaf-spring suspension). Since literature on the vibrations and shocks that occur during railway transport is underdeveloped, every element of information that can add to knowledge is highly recommended (Böröcz & Singh, 2016; Rouillard & Richmond, 2007).

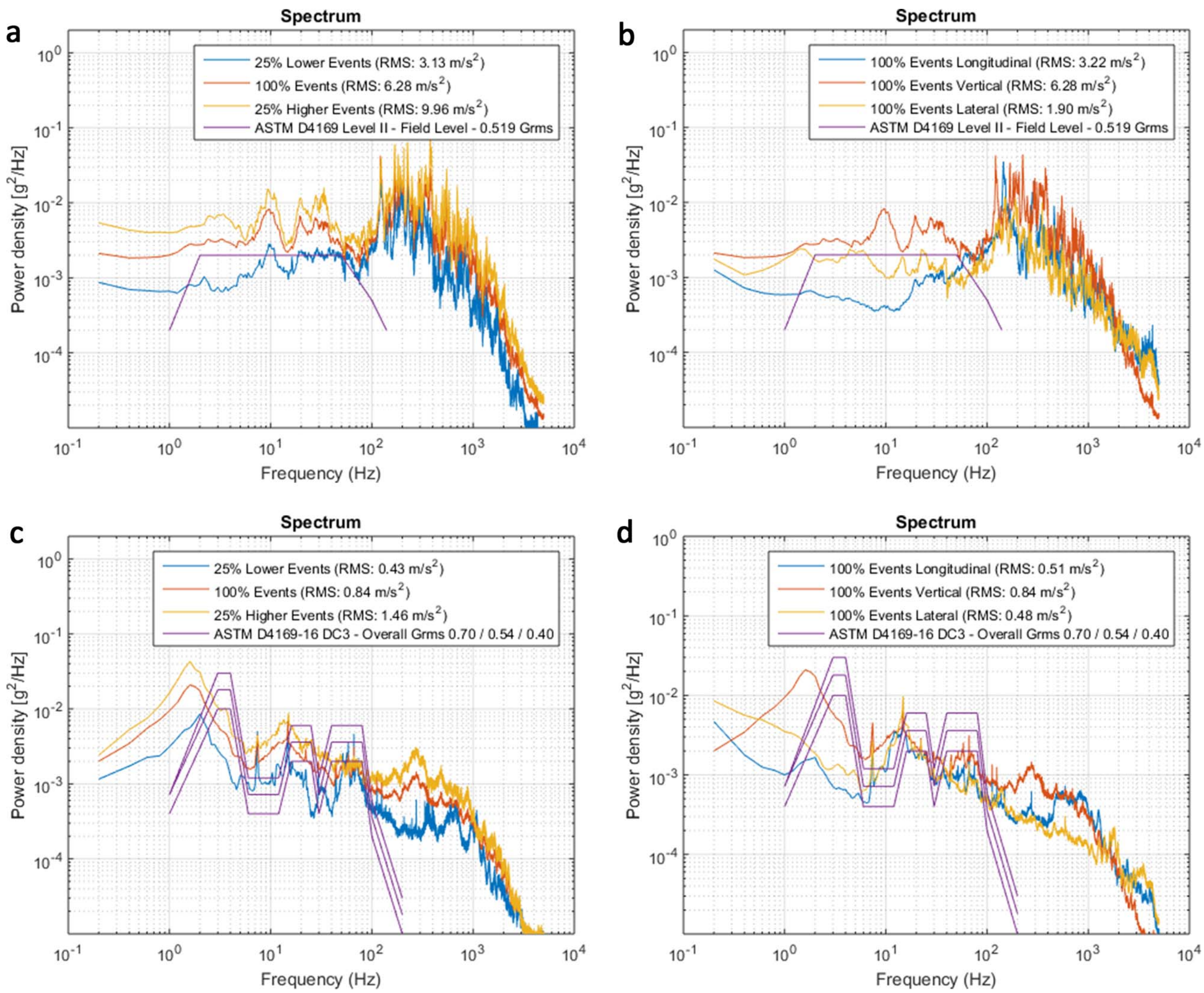


Fig. 2. a: PSD train transport (Vertical container/bogie measurements)/. b: PSD train transport (Container/bogie measurements)/. c: PSD (air-ride) truck transport (Vertical container floor measurements)/. d: PSD (air-ride) truck transport (Container floor measurements).

In order to validate the findings of this study, results were benchmarked with the international standards (ASTM D4169). Vibration measurements in both truck and train significantly differ from the standards, as is also suggested in literature (Böröcz & Singh, 2016; Chonhenchob et al., 2009; Garcia-Romeu-Martinez et al., 2008; Rissi et al., 2008). However, the spectral density plots of trucks described in literature are to a large extent similar to the results presented in this study (e.g. Garcia-Romeu-Martinez et al. (2008), Rissi et al. (2008), Singh et al. (2006), and Soleimani and Ahmadi (2014)). The vibration levels are most comparable with the study of Soleimani and Ahmadi (2014), since the accelerometers were mounted on the lowest crate/pallet to identify the influence of vibrations on food packages. The vibration levels identified by Rissi et al. (2008) measured during multiple truck transports in Brazil are to a lesser extent comparable since the data recorders were mounted on the undercarriage of the truck. Chonhenchob et al. (2009), Garcia-Romeu-Martinez et al. (2008) and Singh et al. (2006), which have measured vibrations on the container surface, observe similar low-frequency vibrations (0.1–10 Hz) but lower high-frequency vibrations (10–100 Hz). In the study of Lu et al. (2010) vibration levels were ought to be considerably lower. In order to realistically simulate transport, the results suggest adaptations to the international standards as well as further improvements of the recommended test methods, such as ASTM D4728 and ISO 13355.

3.2. Shock analysis – train and truck transport

In order to facilitate simulation testing, the complex shocks that occur during train and truck transport are analyzed as a decaying sinusoid. Thirty shocks in both air-ride truck and leaf-spring railcars were studied, as theoretically shown in Section 2 (Material & Methods). During truck transport the frequency of the damped oscillation (ω_d) is on average 153 Hz ± 148 Hz. The damping ratio (β) over the different shocks is on average equal to the dimensionless number 0.08 ± 0.02, which means that the amplitude of the second peak is estimated to be 60 ± 8% of the amplitude of the first peak. With respect to train transport, the frequency of the damped oscillation (ω_d) is identified as 1559 Hz on average ± 1970 Hz. The damping ratio (β) of shocks measured on the railcar is on average 0.05 ± 0.02, which means that the amplitude of the second peak is estimated to be 73 ± 10% of the amplitude of the first peak. The large variance in the damping ratio and the frequency of the damped oscillation is predominantly attributed to the diversity in transient phenomena that occur during transport. This analysis suggests that shocks are more damped during truck transport than during railway transport. Furthermore, the frequency of the damped oscillation is higher during train transport than during truck transport, which is attributed to the complex dynamics and interactions of the couplers. Food scientists or packaging engineers can simulate

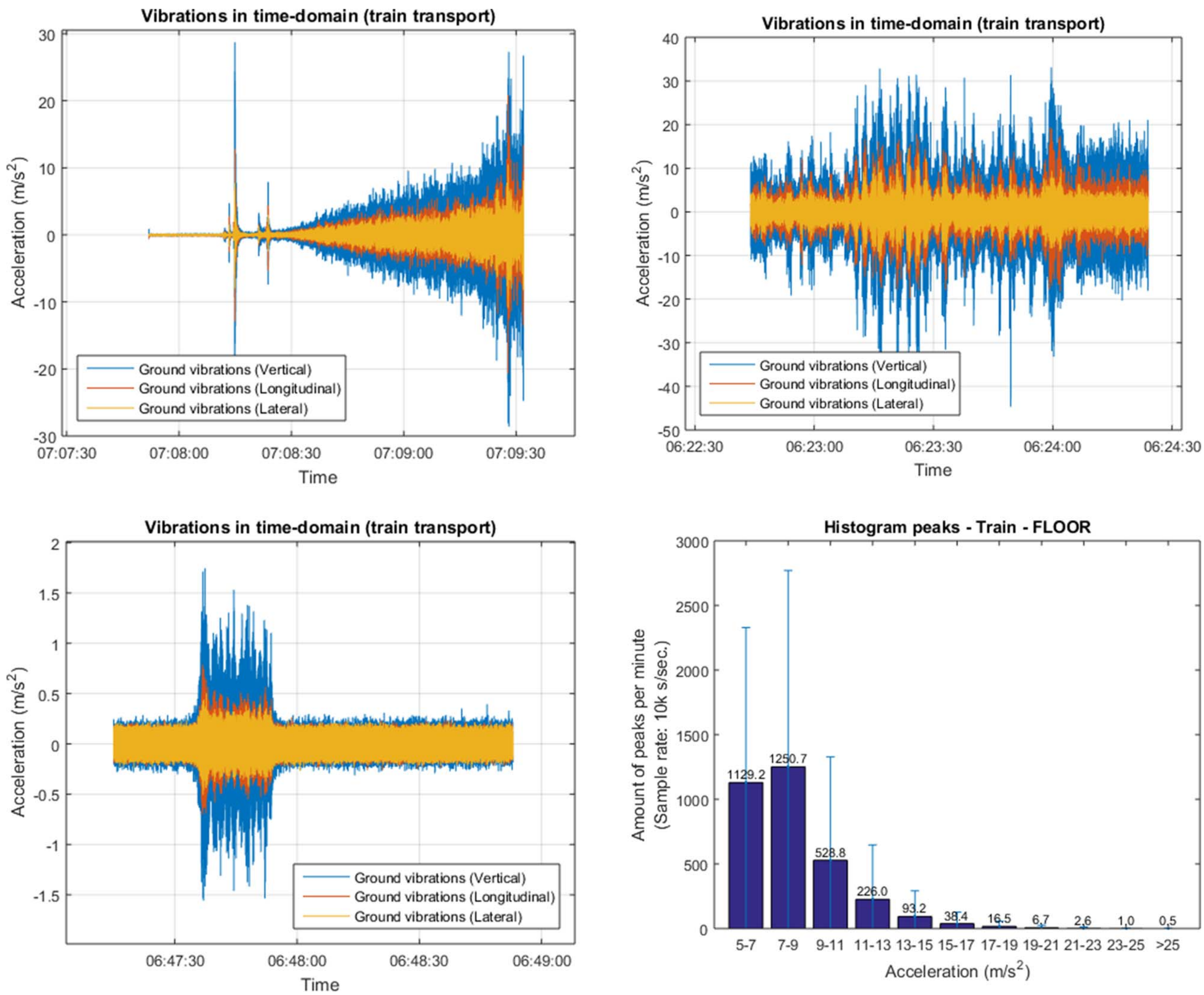


Fig. 3. a: Vibrations in time-domain (train starts and accelerates)/. b: Vibrations in time-domain (train switches on a railway yard)/. c: Vibrations in time-domain (passing of a train while standing still)/. d: Histogram of peaks ($> 5\,m/s^2$) during train transport.

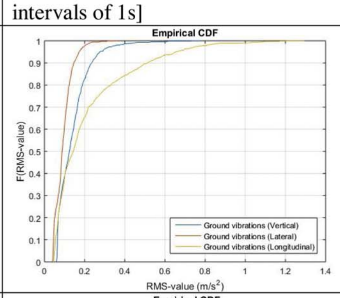
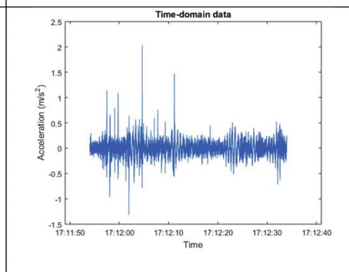
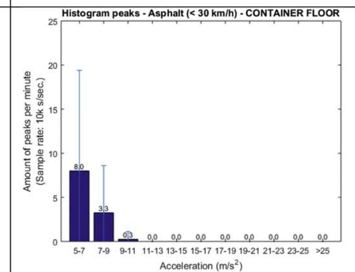
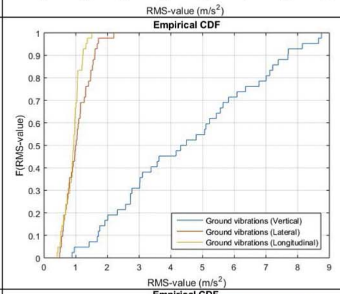
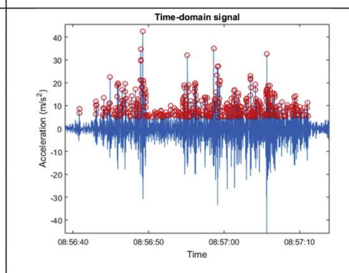
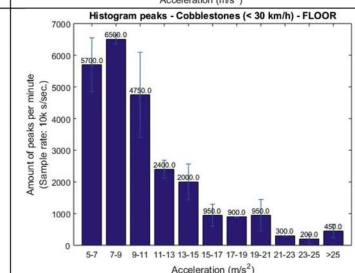
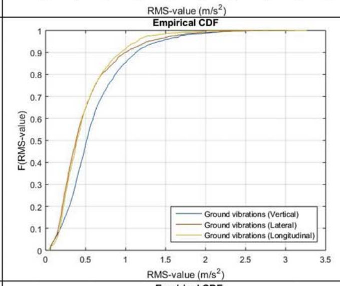
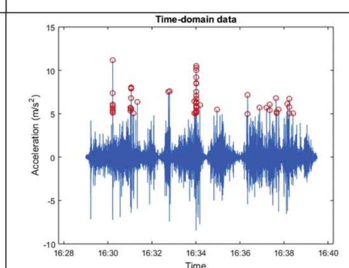
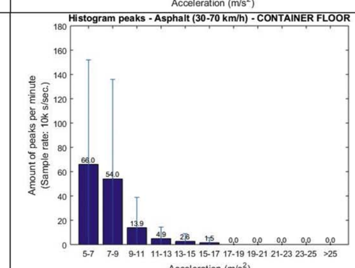
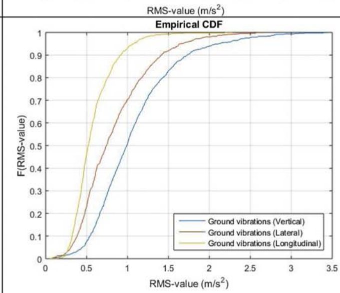
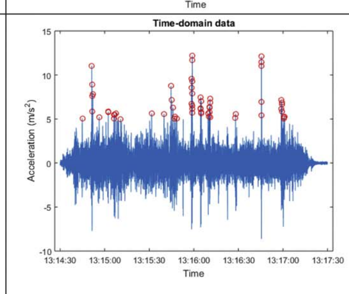
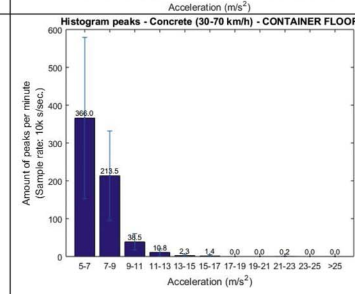
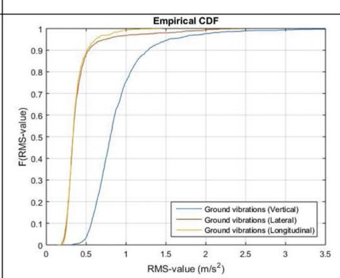
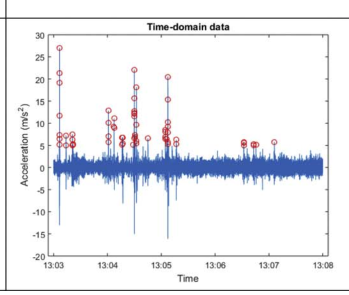
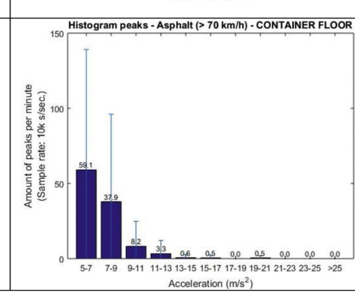
transport shocks with using a free-fall device by artificially changing the damping ratio. In research, often a free-fall device or impact testing is used to simulate shocks to which products are exposed to (e.g. shocks on apples (Gołacki et al., 2009)). By adapting the design of shock simulation tests to the observed phenomena measured during transport, both a better validation of the design of the experiments and more representative results can be guaranteed.

3.3. Analysis of selected events – train and truck transport

In Fig. 3a–d, time-domain vibration plots of vibration and shock phenomena measured on a train transport are presented. Fig. 3a illustrates the vibration pattern when the train accelerates. By accelerating after standing still, the tension of the couplers between the railcars is increased. The inverse phenomenon, in which tension between the railcars is lowered, occurs when braking or coming to a standstill after traveling. Therefore, similar shock phenomena are observed when accelerating after standing still and when stopping and coming to a standstill. The interaction of the couplers not only shapes the vibration spectra, it also adds complexity to the analysis of the measured vibrations and shocks. When traveling over a railway network, trains frequently have the possibility to change tracks. By passing track switches, the train is exposed to a shock of which the magnitude depends on the velocity of traveling. In a railway yard with multiple switches, multiple shocks of high magnitude are generated (although trains are required to decrease speed – Fig. 3b). Also, trains that pass in the opposite direction can generate an elevation in the magnitude of the vibrations. In Fig. 3c, vibration measurements were performed when standing still while a train passes in the opposite direction. Results indicate that the magnitude of the vibrations is elevated by approximately $1\,m/s^2$. When a train travels at full speed (approx. 90 km/h), fewer shocks occur but the vibration level is significantly high. In Fig. 3d, a histogram of the measured time-domain vibration samples higher than $5m/s^2$ was made with the objective to identify the number of shocks that occur per minute. The variation in transient phenomena also causes substantial confidence intervals of the histograms of the measured time-domain vibration samples. The latter histogram can be used by food scientist and packaging engineers to design experimental shock tests.

Different vibration and shock patterns are present during truck transport (air-spring suspension). Shocks of high amplitude are frequently measured during transport, which is caused by road unevenness, potholes or speed control humps. Research findings also indicate that start-stop moments in which the driver needs to brake or accelerate are not the main cause of the occurrence of shocks. However, during start-stop moments the truck is mostly located on or close to crossroads, which frequently induce a change in pavement type (with potholes or road unevenness). In Table 1, time-domain vibration and shock patterns when driving by truck over different Belgian road types are

Table 1
Characterization of Belgian roads (vibration response; truck with air-ride suspension).

Road surface (speed segmentation)	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]	Shocks: Histogram of time-domain vibration samples (> 5 m/s^2) – Peak –
Asphalt pavement (< 30 km/h)			
Cobblestones (< 30 km/h)			
Asphalt pavement (30-70 km/h)			
Concrete pavement (30-70 km/h)			
Asphalt pavement (> 70 km/h)			

characterized. The road network is segmented by the speed of traveling and road type to identify vibration and shock patterns when driving over the most common Belgian urban roads, secondary roads, and highways. The results are summarized as follows.

- *Asphalt roads (< 30 km/h)* induce the lowest RMS-values of the measured time-domain vibration signals (Avg. RMS-values of the vibration signals in time-domain over 1-s intervals: 0.14 m/s^2 ± 0.05 m/s^2). Nearly no shocks are observed when traveling over the specified road section. Furthermore, from the cumulative distribution function (CDF) of the RMS-values of the vibration signals in time-domain can be derived that longitudinal vibrations are of remarkable amplitude. The latter effect can be attributed to braking and acceleration of the truck, which is often unavoidable in road sections with the speed limit at 30 km/h.

– When driving over *cobblestones (< 30 km/h)*, vibration and shock patterns are most severe (Avg. RMS-values of the vibration signals in time-domain over 1-s intervals: 5.46 m/s^2 ± 1.94 m/s^2).

– *Asphalt roads (30–70 km/h)* induce lower RMS-values of the measured time-domain vibration signals than concrete pavement (30–70 km/h), since the average is $0.47\ m/s^2 \pm 0.14\ m/s^2$.
– Roads with *concrete pavement (30–70 km/h)* have average RMS-values of the vibration signals in time-domain of $1.32\ m/s^2 \pm 0.54\ m/s^2$. Shocks are more frequently observed when driving over concrete pavement (30–70 km/h) than when driving over asphalt roads (30–70 km/h and > 70 km/h). Furthermore, when driving over concrete pavement lateral vibrations are more severe than compared to other pavement types and speed limits. The latter effect can be attributed to road unevenness, which is inherent to the pavement type. For instance, broken concrete pavement can induce left or right truck wheels to generate vibrations of different or higher amplitude. Similar vibration patterns that generate lateral vibrations can be found when driving over metal joints, as observed by Lu et al. (2008).
– Highways, i.e. *asphalt roads (> 70 km/h)*, can be characterized by RMS-values of the vibration signals in time-domain of highways with average of $0.77\ m/s^2 \pm 0.21\ m/s^2$.

3.4. Discussion on the design of transport simulations and experiments with respect to food products

Literature reports of different food products that suffer from quality deterioration during transport. Wasala, Dharmasena, Dissanayake, & Thilakarathne (2015) indicate that between 20 and 30% of the initial harvested bananas is allocated to waste due to transport vibrations and shocks (study conducted in Sri Lanka). Also, kiwis (Tabatabaekoloor, Hashemi, & Taghizade, 2013), watermelons (Shahbazi, Rajabipour, Mohtasebi, & Rafie, 2010), tangerines (Jarimopas, Singh, & Saengnil, 2005), eggs (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003), strawberries (La Scalia et al., 2015) and grapes (Fischer, Craig, & Ashby, 1990) face similar problems. A recent study even reports the sensitivity of beer, i.e. the formation of haze, to transport vibrations (Janssen et al., 2014). The largest and most developed research domain with respect to the current topic is the losses of apples due to postharvest transportation (Acıcan, Alibaş, & Özelkök, 2007; Gołacki et al., 2009; Van Zeebroeck et al., 2007). According to recent estimates, a loss rate between approximately 10% and 25% is typically measured in industry (study conducted in Belgium) (Van Zeebroeck et al., 2007). The loss rate is attributed to the appearance of bruises, but also the presence of minor mechanical injuries (punctures, cuts, and abrasions) can later on lead to fungal diseases. Postharvest pathogens such as gray mold (Botrytis) or blue mold (Penicillium) are able to enter the fruit by the dead or wounded tissue and can contaminate the rest of the fruit. Vibrations and shocks occurring during transports are a major contributor to these bruises and punctures on apples, and, as a consequence, need to be avoided (Van Zeebroeck et al., 2007).

Food scientists employed different designs of experiments to simulate transport, to estimate the food losses or the damage to fruits, and the importance of different variables (e.g. apple species). Chonhenchob et al. (2009) and Jarimopas et al. (2005) performed an actual food transport, measured the vibrations, and visually inspected the quality damage to the food products. The current methodology is the most accurate in identifying the damage to fruits, however also lacks the feasibility to adapt the experimental variables (e.g. temperature). Therefore, transport simulations in a dedicated and controlled environment in which repeated experiments can be executed better identify research findings. However, most of the experimental studies focus only on vibrations without investigating the impact of transient vibrations or shocks and, therefore, are incomplete, e.g. Berardinelli et al. (2003), La Scalia et al. (2015), Wasala et al. (2015). Other studies, such as Acıcan et al. (2007) and Gołacki et al. (2009) performed a free fall test of individual apples, respectively a crate of apples, of the drop height of 5 cm, respectively 30 cm, without benchmarking the drop height with shock results during transport. The current study can fill this research gap with providing accurate data, and a methodology to develop a streamlined and benchmarked design of vibration and shock experiments in order to simulate transports.

The researchers of the current study are aware that food scientists are dependent on the vibration equipment that can be adopted for their experimental research. Predominantly shakers that can generate vibrations in a single dimension are adopted by food scientists[2] and, therefore, the developed procedure of transport simulations is based on the latter insight.

– In an initial phase, the transmissibility of the vibrations between the wooden pallet and the highest stacked food packages should be studied. This can be performed in a transport setting (Soleimani & Ahmadi, 2014) or in a simulation setting (La Scalia et al., 2015). This explorative experiment is recommended since vibrations in the highest stacked crates can be attenuated due to the stacking (O'Brien et al., 1965).
– Consecutively, the individual impact of vibrations on the quality of the food product should be studied. Moreover, the effect of individual frequencies (Fischer et al., 1990) or, if possible, the effect of different PSDs (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003) should be derived. For instance, an extreme vertical vibration of $1.5\ m/s^2$ (RMS – Table 1) that was observed during truck transport over asphalt pavement (> 70 km/h) can be imposed.
– In a dedicated shock test, the effect of transient vibrations on the quality of the food product should be identified. A free fall test should be designed in which the drop height and the material of the ground surface should be iteratively identified by measuring the acceleration on the food package. As a consequence, the damping ratio and the frequency of the damped oscillation that is observed during transport can be approximated[3] From the results in Table 1, an input signal can be selected. For instance, when simulating shocks during truck transport over asphalt pavement (> 70 km/h) 8 shocks per minute with a peak acceleration of approx. $10 \pm 1\ m/s^2$ should be imposed, 3 shocks per minute of approx. $12 \pm 1\ m/s^2$, and 1 shocks per minute of approx. $14 \pm 1\ m/s^2$. The samples of a smaller amplitude (acceleration bins) are considered the damping phenomena and are not imposed as individual shocks.
– In a last experiment, the food product should be sequentially exposed to vibrations and shocks (e.g. cycles with 20 min of vibrations and 10 min of shocks). Since the measurements of the current paper identify the frequency of the transient vibrations that occur during transport (i.e. the number of shocks per minute of traversed road), the same shock pattern can be simulated. The reason for imposing both vibrations and shocks in one experiment is the possible multiplicative harmful effect on the food product. For example, shocks could cause punctures, cuts and abrasions on apples, which could provoke the vibrations to generate additional damage.

A vibration test in which the food product is exposed to both vibrations and shocks will produce more reliable results with respect to food losses, mechanical damage or decrease in quality. Additionally, the significance of the effect of the investigated parameters (e.g. apple type, temperature) is better determined since a more realistic transport simulation is performed. Furthermore, the findings in Table 1 provides the food scientist data that make able to simulate transport over different road segments comparable with real-life transport.

[2] Shaking in the vertical dimension is recommended due to higher amplitude of the vertical relative to the lateral and longitudinal vibrations in transport (Fig. 1 a and c).

[3] The drop height is dependent on the mass as well as the packaging material of the food package. Therefore, no fixed drop height can be recommended to food scientists.

4. Conclusions

From the Fourier spectra reported in this study, and the extensive time-domain analysis of the measured vibration and shock patterns that are present when traveling over the Belgian road and railway network, the following main conclusions are deduced.

– Transient phenomena frequently occur in both truck and train transport, which cannot be observed or derived from the averaged PSD plots. A time-domain event analysis indicated that railcars are exposed to shock phenomena when riding over switches in a railway yard, accelerating after standing still and coming to a standstill after braking. During truck transport, road unevenness has a significant impact on the measured vibrations and shocks. Traveling over cobblestones, and concrete pavement generates the most severe RMS-vibrations and shocks. The dependency of vibrations, shocks and the velocity of the truck is also illustrated.
– The damping ratio (β) of shocks measured in the container of the truck and on the railcar is on average 0.08 ± 0.02, respectively 0.05 ± 0.02 (frequency of the damped oscillation 153 ± 148 Hz, respectively 1559 ± 1970 Hz). By artificially adapting the impact and, as a consequence, better approximating the damping ratio and the frequency of the damped oscillation when executing drop tests, food scientists can realistically simulate transient phenomena that occur during transport.

The authors of the current research suggest the research domain to also report on shocks that occur during transport. Furthermore, in future research, food scientists and package engineers can use the insights of this paper to perform advanced simulation testing incorporating both vibrations and shocks. A better design of the simulation test will allow products to be tested on the extreme levels of vibrations and shocks they are exposed to during transport. The streamlined method developed in the current study will result in more reliable results with respect to food losses and food damage, and a better identification of the significance of the tested parameters.

Acknowledgements

The research performed in this paper is part of a research project investigating the impact of vibrations and the interaction with temperature on the beer flavor stability and the sensorial quality of beer. Special acknowledgments go to the sponsor of the research contained in this paper (IWT-VIS/Brewers-120786).

Appendix A

Specifications vibration measurements (truck)

Transport 1: truck + trailer 3 axles (1 + 2) [MAN TGA SH265 FNLC] (length trailer 7.5 m − weight full capacity 26 tons − end of transport 15 tons) − extra trailer 2 axles [Renders RMAC 9.9N] (length trailer 7.5 m − 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 m − 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 m − 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 m − weight full capacity 39 tons − end of transport 16 tons).

The authors of current research had the objective to measure the most extreme vibrations. Therefore, the measuring devices were located on top of a wooden pallet between one forth and one third of the rear end of the (extra) trailer length (respectively 1.8 m − 2.5 m [transport 1], 1.8 m − 2.5 m [transport 2], 3 m − 4.5 m [transport 3 and 4]).

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 order 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.

Specifications vibration measurements (train)

Railcar: Max. 90 tons (of which 24 tons cargo), In total 15–25 wagons

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"The influence of the interaction between vibrations and temperature, simulating transport, on the flavor of beer"

ABSTRACT

BACKGROUND: Beer flavor stability is important to brewers due to the increased global demand for beer. Increasing export lead to prolonged periods of transportation and storage and cause fresh flavor deterioration. Therefore, the effect of different temperatures in combination with vibrations on beer quality is examined. Beer was exposed to vibrations (50Hz, $15 m/s^2$, simulating transport) at 5°C, 30°C and 45°C for 4 days and (half the samples) aged for 60 days at 30°C.
RESULTS: Results indicated decreased oxygen concentrations due to elevated temperature and vibrations. There was no effect ($P>0.05$) on color and limited effect of temperature and vibrations on iso-α-acids. The parameters temperature and vibrations have a significant influence ($P<0.05$) on aldehydes concentrations, i.e. total aldehydes, and especially '2-methylpropanal', '2-methylbutanal' and 'furfural'.
CONCLUSIONS: The impact of vibrations on the aldehydes concentrations was substantial when subjected to elevated temperature. Furthermore, a forced aging test of shorter duration than traditional methods might be developed.

Keywords
Beer flavor stability, vibrations, temperature, beer quality

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1. Introduction

Controlling beer quality is crucial in the brewing industry since export is becoming more important due to market globalization[1]. The taste, aroma, mouthfeel and appearance of beer change over time and results in an irreversible and undesirable quality degradation. Variable storage and transport conditions, which the brewer is not always able to control, are important contributors to the beer aging process (next to the raw materials and the beer brewing process). In particular, exposure to elevated temperature and light attribute to a decrease in beer quality according to literature[1,2]. However, Janssen et al. (2014)[3] suggested vibrations during transport might also negatively influence the beer quality. In a first vibration experiment, the authors indicated not only the accelerated growth of molds due to vibrations contaminating food products, but also the development of turbidity in beer. Since turbidity is only one parameter related to beer quality, an essential in-depth analysis on the influence of vibrations on the sensorial and chemical quality of beer is required and will be, as a consequence, the topic of this paper.

Flavor instability, a complex phenomenon that even after 30 years of research is not completely understood, causes beer to age and induces diverse chemical reactions to generate compounds that alter the sensorial properties of beer[2]. Several parameters can indicate beer aging, i.e. a change in aldehydes, iso-α-acids, permanent haze and color[1,2,4,5]. Furthermore, quality degradation of beer is mostly initiated by oxidative reactions that affect the formation or degradation of flavor active components[1,6,7]. Therefore, the freshness of beer decreases with higher temperatures, increasing the rate of reaction and thereby increasing the amount of oxidative and non-oxidative chemical reactions that take place[1,2]. Beer quality and stability are also sensitive to light. Exposure of beer to light causes the development of an offensive taste and a skunky odor termed the "lightstruck flavor". The sensitivity of iso-α-acids to the light can be indicated as the main contributor to photodegradation of beer or its 'lightstruck flavor'[8].

The influence of transport vibrations and shocks on the beer flavor quality is a research gap that needs to be explored. Therefore, it is essential to identify the vibrations beer bottles are exposed to and, subsequently, the impact of the vibrations on the beer flavor quality. In prior research, the exact vibrations beer bottles are exposed to are identified[9]. Moreover, vibration patterns diverge over the different modes of transport (i.e. truck, ships) but are also altered by the packaging and stacking of beer crates. Two hypothesizes might describe this relation between vibrations and the beer flavor quality:

Hypothesis 1: vibrations and shocks increase molecular energy and, as a consequence, increase the reaction rate of the ageing mechanism (reaction kinetics)

Hypothesis 2: vibrations and shocks could raise the uptake of oxygen from the beer bottleneck into the beer (more flavor active components or off-flavors can be formed/degraded)

The objective of the current study was to experimentally identify the influence of vibrations (in combination with temperature) on the beer quality. By performing an extensive chemical analysis of the beer, not only the impact of the vibrations during transport on beer aging can be assessed, the results can also be benchmarked with the single influence of elevated temperature. Also, the influence of the duration of the vibrations on the beer quality was studied. The scope of the current explorative study is limited to the influence of vibrations and temperature on a limited number of beers brewed in Belgium.

2. Material and methods

Experimental design

In the current research, the influence of one selected vibration in combination with different temperatures and the influence of duration of vibrations on the beer quality is studied. A design of experiments was built prior to executing the experiment and is described.

i. Temperature

Current practice by Belgian and foreign breweries is to transport and store beer under uncooled conditions and, therefore, temperature is a major contributor to flavor instability of (exported) beer. During transport, container temperature can rise up to 55°C under influence of direct sunlight[10] with only the beer packaging that can delay but not prohibit the beer from heating up[11]. In the current vibration experiment, the following temperatures were selected 5°C, 30°C and 45°C, and the ambient temperature of 25°C ± 2°C. Additionally, after the vibration experiment, half of all vibrated and non-vibrated samples were aged for 60 days at 30°C, while the other half of the samples were stored during the same period in 0°C in order to simulate storage. Simulating storage (conform the method used by Jaskula-Goiris et al. (2011)[12] and Malfliet et al. (2008)[13]) was developed in order to see if there is a difference in beer quality with and without vibrations after a prolonged storage. It was possible that delayed aging reactions take place after the vibration experiment is completed (and when exposed to an elevated temperature).

ii. Duration of the vibrations

Beer is mainly transported by truck within the European mainland and by ship when exported overseas. The duration of transport within Europe can be limited to 3 to 4 days before reaching its destination, while by ship the duration can be extended to 30 days. However, the vibration load on cargo during ship transport is less severe when compared with trucks (lower in acceleration < 1 m/s^2 (0-peak))[14]. Therefore, the duration of the vibration experiment for individual setups in the current research was fixed to 22, 38 and 90 hours.

iii. Vibrations

The input vibrations, the stacking and packaging of the beer bottles determine the major contributing frequencies beer bottles are exposed to[15]. However, vibration experiments are regularly conducted by imposing vibrations of one specific frequency and acceleration (due to the specifications of the shaking equipment)[16]. Therefore, the optimal vibration signal (frequency) for the current experiment was identified based on both the occurrence of the vibration pattern during transport and the sensitivity of the beer flavor quality to the specified frequency. Therefore, in the current experiment that experimentally tests the interaction effect between temperature and vibrations, test samples were subjected to vibrations of 50 Hz and 15 m/s^2 (0-peak) in order to expose the test samples to extreme conditions (conform the method used by Paternoster et al. (2017)[15]).

iv. Beer samples

In the current experiment a blond beer without refermentation after bottling was used (chemical characteristics in Table 1). The batch of beer used in the experiment was brewed in the KULeuven technology campus Ghent to optimally control the brewing process and to identify the chemical parameters. Since beer aging relates to the uptake of oxygen, half of all samples were bottled inhibiting oxygen under the metal cap (bottled with O_2 scavengers) while in the other samples no measures were taken to prevent oxygen under the metal cap (bottled by hand without overfoaming). This methodology enables to identify the influence of oxygen in the beer aging process when being exposed to vibrations. In Table 1, an overview is presented of the oxygen concentrations (TPO, HSO, DO) measured directly after bottling.

Table 1: Oxygen concentration after bottling – chemical characteristics beer samples

	Samples with higher initial oxygen content		**Samples with lower initial oxygen content**	
TPO after bottling	Avg. 1265 ppb (Std. dev. 185 ppb)		Avg. 523 ppb (Std. dev. 382 ppb)	
HSO after bottling	Avg. 1207 ppb (Std. dev. 180 ppb)		Avg. 472 ppb (Std. dev. 380 ppb)	
DO after bottling	Avg. 58 ppb (Std. dev. 44 ppb)		Avg. 51 ppb (Std. dev. 38 ppb)	
Chemical characteristics	pH:	4.44	Eorg. (°P)	12.43
	Alc. (v/v%)	5.11	RDF (%)	63.71
	Alc. (w/w%)	4.00	ADF (%)	77.00
	Er (°P)	4.70	Cal. (kJ/100 ml)	188.19
	Ea (°P)	2.86		
Legend: TPO (Total Package Oxygen), HSO (Headspace Oxygen), DO (Dissolved Oxygen), pH (acidity), Alc. (Alcoholic volume or weight in %), Er (realistic extract), Ea (Apparent extract), Eorg. (Original extract), RDF (Realistic degree of fermentation), ADF (Apparent degree of fermentation), Cal. (Caloric content)				

v. Chemical tests

The samples were analyzed in the KULeuven technology campus Ghent and chemically profiled. The chemical parameters [Specifications in Appendix (A)] used in this study are:

- Oxygen concentrations: (TPO – Total package oxygen –, HSO – Headspace oxygen –, DO – Dissolved oxygen –)

  Determination of oxygen concentrations:

  Oxygen in bottled beer is determined using the 'Haffmans Inpack TPO/CO_2 meter Type c-TPO'. The measurement is performed in a sealed bottle and the principle is based on O_2 dependent fluorescence of the sensor. The instrument measures dissolved oxygen (DO) and headspace oxygen (HSO). The total package oxygen (TPO) is calculated as the sum of DO and HSO values. All values are calculated on the beer volume in the package and are given in µg/l.
- Beer color: IOB method: 9.1[17];
- Iso-α-acids: (*trans*-isocohumulone, *cis*-isocohumulone, *trans*-isohumulone, *cis*-isohumulone, *trans*-isoadhumulone, *cis*-isoadhumulone, total iso-α-acids, T/C-ratio)

  UPLC determination of iso-α-acids:

  UPLC separations of iso-α-acids were performed on an Acquity UPLC (Waters, Milford, USA), consisting of a PDA detector, column heater, sample manager, binary solvent delivery system and an Acquity UPLC HSS C18 1.8µm column (2.1 i.d. × 150 mm; Waters, USA). Data reprocessing was done using Empower 2 software. Chromatographic conditions were: eluent A: milli-Q water adjusted to pH 2.80 with H_3PO_4 (85%, Merck, Darmstadt, Germany); eluent B: HPLC-grade CH_3CN (Novasol, Belgium). Elution: isocratic using 52% (v/v) solvent B and 48% (v/v) solvent A. Analysis time: 12 min. Flow rate: 0.5 $mL.min^{-1}$. Column temperature: 35°C. UV detection: 270 nm (iso-α-acids). The *trans*/*cis* iso-α-acids ratio (T/C-ratio) was based on the measured concentrations of *trans*- and *cis*-isocohumulone and *trans*- and *cis*-isohumulone, i.e. the sum of the two trans-parameters devided by the sum of the two cis-parameters[18].

- <u>Aldehydes</u>: (2-methylpropanal, 2-methylbutanal, 3-methylbutanal, hexanal, furfural, methional, benzaldehyde, phenylacetaldehyde, (E)-2-nonenal, total aldehydes)

  GC-MS (gas chromatography mass spectrometry) determination of aldehydes:

  Volatile aldehydes in beer were determined according to Vesely et al. (2003)[19], using headspace-solid phase microextraction (HS-SPME) with on-fibre PFBOA (*o*-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine) derivatization and capillary gas chromatography/mass spectrometry (CGC/MS) (Dual Stage Quadrupole (DSQ™ II) GC/MS system, Interscience Benelux). The DSQ™ II was coupled to a Thermo Trace GC Ultra (Interscience Benelux) equipped with a CTC-PAL autosampler (including SPME sampling), a split/splitless injector with a narrow glass inlet liner (0.5 ml volume), and a RTX-1 fused-silica capillary column (40 m × 0.18 mm i.d. × 0.2 µm film thickness, Restek, Interscience Benelux). The complete set of samples is analysed under the same conditions. Furthermore, recalibration of the device was regularly conducted during the analysis. Data reprocessing was done by the XCalibur™ data system (Thermo Electron Corporation).

vi. Experimental setups

The vibration experiment in this study was conducted in collaboration with the company Bosal (Research and development subsidiary, Dellestraat 20 - 3560 Lummen [Belgium]). Bosal is a leading manufacturer of exhaust systems and provided the project with a dedicated experimental environment in which a large pneumatic shaker was available that was used for executing the vibration test (type MTS 258.05, max. amplitude 50 mm, max. force 50 kN) (Figure 1). A thermostatic cabinet was built over the shaker frame and enabled to perform a vibration experiment while exposing the beer samples to a decreased (5°C) or an elevated temperature (30°C, 45°C). In total, 24 bottles of beer were installed in an aluminum shaker frame, specifically built for this experiment. Furthermore, 24 bottles of beer were placed next to the shaker but inside the insulated cabinet to expose the samples to the same heat as the beer samples on the shaker. Before the start of every setup of the experiment, the climate cabinet was conditioned for two hours. A plastic crate with 24 beer bottles, the reference samples, was placed next to the shaker (inside the dedicated experimental room but outside the climate cabinet) and was exposed to the ambient temperature (25°C ± 2°C). An accelerometer was attached to the beer bottleneck and to the shaker plate to iteratively adapt the generated vibration signal to the preferred pattern or frequency. Since the facilities of Bosal were located approximately one hour driving from the laboratory of KULeuven technology campus Ghent, the samples were transported in an isomo box filled with cool elements to protect from heat. An overview of all setups is presented in Table 2.

Figure 1: Experimental equipment (beer samples in the climate cabinet // beer samples on the shaker frame in the climate cabinet // beer samples in ambient temperature)

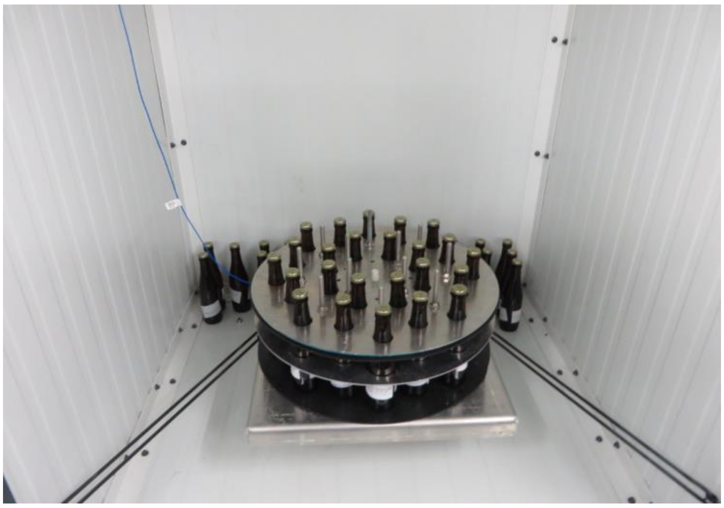


Table 2: Overview of experimental setups

	Shaker in thermostatic cabinet	Climate cabinet	Ambient temperature
Setup 1*	- 90h of vibrations at temperature 5°C	- 90h at temperature 5°C	- 90h at ambient temperature 25°C
Setup 2*	- 90h of vibrations at temperature 30°C	- 90h at temperature 30°C	- 90h at ambient temperature 25°C
Setup 3*	- 90h of vibrations at temperature 45°C	- 90h at temperature 45°C	
Setup 4*	- 90h of vibrations at temperature 45°C	- 90h at temperature 45°C	
Setup 5*	- 22h of vibrations at temperature 45°C	- 22h at temperature 45°C	- 22h at ambient temperature 25°C
Setup 6*	- 22h of vibrations at temperature 45°C	- 22h at temperature 45°C	- 22h at ambient temperature 25°C
Setup 7*	- 38h of vibrations at temperature 45°C	- 38h at temperature 45°C	- 38h at ambient temperature 25°C

*Before the start of each test, the cabinet was conditioned for 2 hours at the selected temperature. After the vibration experiment, half of all vibrated and non-vibrated samples were aged for 60 days in 30°C, while the other half were stored at 0°C to simulate storage conditions after transport. Some of the setups were repeated in order to reduce the degrees of freedom of the experiment and to enable a thorough statistical analysis.

Data Analysis

Multiple parameters may have an influence on the chemical output parameters, i.e. the influence of temperature and vibrations, the duration of vibrations, the aging after the vibration test, and the influence of samples with and without inhibiting oxygen after bottling. Therefore, a mixed model that is able to integrate and estimate the influence of random effects (e.g. bottles together in climate cabinet, bottles together in the setup and crate) was built in the statistical software JMP PRO12 (significance level of 5%).

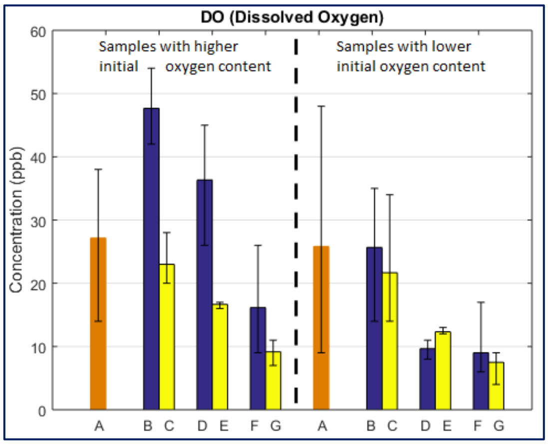
3. Results

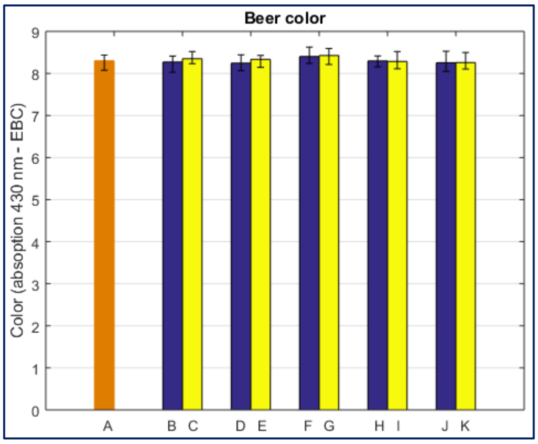
i. Oxygen concentration

An uptake of oxygen in beer results in the formation or degradation of flavor active components. As a consequence, the concentration of dissolved oxygen can be indicative of the flavor change that is taking place or that took place in the past. In the current experiment, the oxygen concentration decreased significantly for both samples with higher and lower initial oxygen content when increasing the exposed temperature (Figure 2a). Figure 2a indicates that apart from temperature, vibrations further facilitate the uptake of oxygen, which indicates there is strong evidence hypothesis 2 is correct (and which does not induce the incorrectness of hypothesis 1). Similar results were found for HSO and TPO measurements [Data in Appendix (B)]. The measured oxygen concentrations for DO, HSO and TPO of samples with higher and lower initial oxygen content reach similar levels after the vibration treatment in combination with an elevated temperature at 45°C. After 60 days of aging at 30°C, a significantly decreased oxygen concentration was measured for all tested samples including the reference samples (data not shown). In conclusion, oxygen concentrations have significantly decreased under a regime of vibrations and temperature.

Figure 2a: Measured oxygen concentration (DO) as a function of temperature, vibrations and time (after the vibration experiment the samples were stored for 60 days at 0°C)

Figure 2b: Measured beer color as a function of temperature, vibrations and time (after the vibration experiment the samples were stored for 60 days at 0°C)





Legend: A: samples stored for 90hrs. at 25°C / B: samples stored for 90hrs. at 5°C / C: samples stored for 90hrs. at 5°C while shaking / D: samples stored for 90hrs. at 30°C / E: samples stored for 90hrs. at 30°C while shaking / F: samples stored for 90hrs. at 45°C / G: samples stored for 90hrs. at 45°C while shaking / H: samples stored for 38hrs. at 45°C / I: samples stored for 38hrs. at 45°C while shaking / J: samples stored for 22hrs. at 45°C / K: samples stored for 22hrs. at 45°C while shaking

BEER COLOR* There was no statistical significant difference observed between the samples with higher and lower initial oxygen content, and, therefore, all samples are included in the former graph. The average with confidence intervals (minimum and maximum value) was calculated for each setup.

ii. Color

A change in beer color is a visual characteristic that can be attributed to the formation of Maillard reaction products and the oxidation of polyphenols during beer aging. In the current experiment, no statistically significant change of the measured beer color was observed when samples of the different setups were compared directly after the vibration experiment (Figure 2b), nor after the vibration experiment and aged at 30°C for 60 days.

iii. Iso-α-acids

Literature reports of the decrease in concentration of iso-α-acids when beer is subjected to an increased temperature[2,20]. However, the results of the current experiment indicate that the impact of the exposure to an elevated temperature and vibrations in a short period of time (90 hrs.) is limited with respect to total iso-α-acids. Moreover, the mixed model that was made to evaluate the explanatory power of the tested variables indicated that only temperature (p=0.025) has a small but significant effect on the total iso-α-acids. A more detailed investigation of the results of the individual *trans*- and *cis*-iso-α-acids (Table 3) indicates that the cis-isomers are stable and the trans-isomers are sensitive to elevated temperature (especially *trans*-isocohumulone and *trans*-isohumulone at 45°C). There was no statistically significant effect observed due to vibrations on individual iso-α-acids. The T/C-ratio, on the contrary, also takes into account the stable and unstable nature of the cis- and trans-isomers[18] and, therefore, is a better indicator than total iso-α-acids for the possible harmful effect of temperature and vibrations[18,21]. With respect to the T/C-ratio, the single effect of temperature (p=0.0002) and the quadratic effect of temperature is significant (p=0.0017). The quadratic effect of temperature on beer quality is described by the Arrhenius equation and the influence of temperature on reaction kinetics (experimentally assessed by various authors in the literature[1,2]). The single effect of vibrations on the T/C ratio is not significant (p=0.1317) (significance level of 5%). The interaction effect between temperature and vibrations is significant (p=0.0473) in the mixed model, although the significance of the interaction effect should be interpreted with caution since the main effect, vibrations, was not significant. After the aging period of 60 days at 30°C, the results indicate no statistically significant differences between the samples when comparing the T/C-ratio over the different setups.

Table 3: A more detailed investigation of the results of the individual *trans*- and *cis*-iso-α-acids

Avg. x 10^{-3} g/L (STD)	*Trans*-isocohumulone	*Cis*-isocohumulone	*Trans*-isohumulone	*Cis*-isohumulone	*Trans*-isoadhumulone	*Cis*-isoadhumulone
90hrs. in 25°C	1.26 (0.02)	6.26 (0.11)	0.78 (0.03)	4.34 (0.11)	0.23 (0.07)	1.13 (0.06)
90hrs. in 5°C	1.24 (0.02)	6.25 (0.03)	0.80 (0.02)	4.34 (0.05)	0.28 (0.03)	1.15 (0.05)
90hrs. in 5°C shaking	1.28 (0.03)	6.37 (0.17)	0.82 (0.01)	4.38 (0.10)	0.21 (0.07)	1.18 (0.05)
90hrs. in 30°C	1.21 (0.01)	6.23 (0.12)	0.77 (0.01)	4.30 (0.06)	0.19 (0.06)	1.14 (0.05)
90hrs. in 30°C shaking	1.24 (0.07)	6.36 (0.36)	0.80 (0.06)	4.41 (0.23)	0.21 (0.06)	1.15 (0.05)
90hrs. in 45°C	1.07 (0.03)	6.11 (0.13)	0.68 (0.04)	4.24 (0.17)	0.24 (0.02)	1.12 (0.06)
90hrs. in 45°C shaking	1.06 (0.03)	6.16 (0.14)	0.66 (0.02)	4.28 (0.14)	0.24 (0.01)	1.15 (0.05)

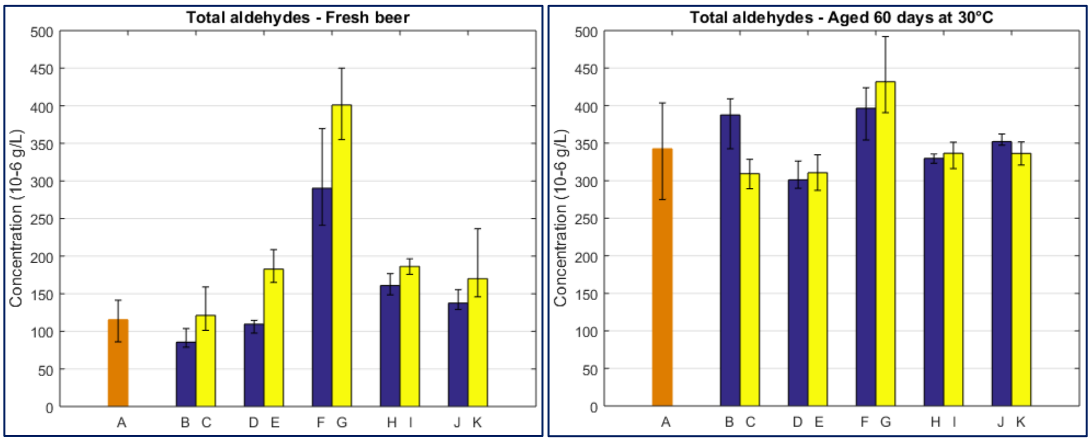
* There was no statistically significant difference observed between the samples with higher and lower initial oxygen content, and, therefore, all samples are included in the former graph.

iv. Aldehydes

In contrast to color and iso-α-acids, aldehydes indicate to be more sensitive when exposing the tested beer samples to the different temperatures in combination with vibrations. Moreover, the aldehydes '2-methylpropanal', '2-methylbutanal' and 'furfural' change considerably in concentration under an elevated temperature and vibrations while the other aldehydes do not increase significantly over all setups. In Figures 4a and 4b, the concentration of the total aldehydes measured directly after the vibration experiment and after an aging period of 60 days in 30°C is displayed. Also, a more detailed view of the results of '2-methylpropanal', '2-methylbutanal' and 'furfural' is presented in Table 4. Figure 4a indicates the exponential effect of exposure to elevated temperature and the additive effect of vibrations that further increase aldehyde concentrations. The effect of vibrations on the aldehydes concentration is visible at all temperatures (5°C, 30°C and 45°C) and all durations (90hrs, 38 hrs. and 22hrs.). Furthermore, the figure also indicates that the higher the exposure of the temperature is, the more pronounced is the effect of vibrations on beer quality. The latter indicates the possible presence of an interaction effect between temperature and vibrations.

The results of Figure 3a demonstrate a significant increase of the total aldehydes concentration due to vibrations when the samples are exposed to an elevated temperature of 45°C in combination with vibrations during 90 hrs. However, after an aging period of 60 days at 30°C, no significant difference is observed between the total aldehydes concentrations of the reference samples (ambient temp. 25°C) and the other samples (Figure 3b). Figure 3b and Table 4 indicates that the total aldehydes concentration possibly saturates, i.e. the samples that have been vibrated under a regime of 45°C for four days only increase marginally in total aldehydes concentration after aging for 60 days. The latter also implies that the total aldehydes concentration reached after 60 days of exposure to 30°C can be approximated by 90 hours of exposure to vibrations and an elevated temperature of 45°C. As a consequence, there is potential to further develop the latter method into a beer aging test that can be used to assess the chemical stability of beer. In current methods, beer is predominantly aged at 30°C for two to four months, since the taste of beer exposed to 30°C best represents storage conditions in contrast to aging over a shorter time span with a higher temperature. A shorter duration of the test improves the number of analyses the beer scientist is able to perform, and, therefore, results in a significant reduction of time and money. However, further analysis is required to validate the possibility to substitute the beer aging method.

Figure 3a: Total aldehydes as a function of temperature, vibrations and time (after the vibration experiment the samples were stored for 60 days at 0°C - fresh beer -)
Figure 3b: Total aldehydes as a function of temperature, vibrations and time (after the vibration experiment the samples were aged for 60 days at 30°C)



Legend: A: samples stored for 90hrs. at 25°C / B: samples stored for 90hrs. at 5°C / C: samples stored for 90hrs. at 5°C while shaking / D: samples stored for 90hrs. at 30°C / E: samples stored for 90hrs. at 30°C while shaking / F: samples stored for 90hrs. at 45°C / G: samples stored for 90hrs. at 45°C while shaking / H: samples stored for 38hrs. at 45°C / I: samples stored for 38hrs. at 45°C while shaking / J: samples stored for 22hrs. at 45°C / K: samples stored for 22hrs. at 45°C while shaking
* There was no statistical significant difference observed between the samples with higher and lower initial oxygen content, and, therefore, all samples are included in the former graph. The average with confidence intervals (minimum and maximum value) was calculated for each setup.

Table 4: A more detailed investigation of the results of '2-methylpropanal', '2-methylbutanal', and 'furfural' (after storage for 60 days at 0°C - fresh beer - and after aging for 60 days at 30°C)

Avg. x 10^{-6} g/L (STD)	2-methylpropanal (fresh beer)	2-methylpropanal (aged 60d. at 30°C)	2-methylbutanal (fresh beer)	2-methylbutanal (aged 60d. at 30°C)	Furfural (fresh beer)	Furfural (aged 60d. at 30°C)
90hrs. in 25°C	17.75 (2.03)	73.39 (6.54)	3.06 (0.26)	5.17 (0.64)	24.86 (4.68)	189.07 (27.57)
90hrs. in 5°C	11.63 (0.45)	82.43 (12.85)	2.65 (0.09)	5.47 (0.28)	10.46 (0.59)	199.65 (14.22)
90hrs. in 5°C shaking	12.34 (0.88)	64.43 (1.90)	2.63 (0.18)	4.74 (0.16)	12.33 (1.40)	177.14 (13.32)
90hrs. in 30°C	18.83 (1.09)	70.75 (2.45)	3.05 (0.19)	4.74 (0.17)	26.73 (1.35)	166.63 (5.74)
90hrs. in 30°C shaking	23.74 (1.03)	67.51 (2.54)	3.61 (0.32)	4.96 (0.25)	39.93 (1.97)	172.35 (23.40)
90hrs. in 45°C	59.22 (6.85)	92.84 (7.10)	4.35 (0.16)	5.94 (0.52)	143.62 (17.77)	253.36 (28.68)
90hrs. in 45°C shaking	79.64 (7.69)	95.15 (8.92)	4.89 (0.36)	6.04 (0.61)	217.14 (15.04)	314.14 (57.02)

* There was no statistically significant difference observed between the samples with high and low oxygen content, and, therefore, all samples are included in the former graphs. Furthermore, only an effect was observed with respect to the three presented aldehydes (and predominantly the fresh beer samples).

In order to statistically analyze the effect of oxygen, temperature, and vibrations on the total aldehydes content, a mixed model was built in which the batch is the random effect. Since the variation of the measured total aldehydes concentration becomes larger when temperature increases, the logarithm of the concentration of aldehydes was identified as the output variable in order to increase the performance and the correctness of the presented model. In Table 5a, the fixed-effects parameter estimates of the initial model are illustrated. The single effect of temperature, the quadratic effect of temperature and the single effect of vibrations are described as significant by the model (significance level of 5%). The effect of oxygen ($p = 0.4571$) and the interaction effect between temperature and vibrations ($p = 0.8528$) are not assessed as significant by the model. The nonsignificant effect of oxygen was not expected before initiating the vibration experiment. However, the descriptive analysis of the beer aging parameters already indicated the latter relation. The interaction effect between temperature and vibrations is intuitively expressed by the plot of the results in Figure 3a. Due to the increased variance in aldehydes concentration when the temperature rises, an interaction effect between temperature and vibrations is not addressed as significant by the model. Furthermore, the optimal model (Table 5b) and the 'effect summary' indicates that temperature (and the exponential effect) is the predominant parameter that describes the concentration of aldehydes. In other words, vibrations have a significant effect on the total aldehydes concentration, but the importance of the parameter is considerably lower compared to temperature. Beer aging due to vibrations is only prominent with respect to aldehydes when the samples are subjected to an elevated temperature (45°C). Similar results and the same significant parameters were found for the aldehydes '2-methylpropanal', '2-methylbutanal' and 'furfural'.

Table 5a: Mixed model – total aldehydes after vibration experiment (first model - JMP output) (after the vibration experiment stored for 60 days at 0°C)

Fixed Effects Parameter Estimates							
Term	**Estimate**	**Std. Error**	**DFDen**	**T Ratio**	**Prob>|t|**	**95% Lower**	**95% Upper**
Intercept	3.98	0.16	5.0	24.13	< 0.01	3.56	4.40
Oxygen	-0.02	0.02	28.1	-0.75	0.46	-0.06	0.03
Temperature	0.04	< 0.01	5.0	9.42	< 0.01	0.03	0.05
(Temperature)^2	< 0.01	< 0.01	5.0	2.85	0.04	8.29e-5	< 0.01
Vibrations	-0.16	0.05	5.0	-2.91	0.03	-0.30	-0.02
Temperature x Vibrations	< 0.01	< 0.01	5.0	-0.20	0.85	-0.01	0.01

Table 5b: Mixed model – total aldehydes after vibration experiment (optimal model - JMP output) (after the vibration experiment stored for 60 days at 0°C)

Fixed Effects Parameter Estimates							
Term	**Estimate**	**Std. Error**	**DFDen**	**T Ratio**	**Prob>|t|**	**95% Lower**	**95% Upper**
Intercept	3.98	0.15	6.0	26.80	< 0.01	3.62	4.35
Temperature	0.04	< 0.01	6.1	10.35	< 0.01	0.03	0.04
(Temperature)^2	< 0.01	< 0.01	6.0	3.12	0.02	< 0.01	< 0.01
Vibrations	-0.16	0.05	6.1	-3.22	0.02	-0.28	-0.04
Random Effects Covariance Parameter Estimates					**Effect Summary**		
Covariance Parameter	**Estimate**	**Std. Error**	**95% Lower**	**95% Upper**	**Source**	**LogWorth**	**PValue**
Batch	0.02	0.01	-0.01	0.04	Temperature	4.35	< 0.01
Residual	0.02	< 0.01	0.01	0.03	Vibrations	1.75	0.02
					(Temp.)^2	1.69	0.02

4. <u>Discussion</u>

A variety of beer parameters, related to beer quality, are analyzed in the current experimental research. Furthermore, the results of the study were extensively benchmarked with the experiments performed prior to the current study[12,15]. Nonetheless, due to the uniqueness of the research topic, the authors indicate that further research is recommended on (1) the development of turbidity in beer under a regime of vibrations and on (2) the influence of shocks on beer quality. In the current experiment, the measured oxygen concentrations decreased (both HSO and DO) due to vibrations, but there was no effect observed on color nor on the iso-α-acids. This is noteworthy since literature indicates that oxidation can be noticed by a change in color and a decrease in the *trans*- and *cis*-iso-α-acids[18,20]. As a consequence, additional research is recommended on the uptake of oxygen due to vibrations. The development of turbidity in beer can be one of the causes of the uptake of oxygen (and the increased interaction between proteins and polyphenols[22]) and, therefore, should be subjected to further research. Also, the influence of shocks, i.e. transient phenomena that damp out over time, on beer quality should be researched since beer bottles are frequently exposed to shocks during truck transport (depending on the packaging)[15]. From a physics point of view, a transient phenomenon is completely different compared to a vibration and, as a consequence, the impact on beer quality might also diverge. The impact of shocks on the flavor stability of beer might be an interesting research track, complementary to the current study.

Additionally, the statistical analysis indicated that the individual effect of temperature and vibrations are significant ($P<0.05$), while the effect of oxygen and the interaction effect are not. The insignificant effect of oxygen was expected due to the high standard deviation of the measured oxygen concentrations after bottling (Table 1). Therefore, additional experiments on the influence of oxygen with respect to vibrations and the flavor quality of different beer types are still recommended. Furthermore, with respect to the interaction effect between vibrations and temperature, the former findings still allow to conclude that the impact of vibrations on the aldehyde concentrations was substantial when subjected to an elevated temperature, and, therefore, predominantly elevated temperatures (during transport and storage) should be avoided. The authors of the current study recommend to further validate the results with real-life flavor quality measurements due to the inherent difficulties of simulating transport (i.e. mechanical specifications of the shaker and the different vibration patterns measured on bottled beer[15]).

5. Conclusions and recommendations

The main conclusions of the experimental study are summarized as follows.

- A significant decrease in oxygen concentrations (TPO, HSO, and DO) is observed due to the exposure to both temperature and vibrations, which indicates that beer aging reactions were initiated.
- No difference in color was detected for beer samples that were subjected to an increased temperature or vibrations.
- The cis-iso-α-acids are stable and do not change when exposed to temperature and vibrations. The trans-iso-α-acids are more sensitive (especially *trans*-isocohumulone and *trans*-isohumulone) and induce both the total iso-α-acids and the T/C-ratio to decrease in concentration, respectively percentage. Only temperature and not vibrations are observed as a significant explanatory parameter with respect to total iso-α-acids and the T/C-ratio.
- Three aldehydes, i.e. '2-methylpropanal', '2-methylbutanal' and 'furfural' (and additionally the total aldehydes concentration), are sensitive to vibrations in combination with temperature. The temperature, the quadratic effect of temperature, and vibrations have a significant impact on the total aldehydes concentration. However, the importance of vibrations is considerably lower compared to temperature. The interaction effect between vibrations and temperature is not identified as significant ($P>0.05$) due to the increased variability at a higher temperature.

Since the impact of vibrations on beer quality is only substantial when subjected to an elevated temperature, reducing temperature during transport and storage should be the main focus to brewers. Furthermore, there is potential to further develop a beer aging method that is shorter in time and duration than traditional methods (with respect to aldehydes). An advanced chemical interpretation of the results will be provided in a follow-up paper.

6. Appendices

A. Overview of the measurement errors of the performed chemical analyses and additional information on the chemical tests. (Table A.1)

Table A.1: Measurement errors of the performed chemical analyses

Oxygen	TPO, HSO, DO	1ppb +/- 2%
Color	Absorption 430 nm	0,062 (EBC)
Iso-α-acids	*trans*-isocohumulone	0.017 mg/L
	cis-isocohumulone	0.011 mg/L
	trans-isohumulone	0.008 mg/L
	cis-isohumulone	0.018 mg/L
	trans-isoadhumulone	0.002 mg/L
	cis-isoadhumulone	0.019 mg/L
Aldehydes	2-methylpropanal	1.61 µg/L
	2-methylbutanal	0.60 µg/L
	3-methylbutanal	2.01 µg/L
	Hexanal	0.20 µg/L
	Furfural	4.37 µg/L
	Methional	0.72 µg/L
	Benzaldehyde	0.30 µg/L
	Phenylacetaldehyde	1.24 µg/L
	(E)-2-nonenal	0.0052 µg/L
*Systematic errors in experimental observations come from the measuring instruments. The systematic error referred to in the current paper is identified as the accuracy of the measurement or the offset or zero setting error in which the instrument does not read zero when the quantity to be measured is zero.		

B. Presentation of the DO, HSO and TPO results for beer samples (Table B.1)

Table B.1: A more detailed investigation of the results of the DO, HSO and TPO measurements of samples with higher/lower initial oxygen content

Avg. in ppb (STD)	DO (samples with higher initial oxygen content)	HSO (samples with higher initial oxygen content)	TPO (samples with higher initial oxygen content)	DO (samples with lower initial oxygen content)	HSO (samples with lower initial oxygen content)	TPO (samples with lower initial oxygen content)
90hrs. in 25°C	31 (8)	258 (48)	289 (48)	19 (12)	129 (74)	148 (75)
90hrs. in 5°C	48 (6)	286 (25)	334 (25)	26 (11)	164 (76)	190 (77)
90hrs. in 5°C shaking	23 (4)	230 (46)	253 (46)	22 (11)	156 (41)	177 (42)
90hrs. in 30°C	36 (10)	259 (43)	295 (44)	10 (2)	89 (7)	99 (7)
90hrs. in 30°C shaking	17 (1)	153 (4)	169 (4)	12 (1)	97 (21)	109 (21)
90hrs. in 45°C	16 (6)	102 (42)	118 (42)	9 (4)	65 (26)	74 (26)
90hrs. in 45°C shaking	9 (2)	72 (28)	81 (28)	8 (2)	49 (25)	56 (25)

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"A first model to simulate the Overall Aging Score (OAS) - the impact of temperature and time on the sensorial quality of lager beer"

ABSTRACT (250 words)

Overall aging scores (OAS) are used by expert beer tasters, able to distinguish between the different aromas and tastes, in order to assess the sensorial quality and flavor stability of beer. Currently, flavor instability is an important issue to brewers due to the increased global demand of beer and the difficulties in controlling beer quality in foreign locations when exported. In the current paper, the idea was constructed and a first model was built that is able to estimate the OAS as a function of temperature and time. The study not only highlights the exponential impact of temperature on lager beer quality, but also the importance of the time of exposure (saturating effect). Furthermore, a hypothetical case-study was performed in which the OAS is explored of Belgian lager beer that is exposed to the temperature conditions in the most important Belgian beer import markets. The results indicate that in mild climate cities (e.g. U.K., Germany) lager beer will only suffer quality degradation to a lesser, limited extent. Temperature in warm climate cities (e.g. Italy, China) will significantly reduce shelf life of lager beer in a short time frame, stressing the importance of flavor quality and stability. The model can be used in both industry and academic research and can be addressed when developing managerial decisions.

Highlights [3 to 5 bullet points (maximum 85 characters, including spaces, per bullet point)]

- The overall aging score (OAS) is modeled as a function of temperature and time
- The change in OAS during transport and storage is simulated by the software tool
- A case-study of Belgian beer exports stressing the problem of flavor instability
- Warm climates (e.g. Italy, China) significantly reduce the shelf life of beer

Keywords

Beer flavor stability, Overall Aging Score, temperature, simulation tool

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1. Introduction

Bottled beer experiences various flavor modifications after leaving the brewery[1]. An aged beer flavor, caused by variable transportation and storage conditions, is undesirable to both brewer and consumer[1,2]. While the problem of beer flavor stability is an intensely studied[1–3] research topic among scientists, the problem becomes more pronounced from an industry perspective. Market globalization causes more brewers to export their beer[4]. The resulting task of monitoring beer quality during storage and transportation is complex and difficult[4]. Furthermore, increasing global and local competition demands an ensured flavor quality of the exported and domestic brew[5]. Since the exposure of beer to an elevated temperature is a major parameter contributing to a degraded beer taste and aroma[1], breweries are inclined to study beer flavor stability (primarily of exported beer) and to assess the impact and implications of cooling transport and storage environments. In the current research, the idea is suggested to build a theoretical model (and a first attempt was made to estimate the model), in which the sensorial properties of beer are estimated when exposing lager beer to temperature (with variable duration). Furthermore, a case-study on Belgian beer exports was performed to extract insights on the quality of Belgian beer, exported to and stored in foreign countries, by applying the model and further deductive reasoning.

1.1 Beer quality

Beer aging is a complex chemical phenomenon in which new molecules that generate undesirable flavors may be formed, and existing molecules may be degraded that lead to a loss of the initial fresh beer flavors[1]. Temperature and light are important contributors to the degradation of the flavor quality of beer[1]. Recently, research indicated that vibrations might also negatively influence beer flavor quality[6]. The aged beer flavors can be attributed to a change of several chemical compounds (i.e. iso-α-acids, aldehydes, e.g. Strecker degradation products)[1,7]. However, the exact chemical pathways that lead to the degraded flavor of beer are after more than 30 years of research not entirely known[1]. Nevertheless, the literature indicates that the freshness of beer decreases with higher temperatures[3]. Moreover, due to an elevated temperature the molecular energy increases, which is required to enable aging reactions (reaction kinetics). As a consequence, exposing beer to different temperatures causes different flavor-associated metabolites to be formed and degraded, which activate or deactivate different aging reactions. In other words, beer that has aged at different temperatures might have different sensorial attributes. Furthermore, the latter also indicates that when beer ages, a saturating effect over time is present at both high and low temperature (i.e. beer ages the fastest during the initial stages of the exposure to heat)[1,3].

1.2 Paper structure and flow

The objective of this paper is twofold: (1) a first attempt was made to build a temperature-time model that is able to estimate the quality of beer and (2) a hypothetical case-study is performed in which the model is tested. As a consequence, the paper is structured as follows: in Section 2, the methodology of the research is described, i.e. the model's assumptions and parameters, and the construction of the model. Section 3 discusses the results in two parts; the characterization of the model, and the case-study respectively. In Section 4, the significance of the results and recommendations to further improve, validate and benchmark the model are explored. Lastly, in section 5, the conclusions of the work are presented.

2. Methodology

In the current research, a two-phase approach or methodology was designed (1) to build the temperature-time-beer quality model and (2) to predict the quality of beer when being exposed to a realistic temperature and time pattern. When building the model, past observations as well as those reported in the literature were incorporated (Section 2.1). During the case-study, the extracted results from the model were translated into practical insights and recommendations. Further sections detail the development of the model, both the construction and its validation (Section 2.2), as well as the estimation of the OAS resulting from the model (Section 2.3).

2.1 The overall aging score (OAS) – data gathering

In order to assess the degree of staling of a beer sample, the general aging score (GAS) or overall aging score (OAS) was developed by beer science[2,3]. The score is created by expert tasters or trained tasters with demonstrated beer knowledge and tasting experience capable of distinguishing between the different predefined tastes and aromas of beer. The OAS is a number[I] between zero and eight and is a measure for the overall satisfaction of the respondent regarding the taste of the beer sample. In order to anchor the score, there are five predefined categories of the overall aging score[3]: 0-1 (fresh, oxidized flavor not detectable), 2-3 (very weakly aged), 4-5 (weakly aged), 6-7 (clearly aged), 8 (strongly aged, undrinkable).

In beer research, beer flavor stability is predominantly assessed by exposing beer to an elevated temperature[3]. As a consequence, there is an availability of data with respect to beer quality when being exposed to heat during different times of exposure. For instance, Vanderhaegen et al.[2] investigated the aging characteristics of different beers and, therefore, exposed beer to the ambient temperature of 20°C, analyzed and profiled the beer on different time instances throughout one year. Malfliet et al.[8,9] used similar procedures to estimate beer quality. The data of these articles was used in addition to the internal data of past/performed experiments at the EFBT lab (KULeuven Campus Ghent). In total, there were 270 cases in which beer was aged over a predefined period of time and sensory evaluated by a panel of minimum five expert tasters. Only the cases consisting of lager beers were considered for this study, excluding 84 of the 270 cases. In the remaining 186 cases, the beer is predominantly aged and stored between 20°C and 30°C, up to 365 days, which emphasizes the accuracy of the model in the defined temperature range. Furthermore, chemical information (concentration of iso-α-acids and aldehydes) is available at different temperatures between 0°C and 45°C, which is only used to further validate the model and was not used in building it[II]. The chemical data indicates an exponential relation between the temperature of exposure and the decrease in beer quality. Furthermore, beer flavor quality decays most rapidly during the initial time period when exposed to temperature, but saturates over time.

2.2 Building and validating the model

As a *first step*, all available data and its variability was studied. Moreover, the data was compiled into histograms in order to determine the most suitable distribution between temperature, time of exposure and OAS. In Figure 1a, an example of a histogram of the OAS of lager beer samples aged over

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[I] The researchers of the current study are aware that it is uncommon for respondents to express sensorial responses on a 0-8 ratio scale (due to psychometry[10]) and, therefore, an ordinal scale best describes the respondent's responses. Furthermore, in order to build a model based on the OAS, the researchers assume that the scale is equidistant (which is not proven up till now).

[II] Experiments were executed in KULeuven, Faculty of Engineering Technology, Department of Microbial and Molecular Systems (M2S), Cluster for Bioengineering Technology (CBeT), Laboratory of Enzyme, Fermentation and Brewing Technology, Technology Campus, Ghent, Belgium.

120 days at 30°C is presented. The figure (other histograms not shown) indicates that a considerable variability in the OAS is observed for beer samples that experienced the same aging pattern. This can be attributed to the flavor instability of the beer samples (resistance to elevated temperature and duration) and the respondent's perception of taste and flavors. Furthermore, the data of the histograms revealed that a skewed distribution is observed.

Figure 1a: Histogram of data cases – overall aging score (OAS) of beer samples aged during 120 days at 30°C
Figure 1b: Theoretical analysis of the predicted variability in the OAS (with constant temperature and changing time of exposure)

Figure 1a

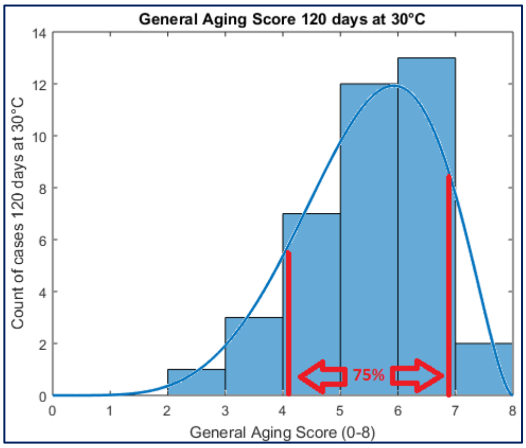


Figure 1b

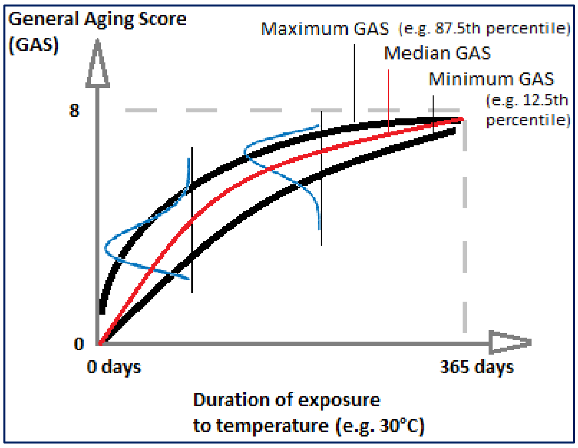


Fig. 1a: A distribution was fitted (current case: Beta-distribution with α= 5.8913 / β= 2.71005) on the responses for the OAS of beer samples aged during 120 days at 30°C (and other temperatures and times of exposure). The variability in the OAS can be explained by the flavor stability of the beer samples (resistance to elevated temperature and duration) and the respondent's perception of taste and flavors.

Fig. 1b: The figure presents the theoretical analysis of the predicted variability in the OAS with the 'median OAS' (50^{th} percentile), 'maximum OAS' and 'minimum OAS' (e.g. 87.5^{th} and 12.5^{th} percentile = 75% of the variability explained). During every time step, the variability of the OAS responses is believed to change. The variability in the OAS for fresh beer (OAS≈0), caused by respondent's perception of taste and flavors, was never assessed before. The researcher also believes the OAS (maximum and minimum) will asymptotically reach 8, i.e. the spread will get smaller and eventually will reach zero, the longer the beer samples are exposed to the elevated temperature. The spread between maximum and minimum OAS is believed to be largest (due to psychometry[10]) when the OAS is not (approximately) equal to 0 nor 8. The current first model estimates the median value of the OAS (OAS between 0-8), but also demonstrates the variability.

In Figure 1b, a theoretical analysis was executed of the predicted variability in the OAS (with constant temperature and changing time of exposure). The researcher of current study assumes that the variability in the OAS will be largest for beer samples that are not completely fresh nor completely aged (0 < OAS < 8), due to the inherent difficulties for a respondent of scoring a beer sample[10]. Furthermore, the researcher believes the variability in the OAS will asymptotically reach 8 the longer the beer samples are exposed to the elevated temperature. However, there is no data available on the natural variation in the OAS for completely fresh (OAS≈0) or aged beer (OAS≈8)[III]. Therefore, the variation in the OAS of the available data was studied in Table 1. The table indicates the considerable

[III] When executing a sensorial experiment, the standard procedure is that the respondents are required to taste two beer samples: an aged beer sample and a fresh beer sample that is provided to serve as a point of reference (the OAS of the fresh beer is mostly not expressed). As a consequence, the natural variation in the OAS of completely aged beer samples, respectively fresh beer samples, was never assessed before and requires further study.

variability in the OAS, and the need for estimating the median, maximum and minimum boundaries of the OAS rather than the average. In the current first model, the median OAS will be estimated and the variability will be demonstrated by indicating a range of +/-1.25 on the median OAS [i.e. spread of 2.5≈75% of the variability in the OAS explained].

Table 1: Analysis of the variation in the OAS of the available data (samples with the same aging pattern - constant temperature and time of exposure) – and validation of the spread between the maximum and minimum boundaries of the OAS-model

	50% of the variability in the OAS explained	75% of the variability in the OAS explained	90% of the variability in the OAS explained
Spread in the OAS of the available data (used to determine the max. and min. of the OAS-model)	1.2 - 1.7	2.0 - 2.8	3.3 - 4.5

The table indicates the variability in the OAS, and the need for estimating the median, maximum and minimum boundaries of the OAS rather than the average. In order to demonstrate the variability of the OAS in the current study, the maximum boundary of the OAS and the minimum boundary of the OAS is presented, which is +/-1.25 compared to the estimated median value [i.e. spread of 2.5≈75% of the variability in the OAS explained].

After the analysis of the available data and the variability in the OAS, in a *second step*, the OAS-model was constructed. Moreover, the median values of the OAS were estimated of all data over the temperature interval between 0°C and 50°C, and the time duration between 0 days and 365 days. Based on the median values of all available data, curves over constant temperature but varying time (and OAS) were fitted by using the Curve Fitting Toolbox in Matlab (Polynomials of degree 3 – due to the exponential nature of the temperature - OAS curves)[IV]. As a consequence, the median OAS pattern between 0 and 365 days on the temperatures of 20°C, 30°C and 40°C was accurately derived. Since there was no information available on the OAS over all temperatures, curves were fitted over a constant time but varying temperature (and OAS) using the curve fitting toolbox based on the previously generated data[V]. Afterwards, curves were fitted again over a constant temperature but varying time (and OAS). The latter fitting induces the OAS to be estimated over a time period of days, hours or even minutes. The result is a three-dimensional model or surface that describes the OAS as a function of temperature and time of exposure.

In a *third and last step*, the model is adapted to allow for estimating the OAS for a beer sample of a certain aging score and subjected to a temperature-time treatment. Since the 3-D model has been fitted to be continuous through interpolation techniques and fittings, any proposed simulation can be done by supplying the parameters of the experiment, i.e. if a timeframe is given at a certain temperature, the resulting path on the 3-D surface can be determined. Moreover, after the surface being adapted to a certain sample frequency, the model can iteratively calculate in each proposed point or timestamp (with corresponding temperature of exposure) what the OAS is. The previous OAS

[IV] Calculations were performed in MATLAB and Statistics Curve fitting Toolbox Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States.

[V] In the current study, a first attempt was made to construct a OAS-model through excessive interpolation techniques and fittings based on a sufficient but limited number of data samples. Moreover, the fittings of the OAS-curves at 20°C, 30°C and 40°C and variable time were used to develop the fittings of the OAS-curves over constant time and variable temperature. Therefore, the researchers suggest that an extensive benchmarking study with experimental data is required in order to further reduce the variability and increase the robustness of the OAS-model.

is then used as an input to calculate the next step, resulting in a final OAS determined by the parameters of the experiment.

2.3 Estimation of the OAS with realistic temperature patterns

The model that was built in section 2.2 thus incorporates the possible exposure of beer to temperature variations. In literature, an elevated temperature is identified as the main contributor to beer aging, i.e. an elevation in temperature will result in a proportionally faster decrease in beer quality. However, no evidence in literature was observed on the possible negative effect of the (natural) fluctuations of temperature themselves. Therefore, an explorative temperature experiment was designed and indicated that there was no negative effect of temperature fluctuations on beer quality in the temperature range between 25°C and 45°C [Specifications in Appendix A.]. As a consequence, the assumption was made that the effect of temperature fluctuations is negligible and is not considered.

In order to assess flavor quality and stability of beer samples intended for export, brewers and researchers aim to simulate transport or storage (destructive testing). Moreover, changes in the chemical composition of the beer mixture can be tested by performing a temperature simulation. If the temperature is monitored during beer transport and storage, multiple simulations can be performed and beer can be analyzed without performing the actual transport. One of the advantages of this model is that once the temperature progression of a transport is known, there will be no need to simulate it by performing the actual transport and subsequent destructive testing of the samples. The resulting change in the OAS can be calculated, winning tremendously in both time needed to do the analysis as well as the resources used. Furthermore, not only does the simulation model generate the estimated OAS as an output, it also provides the time fresh beer samples are required to be exposed to 20°C or 30°C during destructive testing to generate the same aging score. This allows brewers or researchers to perform a simulation experiment at constant temperature instead of the varying temperatures that are measured during transport and storage, further reducing the complexity of the practical aging experiments.

3. Results

3.1 The overall aging score model

In Figure 2a-c, the aging model of lager beer as a function of time and temperature is presented. As can be derived from the figures, the median OAS model starts from the OAS of 0 and ends at 8. The minimum model, respectively maximum model, is 1.25 in OAS lower/higher than the median value and demonstrates the variability in the OAS. Furthermore, the model indicates the exponential effect of temperature on the OAS. Beer samples that are exposed to an elevated temperature of 42°C will reach a OAS score of 8 in approximately 10 days while samples being exposed to 30°C only after approximately 250 days. The saturating effect of temperature over time of exposure can also be derived from the figure. The effect of temperature on the OAS is most substantial in the initial time phases, which can be observed, for instance, from the OAS responses when exposed to the temperatures of 20°C and 30°C.

Figure 2a: The OAS as a function of temperature and time of exposure (MEDIAN)
Figure 2b: The OAS as a function of temperature and time of exposure (MINIMUM)
Figure 2c: The OAS as a function of temperature and time of exposure (MAXIMUM)

Figure 2a

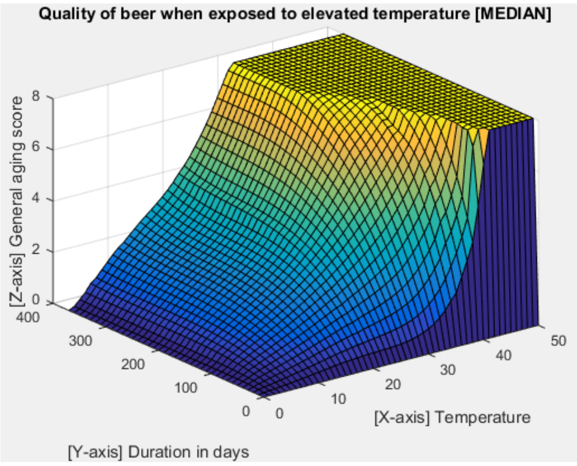


Figure 2b

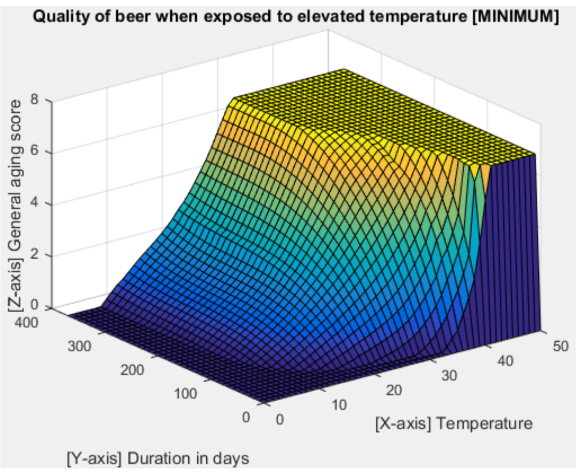
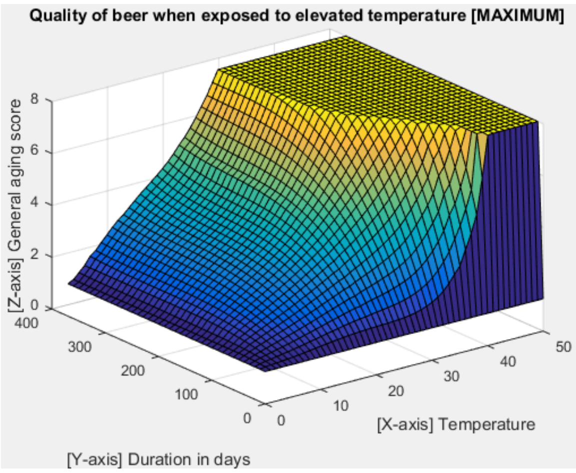


Figure 2c



3.2 Case-study: Belgian beer exports

Roughly 60% of all beer brewed by Belgian breweries in Belgium is exported to foreign countries[11]. Due to the variety in export destinations (and the absence of facilities to perform beer quality tests), it is difficult to control the quality of the beer after being exported. In the considered case-study, the effect of exposing beer to the outside temperature conditions in Belgium's most important export markets is explored. Moreover, in Table 4 [Appendix B.] an overview is presented of Belgian beer importers, the volume of beer sold and the temperature conditions of maximum three of the largest cities in the country. The temperature data, presented in the table, is the input of the model and the scope of analysis.

In the case-study, the influence of exposing beer to the average maximum and minimum daily temperatures and the average monthly temperature during the warmest three months, respectively the warmest month of the year will be identified. Bottled Belgian beer, destined for export, is predominantly packaged in one-way bottles in corrugated boxes. One-way refers to the single use of the bottles, which is different from the domestic bottles that can be recycled and reused[12]. Due to the insulating properties of the secondary cardboard packaging, bottled beer is protected against extreme temperature variations[13]. Therefore, two cases were performed: (1) exposure to the average monthly temperature (corresponds to beer that experiences absolutely no temperature variations) (2) exposure to the average maximum and minimum daily temperatures (corresponds to beer that experiences extreme temperature variations). These two cases are considered to estimate the two boundaries of the OAS in the warmest three months and warmest month of the year in the analyzed cities.

In general, Belgian beer has an expiration date that is fixed to one year after bottling[2]. The latter implies that the beer should be consumed within the period of one year even when the beer is constantly exposed to 20°C[2]. Exposing fresh beer to 20°C for one year results in a OAS of 4.2 (+/- 1.25) [and can be approximated by exposing beer samples to 30°C during 71 – 87 days]. As a consequence, the remaining shelf life of beer samples exposed to a temperature-time treatment can be calculated. Moreover, the software provides the time fresh beer samples are required to be exposed to 20°C during destructive testing to generate the same aging score. The latter number of days can be subtracted from the initial shelf life of 365 days to calculate the remaining shelf life.

In Table 2 and 3, an overview of the case-study results with respect to simulated beer quality is presented. The tables identify:

- the estimated OAS (starting from a OAS of 0),
- the number of days at 20°C to approximate the estimated OAS,
- the number of days at 30°C to approximate the estimated OAS,
- and the remaining shelf life.

Table 2, describing the results of the average maximum and minimum daily temperatures of the warmest 3 months, indicates more extreme aging scores than the data in Table 3 with the average monthly temperature of the warmest 3 months. This can be attributed to the exponential effect of higher temperature on the OAS. The results of Table 2 and 3 indicate that locations with a moderate climate (e.g. Belgium, The Netherlands, France, Germany, the UK, and Canada) will have limited problems with lager beer quality due to temperature[VI]. In warm locations (e.g. Italy, parts of the USA,

[VI] Also in locations with a moderate climate, bottled beer can be exposed to extreme temperatures (higher than ambient temperature) depending on the storage unit, e.g. in transport containers, temperature can rise up to 50°C due to solar radiation[14]. As a consequence, temperature should be measured throughout all phases of the value chain in order to correctly predict the OAS.

and China), the high temperature will induce a significant decrease in quality of lager beer. For instance, in all studied Chinese locations, the shelf life is reduced considerably after exposing the beer to the defined temperatures. However, when exposing the beer to the warmest month temperatures [results in Appendix C.] the OAS is considerably lower but the beer has not entirely decayed in quality. As a consequence, both the temperature and the duration of exposure are extremely important parameters that are required to be controlled. Based on previous analysis, it can be worthwhile to examine beer quality in the identified locations. Also, the economic feasibility of cooled storage facilities should be investigated.

Table 2: Case-study results, Avg. max-min daily temperature warmest 3 months

			Warmest 3 months	OAS (+/- 1.25)	Approximation Days at 20°C	Approximation Days at 30°C	Shelf life remaining (days)
EU	Belgium	Brussels	Jun.-Aug.	3.0	103-126 days	47-57 days	239-262 days
	The Netherlands	Amsterdam	Jun.-Aug.	2.8	91-112 days	43-52 days	253-274 days
	France	Paris	Jun.-Aug.	3.4	129-158 days	54-65 days	207-236 days
		Bordeaux	Jun.-Aug.	3.7	175-214 days	61-74 days	151-190 days
		Marseille	Jun.-Aug.	4.3	>365 days	74-90 days	0 days
	Germany	Berlin	Jun.-Aug.	3.3	122-149 days	52-63 days	216-243 days
		Hamburg	Jun.-Aug.	2.9	96-117 days	45-54 days	248-269 days
		Munich	Jun.-Aug.	3.1	107-131 days	48-58 days	234-258 days
	Italy	Rome	Jun.-Aug.	4.7	>365 days	81-100 days	0 days
		Milan	Jun.-Aug.	4.2	>365 days	70-85 days	0 days
		Naples	Jun.-Aug.	4.4	>365 days	74-91 days	0 days
	U.K.	London	Jun.-Aug.	3.1	106-130 days	48-58 days	235-259 days
		Edinburgh	Jun.-Aug.	2.4	72-87 days	36-43 days	278-293 days
		Belfast	Jun.-Aug.	2.4	71-86 days	36-43 days	279-294 days
EX-EU	U.S.A.	New York	Jun.-Aug.	4.4	>365 days	74-91 days	0 days
		Los Angeles	Jul.-Sept.	4.3	>365 days	73-89 days	0 days
		Houston	Jun.-Aug.	5.6	>365 days	106-129 days	0 days
	Canada	Ottawa	Jun.-Aug.	3.5	148-180 days	57-70 days	185-217 days
		Montreal	Jul.-Sept.	3.2	113-140 days	50-61 days	225-252 days
		Vancouver	Jun.-Aug.	2.9	95-116 days	44-54 days	249-270 days
	China	Beijing	Jun.-Aug.	4.7	>365 days	83-102 days	0 days
		Shanghai	Jul.-Sept.	5.0	>365 days	91-111 days	0 days
		Kaifeng	Jun.-Aug.	5.1	>365 days	94-114 days	0 days

Table 3: Case-study results, Avg. monthly temperature warmest 3 months

			Warmest 3 months	OAS (+/- 1.25)	Approximation Days at 20°C	Approximation Days at 30°C	Shelf life remaining
EU	Belgium	Brussels	Jun.-Aug.	2.3	65-80 days	33-41 days	285-300 days
	The Netherlands	Amsterdam	Jun.-Aug.	2.1	60-73 days	31-37 days	292-305 days
	France	Paris	Jun.-Aug.	2.6	79-96 days	38-47 days	269-286 days
		Bordeaux	Jun.-Aug.	2.7	86-105 days	41-50 days	260-279 days
		Marseille	Jun.-Aug.	3.2	118-144 days	51-62 days	221-247 days
	Germany	Berlin	Jun.-Aug.	2.4	72-88 days	36-44 days	277-293 days
		Hamburg	Jun.-Aug.	2.1	60-73 days	31-37 days	292-305 days
		Munich	Jun.-Aug.	2.1	60-73 days	31-37 days	292-305 days
	Italy	Rome	Jun.-Aug.	3.2	118-145 days	51-62 days	220-247 days
		Milan	Jun.-Aug.	3.0	102-125 days	46-57 days	240-263 days
		Naples	Jun.-Aug.	3.2	118-145 days	51-62 days	220-247 days
	U.K.	London	Jun.-Aug.	2.4	71-86 days	35-43 days	279-294 days
		Edinburgh	Jun.-Aug.	1.8	49-60 days	26-32 days	305-316 days
		Belfast	Jun.-Aug.	1.8	49-60 days	26-32 days	305-316 days
EX-EU	U.S.A.	New York	Jun.-Aug.	3.3	126-155 days	53-64 days	210-239 days
		Los Angeles	Jul.-Sept.	3.3	119-145 days	51-62 days	220-246 days
		Houston	Jun.-Aug.	4.1	305-365 days	68-84 days	0 days

	Canada	Ottawa	Jun.-Aug.	2.5	78-95 days	38-47 days	270-287 days
		Montreal	Jul.-Sept.	2.2	63-76 days	32-39 days	289-302 days
		Vancouver	Jun.-Aug.	2.1	60-73 days	31-37 days	292-305 days
	China	Beijing	Jun.-Aug.	3.5	149-182 days	57-70 days	183-216 days
		Shanghai	Jul.-Sept.	3.8	180-221 days	62-75 days	144-185 days
		Kaifeng	Jun.-Aug.	3.8	186-227 days	62-76 days	138-179 days

4. Discussion

The case-study performed in the current research is limited to lager beer that has been theoretically exposed to the identified temperature patterns in Table 4 [Appendix B.]. In future research, the findings of current theoretical case-study will be validated with real life sensorial data. Other parameters that possibly influence beer quality, e.g. light, vibrations or shocks, are not considered in this paper. Furthermore, the studied case is applicable to storage at the presented locations of Table 4 [Appendix B.]. However, beer can be exposed to possibly more extreme temperatures during transport. Moreover, the literature indicates that containers can occasionally heat up to 50°C due to solar radiation[14]. As a consequence, it is crucial to study the complete value chain with respect to beer quality and exposure to heat (temperature). The latter suggestion is further emphasized by the nonlinear nature of the impact of time of exposure on the OAS, i.e. exposure to an elevated temperature during a short time of exposure can already significantly reduce beer quality.

While the current first model presented in this paper is substantially benchmarked and validated with the available data, the authors suggest further benchmarking with real-life data. The model is predominantly accurate between 20°C and 30°C, which is an important range with respect to the climate conditions of the studied cities in the case-study. However, also the influence of the exposure to temperatures lower than 20°C and higher than 30°C should be further investigated. Currently, the model is based on and validated by chemical data in the before mentioned temperature ranges. Additional sensorial experiments will generate data that can help in developing an improved and updated model that is more accurate and is better in estimating the variability in the OAS. Also the natural variability in the OAS for completely fresh (OAS≈0) or aged beer (OAS≈8) is a topic of future study. Further research is also required on the influence of temperature variations on beer quality, although fluctuations are limited to a large extent due to the secondary cardboard packaging.

5. Conclusions

Since temperature is a crucial parameter that determines beer flavor quality, a tool was built that aims to estimate the OAS of lager beer as a function of the temperature and duration of exposure. The insights and current first model can be used by researchers and scientists to perform simulations of beer transports and storage in order to assess flavor stability, without the need of lengthy practical simulations or the use of considerable resources. The ease of use and speed of the predictive model will be invaluable to breweries when it comes to assessing the quality and needed infrastructure of their beer export ventures.

A case-study was presented, in which the estimated beer quality was explored of Belgian beer stored at foreign locations during the warmest three months of the year. Only the most important importers of Belgian beer (in 2015) were considered as locations in this study, therefore its results are both relevant and applicable. It can be concluded from the case-study, that lager beer stored in cities with mild climates will only suffer limited quality degradation as opposed to lager beer stored in warm climates, for which there was a significant reduction in beer quality in a short timeframe, thereby shortening shelf life. This result once again highlights the importance of assessing flavor quality and flavor stability in bottled lager beer. Furthermore, the results of this paper indicate that a revision of the study on the necessity and feasibility of cooled transports and storage facilities might be needed in order to guarantee optimal beer quality.

6. Appendices

A. In order to identify the influence of variations in temperature on the beer quality, an experiment was executed over the course of 40 days that involved exposing beer samples (a Belgian domestic lager beer) to different temperature patterns. In experimental setups 1-4, beer is exposed to a constant temperature of 0°C, 25°C, 30°C, and 40°C. Beer samples of experimental setups 1 (0°C) and 3 (30°C) were stored in a temperature chamber (still air), while beer samples of setup 2 were exposed to room temperature (25°C) and beer samples of setup 4 (40°C) were stored in a climate cabinet (forced air). Experimental setup 5 was designed to expose the beer samples to temperature variations of 15°C (between 40°C and 25°C), which is comparable for the difference in temperature between day and night. The samples were stored in a climate cabinet (forced air) and a temperature cycle was imposed. First, the samples were heated for 12 hours at 40°C and afterwards the climate cabinet was turned off for 24 hours, which enables the samples to cool down to 25°C. Due to the insulating properties of the climate cabinet, the cooling process from 40°C to 25°C took 12 hours and 30 minutes while the heating process only took 1 hour and 40 minutes. In setup 6, it was ensured that exactly the same heat was transmitted to the beer samples as in setup 5. The integral of the temperature pattern of setup 5 was calculated and resulted in exposing the beer samples for 56% of the time to 40°C and 44% of the time to 25°C. In total, the beer samples were stored in a climate cabinet of 40°C (forced air) for 22 days and 10 hours and, afterwards, stored at room temperature of 25°C for 17 days and 4 hours.

Figure 3a: Results total aldehydes

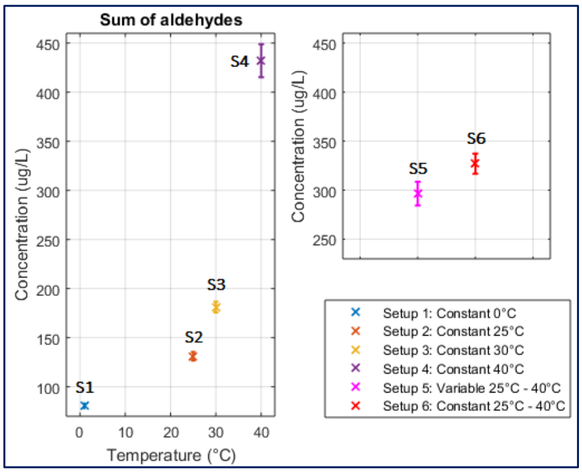
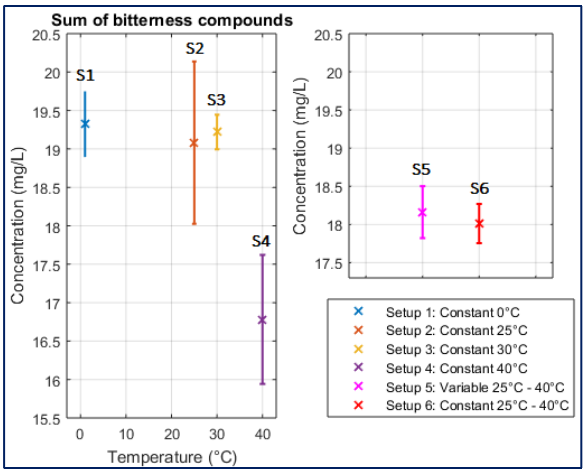


Figure 3b: Results total iso-α-acids



Based on the current findings and taking into consideration that the experiment was performed on one type of beer, a temperature variation between 25°C and 40°C does not have an increased effect on beer flavor quality of the tested beer samples (Figure 3a-b). However, it is essential to limit the exposure of beer to an elevated or increased temperature in order to delay flavor aging reactions. Furthermore, the results of the study are beneficial when simulating transport and storage since temperature can be approximated by a constant temperature instead of imposing the identical (fluctuating) temperature pattern.

B. In Table 4, the input data of the case-study is presented.

Table 4: Case-study input data; volume of beer sold, temperatures (Avg-max-min) warmest 3 months

		hL beer sold in 2015 (produced in Belgium) (a)	Cities incorporated in the study	Warmest 3 months	Average daily (24h) temperature (°C) per month** (b)	Average max. daily (24h) temperature (°C) per month** (b)	Average min. daily (24h) temperature (°C) per month** (b)
EU	Belgium	7,950,000 hL	Brussels	Jun.	15.6	20	11.5
				Jul.	17.8	22.4	13.6
				Aug.	17.8	22.5	13.4
	The Netherlands	2,281,091 hL	Amsterdam	Jun.	15	19.2	10.4
				Jul.	17.1	21.4	12.5
				Aug.	17.1	21.8	12.3
	France	3,695,161 hL	Paris / Bordeaux / Marseille	Jun.	17.5 / 18.3 / 21.1	21.8 / 23.5 / 26.1	13.3 / 13 / 16
				Jul.	20 / 20.8 / 24.1	24.4 / 26.4 / 29.5	15.5 / 15.1 / 18.7
				Aug.	20 / 20.9 / 23.9	24.6 / 26.6 / 29.2	15.4 / 15.2 / 18.7
	Germany	2,281,091 hL	Berlin / Hamburg / Munich	Jun.	17.1 / 15.4 / 15.4	21.6 / 19.9 / 21.4	12.3 / 10.5 / 10.4
				Jul.	19.2 / 17.4 / 17.3	23.7 / 22.1 / 23.3	14.3 / 12.7 / 12
				Aug.	18.9 / 17.2 / 16.6	23.6 / 22.2 / 22.9	14.1 / 12.5 / 11.7
	Italy	533,988 hL	Rome / Milan / Naples	Jun.	21 / 20.5 / 20.9	27.7 / 26.1 / 26.2	14.3 / 15 / 15.6
				Jul.	23.9 / 23.1 / 23.6	31.2 / 28.9 / 29.3	16.7 / 17.3 / 18
				Aug.	23.9 / 22.2 / 23.7	30.9 / 27.7 / 29.5	16.9 / 16.7 / 17.9
	U.K.	354,471 hL	London / Edinburgh / Belfast	Jun.	16.2 / 13 / 13.1	20 / 17.3 / 17.1	12.3 / 8.7 / 9.1
				Jul.	18.6 / 15 / 15.2	22.6 / 19.3 / 19	14.6 / 10.6 / 11.4
				Aug.	18.6 / 14.8 / 14.8	22.5 / 19.1 / 18.6	14.7 / 10.5 / 11.1
EX-EU	U.S.A.	1,900,976 hL	New York / Los Angeles* / Houston	Jun. /Jul.*	22 / 23.5* / 26.9	26.7 / 28.9* / 32.3	17.2 / 18.1* / 21.4
				Jul. /Aug.*	24.9 / 23.9* / 28.1	29.6 / 29.2* / 33.7	20.2 / 18.7* / 22.4
				Aug./Sept.*	24.2 / 23.2* / 27.9	28.7 / 28.2* / 33.6	19.6 / 18.1* / 22.2
	Canada	402,389 hL	Ottawa / Montreal* / Vancouver	Jun. /Jul.*	18.1 / 20.6* / 15.2	23.6 / 26.5* / 19.3	12.5 / 14.7* / 11
				Jul. /Aug.*	20.8 / 19* / 17.2	26.4 / 24.8* / 21.7	15.3 / 13.2* / 12.7
				Aug./Sept.*	19.4 / 14.2* / 17.4	24.7 / 19.9* / 21.7	14.1 / 8.4* / 12.9
	China	490,059 hL	Beijing / Shanghai* / Kaifeng	Jun. /Jul.*	24.2 / 27.8* / 25.9	30.3 / 31.6* / 32.0	18.2 / 24.8* / 19.8
				Jul. /Aug.*	25.9 / 27.7* / 27.1	30.8 / 31.5* / 32.1	21.6 / 24.7* / 22.8
				Aug./Sept.*	24.6 / 23.6* / 25.8	29.5 / 27.2* / 30.8	20.4 / 20.5* / 21.7

**: The temperature normals are measured in the period 1961-1990

Source: (a) (Belgische Brouwers, 2016)[11] (b) (YR, 2017)[15]

C. In Table 5 and 6, the results on the impact of exposing beer to the average max. and min. daily temperatures / the average temperature during the warmest month of the year is presented. Analysis indicates that lager beer significantly reduces in quality in a one month period, although a longer time of exposure is needed to completely reduce the shelf life of lager beer.

Table 5: Case-study results, Avg. max-min daily temperature warmest month

			Warmest month	OAS (+/- 1.25)	Approximation Days at 20°C	Approximation Days at 30°C	Shelf life remaining
EU	Belgium	Brussels	Aug.	1.4	34-41 days	18-23 days	324-331 days
	The Netherlands	Amsterdam	Aug.	1.3	32-39 days	17-21 days	326-333 days
	France	Paris	Aug.	1.5	38-46 days	21-25 days	319-327 days
		Bordeaux	Aug.	1.6	42-51 days	23-28 days	314-323 days
		Marseille	Jul.	2.0	54-66 days	28-35 days	299-311 days
	Germany	Berlin	Jul.	1.4	35-43 days	19-24 days	322-330 days
		Hamburg	Jul.	1.3	32-39 days	18-21 days	326-333 days
		Munich	Aug.	1.3	33-40 days	18-22 days	325-332 days
	Italy	Rome	Jul.	2.1	57-70 days	30-36 days	295-308 days
		Milan	Jul.	1.8	47-58 days	25-31 days	307-318 days
		Naples	Aug.	1.9	51-62 days	27-33 days	303-314 days
	U.K.	London	Jul.	1.5	37-45 days	20-25 days	320-328 days
		Edinburgh	Jul.	1.1	26-32 days	14-18 days	333-339 days
		Belfast	Jul.	1.1	26-32 days	14-18 days	333-339 days
EX-EU	U.S.A.	New York	Jul.	2.0	56-68 days	29-35 days	297-309 days
		Los Angeles	Aug.	1.9	52-63 days	27-34 days	302-313 days
		Houston	Jul.	2.8	92-113 days	43-53 days	252-273 days
	Canada	Ottawa	Jul.	1.6	40-49 days	22-26 days	316-325 days
		Montreal	Jul.	1.6	42-51 days	23-28 days	314-323 days
		Vancouver	Aug.	1.3	31-39 days	18-21 days	326-333 days
	China	Beijing	Jul.	2.3	68-83 days	34-42 days	297-282 days
		Shanghai	Jul.	2.5	77-95 days	38-46 days	270-288 days
		Kaifeng	Jul.	2.5	78-95 days	38-47 days	270-287 days

Table 6: Case-study results, Avg. monthly temperature warmest month

			Warmest month of the year	OAS (+/- 1.25)	Approximation Days at 20°C	Approximation Days at 30°C	Shelf life remaining
EU	Belgium	Brussels	Aug.	1.0	24-30 days	14-17 days	335-341 days
	The Netherlands	Amsterdam	Aug.	1.0	23-28 days	13-15 days	337-342 days
	France	Paris	Aug.	1.1	27-33 days	15-18 days	332-338 days
		Bordeaux	Aug.	1.2	29-36 days	16-19 days	329-336 days
		Marseille	Jul.	1.4	34-41 days	18-23 days	324-331 days
	Germany	Berlin	Jul.	1.1	26-32 days	14-18 days	333-339 days
		Hamburg	Jul.	1.0	23-28 days	13-15 days	337-342 days
		Munich	Aug.	1.0	23-28 days	13-15 days	337-342 days
	Italy	Rome	Jul.	1.4	34-41 days	18-23 days	324-331 days
		Milan	Jul.	1.3	32-39 days	18-21 days	326-333 days
		Naples	Aug.	1.4	34-41 days	18-23 days	324-331 days
	U.K.	London	Jul.	1.1	26-32 days	14-18 days	333-339 days
		Edinburgh	Jul.	0.9	20-24 days	11-13 days	341-345 days
		Belfast	Jul.	0.9	20-24 days	11-13 days	341-345 days
EX-EU	U.S.A.	New York	Jul.	1.4	36-43 days	19-24 days	322-329 days
		Los Angeles	Aug.	1.4	34-41 days	18-23 days	324-331 days
		Houston	Jul.	1.6	43-53 days	23-28 days	312-322 days
	Canada	Ottawa	Jul.	1.2	29-36 days	16-19 days	329-336 days
		Montreal	Jul.	1.2	29-36 days	16-19 days	329-336 days
		Vancouver	Aug.	1.0	23-28 days	13-15 days	337-342 days
	China	Beijing	Jul.	1.5	38-46 days	20-25 days	319-327 days
		Shanghai	Jul.	1.6	43-53 days	23-28 days	312-322 days
		Kaifeng	Jul.	1.6	40-49 days	22-26 days	316-325 days

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“The relation between beer flavor instability, the preference & the drinkability of fresh over aged beer”

ABSTRACT

In this experimental paper the preference and drinkability of fresh over aged beer was tested. The ‘paired comparison test’ was adopted and entails that after a duo test with small samples respondents can freely consume the beer of their choice.

The results show that the initial preference for fresh beer was significantly higher than the preference for aged beer, i.e. 65% of the respondents took fresh beer as their first consumption after the duo test. The drinkability of fresh beer also scored significantly higher, since 35% more fresh beer was consumed. However, since multiple respondents consecutively consumed multiple aged consumptions, it cannot be concluded that the consumption of aged beer results in a lower consumption volume (per capita) when compared to fresh beer. Additionally, the test revealed that Belgians older than 24 particularly favored and consumed the fresh beer in the experiment. The latter was predominantly attributed to the influencing and mimicking behavior of the other respondent groups, since the table setting and table sizes were also found to be important explanatory parameters. In this paper, we show the importance of researching and investing in beer flavor stability issues.

Highlights

- The paired comparison test was adopted with fresh and aged beer (4 months - 30°C)
- 65% (initially) preferred fresh over aged beer (significant)
- The drinkability of fresh beer is higher, 35% more fresh beer (significant)
- Influencing and mimicking behavior of consumers is important

Keywords
Drinkability, preference, beer flavor stability, paired comparison test, mimicking behavior, influencing behavior

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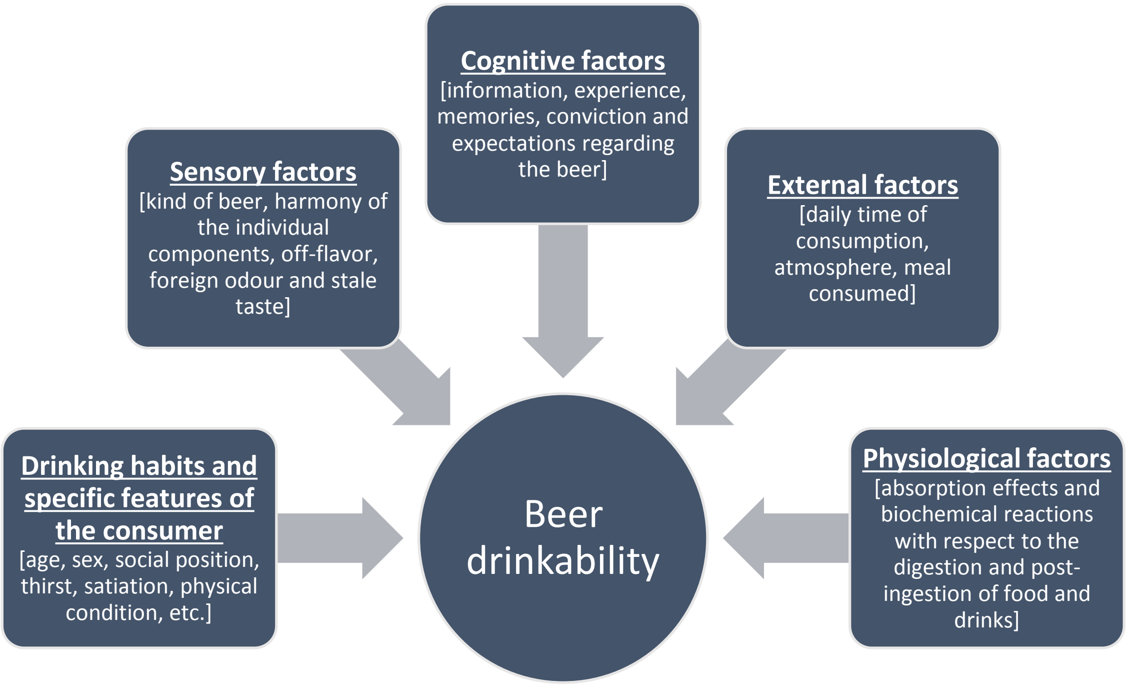
1. Introduction

Beer flavor instability causes beer to irreversibly degrade in flavor, aroma and taste[1]. During transport and storage, bottled beer has shown to be sensitive to exposure to an elevated temperature[2], vibrations[3], and light[4]. The rise in beer export[5,6], together with the increasing consumer demand for new and fresh beers[7], have caused the competitive landscape to change, resulting in an incentive for breweries to try to ameliorate flavor stability. Nevertheless, delaying the beer aging process is challenging to brewers and requires additional financial investments. However, neither academia, nor industry are certain whether these investment regarding flavor stability are justified. Furthermore, to what extent is the consumer able to distinguish between fresh and aged beer? Is fresh beer significantly preferred over aged beer and if so, is it consumed more or not? These research questions are the topic of this paper: the preference and drinkability of fresh over aged beer was investigated in a mixed respondents group.

(a) Definitions

As both the preference and the drinkability of beer are examined in this study, the two concepts have to be defined. Preference is characterized as "*a greater liking of one alternative over another or others*"[8]. The drinkability of beer is defined as constructed by Simpson (2011)[9] "*When speaking of drinkability most brewers take it to refer to the quality of beer which motivates a consumer to have another one – i.e. to have two pints when they intended to have one, or have three when they intended to have two. What motivates a consumer to do this is a complex mixture of situation, psychology, physiology, beer chemistry and beer physics*." There are a myriad of parameters influencing beer drinkability (presented in Figure 1): the drinking habits and specific features of the consumer, the sensory factors, the cognitive, and external and physiological factors[10].

Figure 1: Overview of the factors influencing beer drinkability



Source: Cejka et al. (2011)

One key difference that derives from the definitions is that while preference is related to the process of choosing between alternatives (based on previous experiences and memory), the drinkability also takes into account the volume/quantity consumed. An example to distinguish the two concepts can be presented: the drinkability of a lager beer will be higher than the drinkability of a dark high alcoholic specialty beer, even if the consumer does not have a preference for either one. Hence, both concepts are crucial to brewers from an economical and beer quality perspective.

(b) Literature on preference and drinkability

Fresh beer is assumed to be preferred and more drinkable than aged beer since the taste and aroma of fresh beer is better balanced compared to aged beer (sensory factors influencing drinkability - Figure 1). While preference with respect to the flavor instability of beer is frequently examined in literature[11,12], limited studies on the drinkability of beer are available, which emphasizes the uniqueness of this paper. Related research on the topic is developed by Guinard et al. (1998)[13] and French et al. (1993)[14] that investigate and describe the thirst-quenching character of beer. Nagao et al. (1998)[15] researched the post-ingestion effects of beer and the rate of gastric emptying, concluding that the beer with the lowest degree of stomach fullness was appraised to be tasty and highly drinkable. The objective of this experimental study was to fill and investigate the research gap with respect to the impact of flavor stability on the preference and the drinkability of beer. Cejka et al. (2011)[10] developed the methodology to assess beer drinkability and, therefore, proved to be a valuable source in establishing the current experimental work. The focus of this study was on detecting differences in the consumption behavior of respondents between drinking Belgian fresh and aged lager beer in a predefined experimental design. Insights on the willingness to pay for fresh over aged beer and other economic variables were beyond the scope of the study and will be considered in further research.

2. Material and methods

(a) Experimental design

In order to investigate the drinkability and preference of fresh over aged beer, the 'paired comparison test' was adopted, as is described by Cejka et al. (2011)[10]. In the experiment, respondents first drink small test samples (10cl.) of the two studied beers (fresh and aged beer, presented as Beer Y and Beer X respectively) prior to the general test. Afterwards, the respondents are free to decide which beer (25cl.) to consume. The volume and the time between consecutive consumptions was saved since a more drinkable beer is defined by a higher consumed volume and faster consumption. Additionally, a proxy for the preference of one of the two samples was derived by the identification of the first consumption after the duo test (prior to the actual experiment).

In order to study drinkability as close as possible to real life, a pub like environment was simulated. To this end, a university venue, in daytime used as a coffee bar and in evenings as a reception setting, was reserved and organized with tables, dimmed lights, and music. The researchers made sure that during the experiment responsible drinking was high on the agenda.

(b) Participants

While sensory evaluations are generally carried out by professional tasters in order to derive the organoleptic properties of the beer[10], in this research, the objective was to study the drinking behavior of the general consumer. Respondents of diverse age groups from both foreign countries and Belgium participated in the experiment. Diverse communication channels were utilized to distribute information concerning the experiment and to gather respondents. Moreover, a general call from the researcher's profile and targeted messages in the group 'expats in Antwerp' and 'PhD researchers in Antwerp' were generated by using social media (Facebook). Furthermore, a call was distributed in the university network to inform employees and students from the University of Antwerp. The tasters participated without a preceding selection process. Prior to the experiment, the respondent had to ensure to be of legal drinking age or older.

(c) Beer samples

The beer used in this experiment was a lager beer brewed by a Belgian brewery. Half of the beer samples were aged for 120 days (4 months) at 30°C in a climate controlled room (still air) (aged beer)while the other half was stored in a climate controlled room (still air) at 5°C during the same time period (fresh beer). The chemical parameters characterizing the beer samples are presented in Appendix A. The process of exposing the beer samples to an elevated temperature is a standardized procedure in beer stability research in order to simulate storage[2,16].

(d) Procedures

While the preference and drinkability of fresh and aged beer were assessed in this experiment, this information was not communicated to the respondents. Moreover, the participants assumed that two types of lager beer were tested (Beer X and Beer Y) differing only in recipe. Participants were required to register prior to the experiment and had to supply general information (e.g. age, gender, etc.) as well as their beer drinking habits. Participants were given six consumption vouchers with an identification number, assigned to each participant before the experiment. The consumption tickets were handed over to the respondent at the beginning of the experiment (after executing the duo test). The maximum number of consumptions was set to six as a balance between being able to investigate the drinking patterns over a longer time, and preventing irresponsible drinking. Respondents had to order a consumption of their preferred beer (X or Y) at the counter by handing over a consumption ticket (that is linked to their registered profile). A software program (built in Matlab 2015a) registered the time, the type of the sample (X or Y) and the identification number. It was ensured that there were no queues at the counter and that respondents were not able to see the type of beer the other respondents were served. Furthermore, the beer brand was not visible to the respondent. While the beers (25cl.) in the drinkability experiment were served in glasses as is in a normal pub, the glasses of the duo test (prior to the drinkability experiment) were served in black opaque plastic cups (10cl.). The reasoning of using the plastic cups was to design the duo test as a blind tasting experiment (with no visual clues like color or foam, the preference decision can only be based on taste and aroma). Before and during the experiment sandwiches and crackers were served in order to allow the respondents to perform the experiment without an empty stomach, as well as to clean their flavor palate. Before the actual test, a pre-test was organized with 17 respondents (17 out of the total 91 respondents) in order to have a test-run of the experiment. The duration of the experiment was 2 hours (informed to the respondents before the experiment), although the respondents did not enter simultaneous. Therefore, the total duration of the experiment was 3.5 hours.

(e) Data analysis

The data generated by this experiment was analyzed by variable methods:

- The Wilcoxon's signed rank sum test (e.g. in order to identify the beer type X or Y with the highest drinkability, i.e. the median of the difference between the number of fresh and aged samples per capita should be significantly different from zero)
- The Chi-square test [Likelihood, Pearson and Fischer] (e.g. identifying the significance of the segmentation of data, i.e. by building a contingency table and comparing the expected and observed frequency of success between different variables)
- The Chi-square test [Randomness test] (e.g. identifying the significance of success within one variable, i.e. comparing the expected and observed frequency of success for a specific variable)

The statistical analysis of the current research was performed within JMP®, Version Pro13. SAS Institute Inc., Cary, NC, 1989-2007.

3. Results

(a) Participants

In total, 91 respondents enrolled in the consumer investigation of which 35 respondents (38%) were foreigners and 56 respondents (62%) were Belgians. The international participants came from diverse countries (Figure 1a). In the current experiment, respondents with the age between 20 and 30 – 'Millennials' – predominantly participated in the experiment (Figure 1b). Furthermore, 56% of the enrolled respondents was male and 44% female. As presented in Table 1, the test population revealed relative moderation in their drinking habits.

Figure 1a: Segmentation of foreign respondents by home country – drinkability test
Figure 1b: Histogram of the age of the respondents – drinkability test

Figure 1a

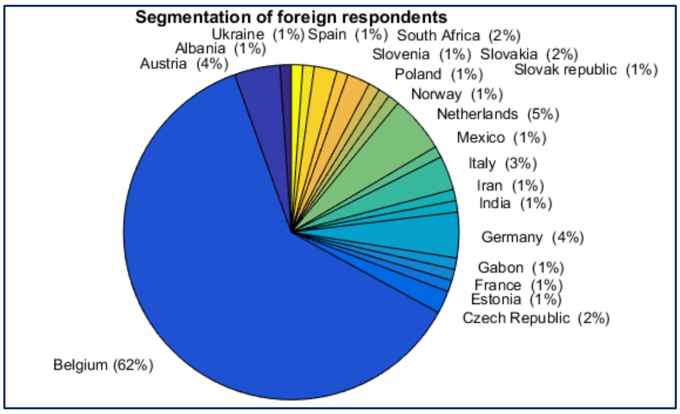


Figure 1b

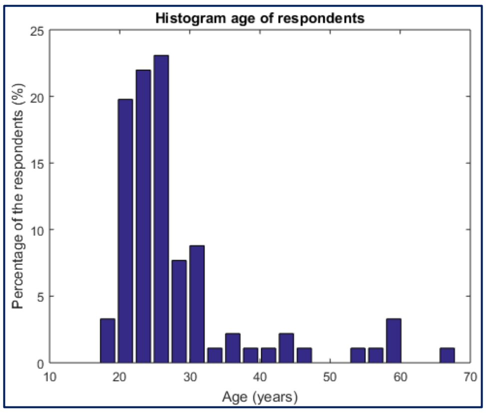


Table 1: Drinking habits – drinkability test

	Lager beers	Specialty beers
≤ 4 beers per month	48%	58%
> 4 beers per month	52%	42%

(b) Preference and drinkability results

The consumption pattern of all respondents was tracked throughout the experiment. In Figure 2a and 2b, the results of the drinkability experiment are presented ranked by table and age. In total, 376 beers of 25cl. were consumed of which 160 were aged and 216 were fresh (statistically significant difference according to the chi-square randomness test on a 5% significance level). In 65% of the cases the first consumption after the duo test was a fresh beer (59 out of 91 respondents – statistically significant difference according to the chi-square randomness test on a 5% significance level). Furthermore, 81% of the respondents that consumed fresh beer, as a first consumption chose the same type for their second consumption (84% for aged beer). In total 57 respondents kept on drinking their initial choice for every consumption.

From the figures, the reader may conclude that some respondents consumed the two beer types, although they performed the duo test prior to the experiment. This may be attributed to curiosity in the other beer type (as they were told they were different recipes), the influence of the other respondents (sitting at their table), or indifference towards the two offered beer types.

Additionally, Figure 2a indicates that there are strong indications that the table at which the respondent is sitting influences the consumption of the two beer types. Moreover, the tables can be segmented in fresh and aged tables (strong preference per table) while it is expected that the larger the table size the more the consumption volume per table would approach the overall average consumption of 58% fresh beer. A descriptive analysis of the nominal homogeneity index[17] (nHi), presented in Appendix B supports this result. The descriptive analysis of the age of the respondents and their consumption profile (Figure 2b) indicates that older respondents are more inclined to prefer fresh over aged beer.

The Wilcoxon's signed rank sum test was executed in order to test the overall drinkability for fresh and aged beer (with null-hypothesis H_0: The drinkability of fresh beer is identical to the drinkability of aged beer – the volume of fresh beer is identical to the volume of aged beer). The statistical analysis indicated that the null-hypothesis (H_0) should be rejected on a 10% significance level (p-value of 0.056), and, therefore, fresh beer is considered more drinkable than aged beer.

Nevertheless, while the preference for fresh over aged beer is manifest (65% of the first consumptions was fresh beer), which contributes to the higher consumption volumes of fresh beer, the study also indicates that several respondents are capable of consecutively drinking multiple aged beer consumptions (max. 6 consumptions). Therefore, consumers that drink aged beer do not necessarily consume less of the aged beer compared to the respondents drinking fresh beer.

The Wilcoxon's signed rank sum test was also executed on the time interval of the respondents drinking their first fresh, respectively aged, beer (with H_0: The drinkability of fresh beer is identical to the drinkability of aged beer – the volume of fresh beer is identical to the volume of aged beer). There was no statistical significant difference observed between the time of consumption of a fresh or an aged beer, and, therefore, the null-hypothesis (H_0) is not rejected (p-value of 0.731).

Figure 2a: Results of the performed drinkability test (respondents ranked by table)

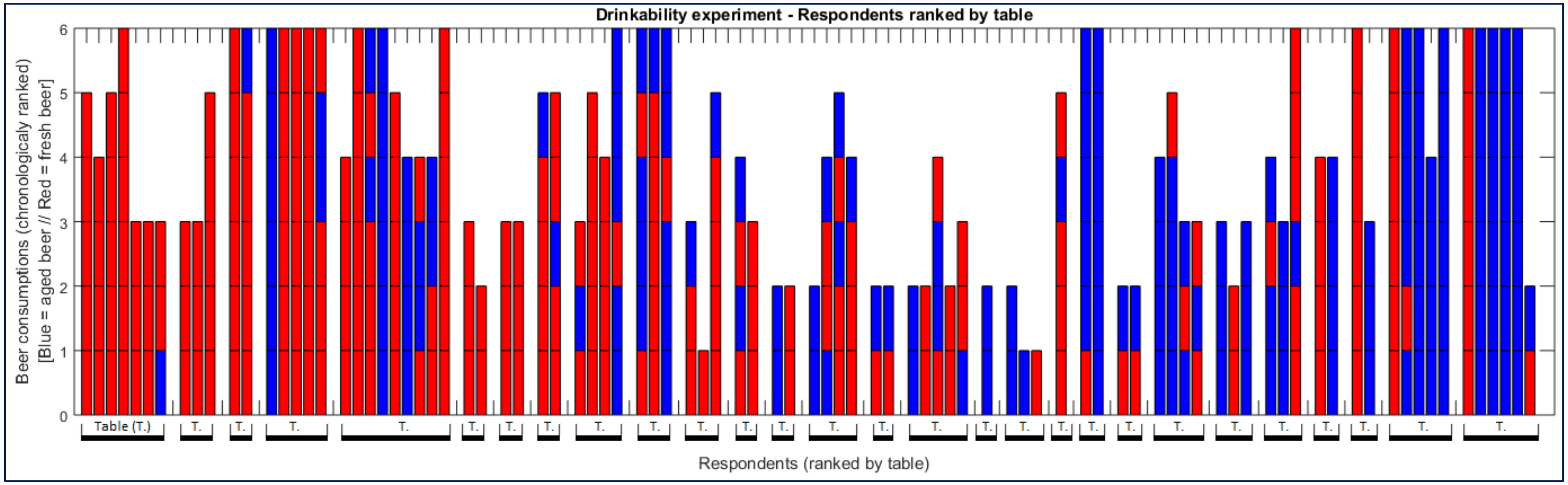
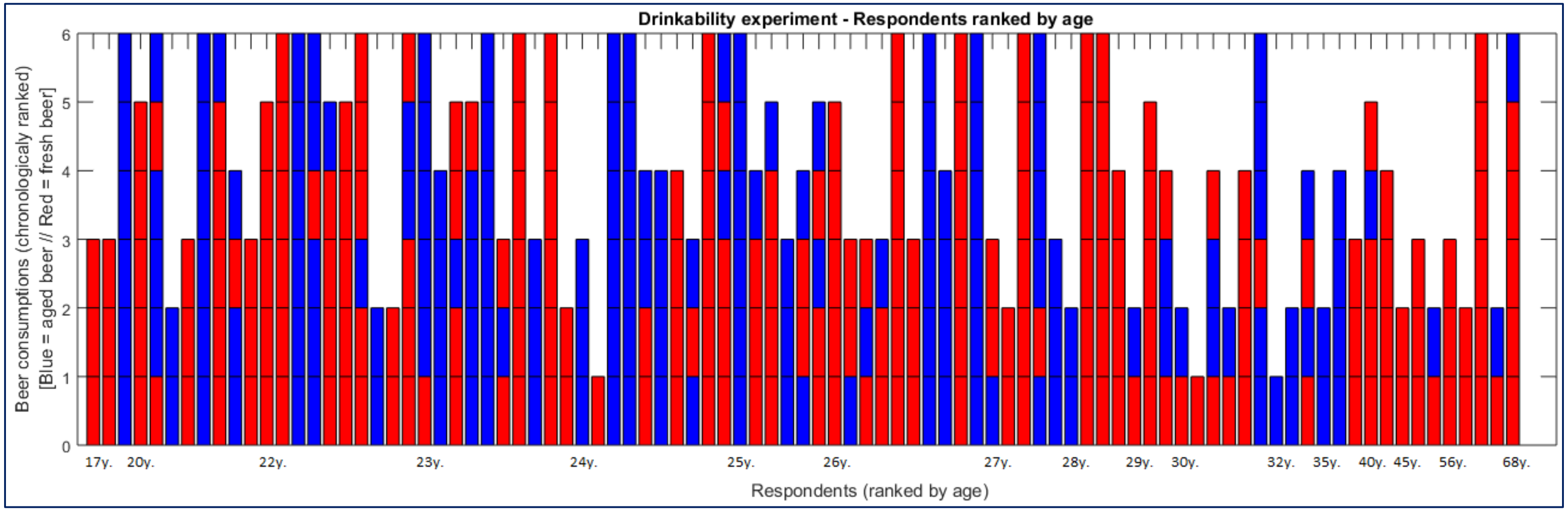


Figure 2b: Results of the performed drinkability test (respondents ranked by age)



An explorative analysis was performed on the parameters that may contribute to the increased drinkability and preference of fresh over aged beer. Therefore, contingency tables were built that present a segmentation of the total consumed volume of fresh and aged beer among the nationality, the age and the table size of the table at which they performed the experiment (Table 2). The contingency tables enable to perform statistical Chi-square tests [Likelihood, Pearson and Fischer, Randomness]. The following null-hypothesizes (H_0) were formed:

- The segmentation between Belgians and non-Belgians is not relevant with respect to the results of the drinkability experiment. [Likelihood, Pearson and Fischer]
- Within the category of the Belgian respondents, the consumed volume of fresh and aged beer is not significantly different from each other. [Randomness test].

Table 2: Contingency tables - influence of nationality, age and table size in consumption volume

NATIONALITY	Belgians (56p.)	Non-Belgians (35p.)	Total
Fresh	152 (= 64%)	64 (= 47%)	216 (= 57%)
Aged	87	73	160
TOTAL	239	137	376
AGE	Age (≤ 27y.) (62p.)	Age (> 27y.) (29p.)	Total
Fresh	146 (= 53%)	70 (= 71%)	216 (= 57%)
Aged	131	29	160
TOTAL	277	99	376
TABLE SIZE	Tables (≤ 2p. per table) (24p.)	Tables (> 2p. per table) (67p.)	Total
Fresh	56 (=64%)	160 (= 56%)	216 (= 57%)
Aged	32	128	160
TOTAL	88	288	376

The contingency tables of Table 2 and the performed statistical analysis indicate that the segmentation between Belgians and non-Belgians is relevant (Likelihood, Pearson and Fischer - rejection of H_0 with p-value < 0.001). Belgians also significantly consumed more fresh than aged beer (randomness test - rejection of H_0 with p-value < 0.05). The consumed volume of fresh and aged beer of non-Belgians is not significantly different from each other. With respect to the age of the respondents, the segmentation of the respondents younger and older than 27 years is relevant (Likelihood, Pearson and Fischer - rejection of H_0 with p-value < 0.001).

A sensitivity analysis was performed on the age of the respondents (with respect to the same analysis). The same but less substantial results were found when the segmented cut-off age was lowered to 26, 25 and 24 years (but not at 23 years old). Furthermore, the respondents older than 27 years significantly consumed more fresh than aged beer (on a significance level of 5%) while this finding was not observed for the younger respondents.

There are strong indications (Figure 2a) that the table size has an influence on the consumption pattern of the respondents. Therefore, a segmentation was performed on tables smaller and larger than 2 respondents per table. However, the statistical analysis indicates that the segmentation of the data is not relevant (Likelihood, Pearson and Fischer - acceptance of H_0 with p-value = 0.11). Nevertheless, the data indicates that respondents at tables smaller than or equal to 2 persons per table significantly consume more fresh beer. The same finding is not observed for tables larger than 2 persons. A similar analysis was performed in order to identify the impact of the gender of the respondents, and the consumption pattern (≤ and > 4 consumed lager beers per month) but no statistically significant findings were observed.

Further segmentations were performed in order to understand the findings of the drinkability experiment. The respondents were segmented by nationality, consumption pattern and age (Table 3). However, the results are predominantly indicative due to the relative small sample sizes. Nevertheless, from Table 3 can be deduced that Belgians older than 27 significantly prefer fresh over aged beer irrespective of the consumption habits of the respondent (sensitivity analysis indicates the cut-off at 25 years). Furthermore, Belgians younger than 27 and non-Belgians of all age categories that participated in this experiment did not significantly consume more fresh than aged beer. Additional analysis of the Belgian respondents older than 27 years old was executed with respect to the table sizes (Table 4). The results of Table 4 indicate that the higher consumed volume of fresh over aged beer (at different table sizes) is predominantly attributed to the Belgians that are older than 27. This finding might also indicate that the opinion of these respondents on the perceived flavor quality of the beer is less influenced by the other respondents at their table compared to the other age groups and nationalities.

Table 3: Contingency table influence of segmenting by nationality, consumption pattern and age in consumption volume

	(Belgian) + (≤ 4 consumed lager beers per month) + (Age ≤ 27y.) (16p.)	(Belgian) + (≤ 4 consumed lager beers per month) + (Age > 27y.) (8p.)	(Belgian) + (> 4 consumed lager beers per month) + (Age ≤ 27y.) (24p.)	(Belgian) + (> 4 consumed lager beers per month) + (Age > 27y.) (8p.)	Total (56p.)
Fresh	35 (= 57%)	**22 (= 85%)**	67 (= 55%)	**28 (= 87%)**	152 (= 64%)
Aged	26	**4**	53	**4**	87
TOTAL	61	**26**	120	**32**	239
	(non-Belgian) + (≤ 4 consumed lager beers per month) + (Age ≤ 27y.) (13p.)	(non-Belgian) + (≤ 4 consumed lager beers per month) + (Age > 27y.) (7p.)	(non-Belgian) + (> 4 consumed lager beers per month) + (Age ≤ 27y.) (9p.)	(non-Belgian) + (> 4 consumed lager beers per month) + (Age > 27y.) (6p.)	Total (35p.)
Fresh	26 (= 50%)	8 (= 53%)	18 (= 41%)	12 (= 46%)	64 (= 47%)
Aged	26	7	26	14	73
TOTAL	52	15	44	26	137

Table 4: Contingency table influence of segmenting by age and table size (Belgian respondents) in consumption volume

	(Belgian) + (Age > 27y.) + (Tables with ≤ 2p. per table) (9p.)	(Belgian) + (Age > 27y.) + (Tables with > 2p. per table) (7p.)	OTHER RESPONDENTS at tables with ≤ 2p. per table (15p.)	OTHER RESPONDENTS at tables with > 2p. per table (60p.)
Fresh	**28 (= 85%)**	**22 (= 88%)**	28 (= 51%)	138 (= 52%)
Aged	**5**	**3**	27	125
TOTAL	**33**	**25**	55	263

4. Discussion

In this paper, statistical significant results were found with respect to the parameters that describe and contribute to the preference and drinkability results concerning fresh and aged beer. The nationality (Belgian vs. non-Belgian), age, and size of the table the respondent was sitting, were identified as relevant and significant parameters. While the explanatory power of the variables cannot be doubted, the researchers of this experimental study rather expect that the influencing and mimicking behavior of the human species explain the results. More specifically, Belgians and respondents that have reached the age of 24-27 years and older (as compared to non-Belgians and respondents younger than 24-27 years old) are believed to be more certain of the beer of their choice and less influenced by the other respondents. Nevertheless, this insight does not invalidate the presented results. On the contrary, as we designed the experiment to mimic a pub environment, the influence of peers is a factor we cannot rule out.

From this study, we can deduce that the drinkability and preference of fresh beer is significantly higher compared to aged beer. During the duo test (prior to the actual experiment), the exposure to other people's opinion is little (due to no communication between respondents), and, therefore, the higher preference for fresh beer should be emphasized. The increased preference for fresh beer also contributes to the total volume of the fresh beer consumed and, as a consequence, the drinkability results. Since multiple respondents consecutively consumed six aged consumptions, it cannot be concluded that the consumption of aged beer results in a lower consumption volume (per capita) as compared to fresh beer.

In conclusion, the flavor stability of beer predominantly influences the overall satisfaction, i.e. preference effects of the consumer. The fact that people consume aged beer without further consideration is not remarkable since severely flavor degraded beer reaches the exported markets and is sold and consumed without further complaints[18]. However, the latter information is not a safe conduct in continuing to export flavor degraded beer. The preference for fresh beer means that the flavor degraded beer is less competitive in a pub-environment and, therefore, exported (flavor degraded) beer loses a competitive edge.

Nevertheless, experiments on a bigger scale should be performed to further validate these results. The experiment could be expanded to include the assessment of other economic factors like the willingness to pay (e.g. by including and changing the price respondents pay for ordering a fresh and aged beer), which can provide brewers a framework for benchmarking investment decisions in flavor stability.

5. Conclusions

The drinkability experiment induces the following conclusions:

- The drinkability of fresh beer is statistically significantly higher for fresh than for aged beer (216 consumptions fresh beer and 160 consumptions aged beer – 35% higher consumption volume of fresh beer)
- The preference for fresh beer is statically significantly higher for fresh than for aged beer (65% fresh beer as a first consumption)
- The consumption of aged beer does not discourage the respondent to stop further drinking of aged beer (there are 9 respondents with 6 aged beer consumptions)
- Belgians that are older than 27 years (sensitivity analysis indicates the cut-off at 24 years) have a strong preference for fresh beer (and perceive to be less influenced by other respondents (at their table)). Foreign respondents and Belgians younger than 27 years (sensitivity analysis indicates the cut-off at 24 years) have no statistically significant preference for fresh beer.
- The tables and table sizes significantly influence the type of beer consumed (since respondents influence each other). Moreover, the influencing and mimicking behavior of respondents is an important parameter that should be taken into account.
- The influence of the drinking behavior and gender were not significant. The influence of smoking was not assessed (due to the limited number of smokers in the respondents group).

As a consequence, and taking into consideration the prior conclusions, brewers should be aware of the impact of the beer flavor stability problem. Moreover, this research suggests the possible impact of investing in beer flavor stability since this action may alter the competitive forces. Furthermore, in an ever digital world it is essential to not underestimate the influence of other people's opinions (e.g. groups of people in a pub or (online) expert reviews) on the mimicking behavior of consumers[19].

6. Appendices

A. Chemical profile of the beer samples

Table 5: Chemical characteristics beer samples

Density (g/cm3)	*1.006*	*SG 20/20*	*1.008*
Alc. (V/V%)	*4.92*	*RDF (%)*	*67.52*
Alc. (m/m%)	*3.86*	*ADF (%)*	*81.96*
Er (g/100ml)	*3.89*	*Cal. (kJ/100 ml)*	*170.52*
Ea (g/100ml)	*2.06*	*P (g/100ml)*	*11.84*
Legend: pH (acidity), Alc. (Alcoholic volume or weight in %), Er (realistic extract), Ea (Apparent extract), RDF (Realistic degree of fermentation), ADF (Apparent degree of fermentation), Cal. (Caloric content)			

Table 6: A more detailed investigation of the permanent haze, cold haze and color

EBC	*Permanent Haze (H90)*	*Permanent Haze (H25)*	*Cold Haze (H90)*	*Cold Haze (H25)*	*Color*
Fresh beer	0.38 / 0.39	0.2 / 0.12	0.89 / 0.92	1.05 / 1.58	7.25 / 7.63
Aged beer	1.31 / 1.31	0.5 / 0.38	3.88 / 3.55	2.09 / 1.92	8.08 / 8.02

Table 7: A more detailed investigation of the individual *trans*- and *cis*-iso-α-acids

Conc. x 10-3 g/L	*Trans*-isoco-humulone	*Cis*-isoco-humulone	*Trans*-iso-humulone	*Cis*-iso-humulone	*Trans*-isoad-humulone	*Cis*-isoad-humulone	*Total*	*TC-ratio (%)*
Fresh beer	2.59 / 2.48	5.98 / 6.00	2.95 / 2.86	6.27 / 6.34	0.62 / 0.59	1.43 / 1.39	19.84 / 19.66	45.22 / 43.27
Aged beer	1.85 / 1.79	5.79 / 5.81	2.06 / 1.99	6.12 / 6.26	0.39 / 0.35	1.38 / 1.36	17.59 / 17.56	32.83 / 31.32

Table 8: A more detailed investigation of the individual aldehydes

Conc. x 10-6 g/L	2-methyl-propanal	2-methyl-butanal	3-methyl-butanal	hexanal	furfural	methional	*Benz-aldehyde*	*Phenyl-acet-aldehyde*	*(E)-2-nonenal*
Fresh beer	1.5 / 1.5 / 1.7	0.8 / 0.8 / 0.9	3.6 / 3.5 / 3.7	0.4 / 0.3	18.3 / 16.1 / 19.5	0.8 / 0.6 / 0.8	0.9 / 0.7 / 0.8	6.4 / 6.8 / 7.5	0.07 / 0.06 / 0.10
Aged beer	8.7 / 8.7 / 8.7	2.4 / 2.4 / 2.5	7.2 / 7.2 / 7.5	1.0 / 1.1	338.4 / 338.5/ 336.7	2.2 / 1.2 / 1.6	1.5 / 1.4 / 1.5	9.4 / 9.4 / 11.1	0.13 / 0.16 / 0.012

B. Nominal homogeneity index

The nominal homogeneity index (nHi) = $\frac{1-\sum_{i=1}^{k}(F(i))^2}{\frac{k-1}{k}}$

With
K= the number of categories
F= the relative percentages

Since the current analysis is performed with two categories (fresh and aged beer), the prior described formula can be simplified.

The nominal homogeneity index (nHi) = $4 * p1 * (1 - p1)$

With
p1= the percentage of consumed fresh beer (per table)
p2 = (1 − p1) = the percentage of consumed aged beer (per table)

If
nHi = 0, then there is a clear preference for fresh or aged beer
nHi = 1, then there is a 50% preference for / consumption of fresh and a 50% preference / consumption of aged beer

When the nHi of all respondents was calculated the number 0.98 was found. This number indicates there was a close to 50-50% consumption of fresh and aged beer (in the experiment, 58% of the consumed beer was fresh beer). The nHi calculated by table is mostly considerably different from 0.98. We expect the variation in nHi for small tables to be large and larger tables to be smaller. There are no statistics tests developed (yet) to test this hypothesis.

Table 9: The nominal homogeneity index (nHi) for fresh and aged beer segmented by table

Table size	nHi	Table size	nHi	Table size	nHi	Table size	nHi
1 p.	0	2 p.	1	3 p.	0	4 p.	0.78
1 p.	0.64	2 p.	1	3 p.	0.98	5 p.	0.94
2 p.	0	2 p.	1	3 p.	0.69	5 p.	0.78
2 p.	0.31	2 p.	0.88	3 p.	0.75	5 p.	0.75
2 p.	0	2 p.	0.31	4 p.	0.99	6 p.	0.68
2 p.	0.64	2 p.	1	4 p.	0.89	7 p.	0.13
2 p.	0.82	3 p.	0.75	4 p.	1	9 p.	0.92

Legend	
0.64	The background color is green: The most consumed type of beer at the current table was fresh beer
0.31	The background color is orange: The most consumed type of beer at the current table was aged beer
1	The background color is grey: There is a 50% preference for / consumption of fresh and a 50% preference / consumption of aged beer

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Appendices

Appendix 1 (Specifications of the performed chemical tests)

Referred to in different Chapters of the dissertation

- Oxygen concentrations: (TPO – Total package oxygen –, HSO – Headspace oxygen –, DO – Dissolved oxygen –)

  Determination of oxygen concentrations:

  Oxygen in bottled beer is determined using the 'Haffmans Inpack TPO/CO_2 meter Type c-TPO'. The measurement is performed in a sealed bottle and the principle is based on O_2 dependent fluorescence of the sensor. Calibration of the sensor is checked periodically as well as the sensor condition and performance. The instrument measures dissolved oxygen (DO) and headspace oxygen (HSO). The total package oxygen (TPO) is calculated as the sum of DO and HSO values. All values are calculated on the beer volume in the package and are given in µg/l.
- Beer colour: IOB method: 9.1[22];
- Iso-α-acids: (*trans*-isocohumulone, *cis*-isocohumulone, *trans*-isohumulone, *cis*-isohumulone, *trans*-isoadhumulone, *cis*-isoadhumulone, total iso-α-acids, T/C-ratio)

  UPLC determination of iso-α-acids:

  UPLC separations of iso-α-acids were performed on an Acquity UPLC (Waters, Milford, USA), consisting of a PDA detector, column heater, sample manager, binary solvent delivery system and an Acquity UPLC HSS C18 1.8µm column (2.1 i.d. × 150 mm; Waters, USA). Data reprocessing was done using Empower 2 software. Chromatographic conditions were: eluent A: milli-Q water adjusted to pH 2.80 with H_3PO_4 (85%, Merck, Darmstadt, Germany); eluent B: HPLC-grade CH_3CN (Novasol, Belgium). Elution: isocratic using 52% (v/v) solvent B and 48% (v/v) solvent A. Analysis time: 12 min. Flow rate: 0.5 mL.min^{-1}. Column temperature: 35°C. UV detection: 270 nm (iso-α-acids). The *trans*/*cis* iso-α-acids ratio (T/C-ratio) was based on the measured concentrations of *trans*- and *cis*-isocohumulone and *trans*- and *cis*-isohumulone[20].
- Aldehydes: (2-methylpropanal, 2-methylbutanal, 3-methylbutanal, hexanal, furfural, methional, benzaldehyde, phenylacetaldehyde, (E)-2-nonenal, total aldehydes)

  GC-MS determination of aldehydes:

  Volatile aldehydes in beer were determined according to Vesely et al. (2003)[89], using headspace-solid phase microextraction (HS-SPME) with on-fibre PFBOA (*o*-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine) derivatization and capillary gas chromatography/mass spectrometry (CGC/MS) (Dual Stage Quadrupole (DSQ™ II) GC/MS system, Interscience Benelux). The DSQ™ II was coupled to a Thermo Trace GC Ultra (Interscience Benelux) equipped with a CTC-PAL autosampler (including SPME sampling), a split/splitless injector with a narrow glass inlet liner (0.5 ml volume), and a RTX-1 fused-silica capillary column (40 m × 0.18 mm i.d. × 0.2 µm film thickness, Restek, Interscience Benelux). Data reprocessing was done by the XCalibur™ data system (Thermo Electron Corporation).

Overview of the measurement errors of the performed chemical analyses and additional information on the chemical tests.

Table 28: Systematic error of performed chemical tests

	Chemical test/parameter	**Systematic error**
Oxygen	TPO, HSO, DO	1ppb +/- 2%
Color	Absorption 430 nm	0,062 (EBC)
Iso-α-acids	*trans*-isocohumulone	0.017 mg/l
	cis-isocohumulone	0.011 mg/l
	trans-isohumulone	0.008 mg/l
	cis-isohumulone	0.018 mg/l
	trans-isoadhumulone	0.002 mg/l
	cis-isoadhumulone	0.019 mg/l
Aldehydes	2-methylpropanal	1.61 µg/l
	2-methylbutanal	0.60 µg/l
	3-methylbutanal	2.01 µg/l
	Hexanal	0.20 µg/l
	Furfural	4.37 µg/l
	Methional	0.72 µg/l
	Benzaldehyde	0.30 µg/l
	Phenylacetaldehyde	1.24 µg/l
	(E)-2-nonenal	0.0052 µg/l

Source: KU Leuven technology campus Ghent, 2017[88]

Appendix 2 (Additional information on the vibration measurements during transport)

Referred to in Part 5 Chapter 1 section 1.3

The transports, attended in the context of this research, are presented:

Truck transport

- Transport 1: 3/02/2016 (rec. time: 9hrs. 44mins) [air-ride spring]
- Transport 2: 12/04/2016 (rec. time: 3hrs. 26mins) [Leaf spring]
- Transport 3: 23/08/2016 (rec. time: 2hrs. 28mins) [air-ride spring]
- Transport 4: 27/09/2016 (rec. time: 1hrs 50mins) [air-ride spring]

Train transport

- Transport 1: 27/06/2016 (rec. time: 1hrs. 43mins) [Leaf spring with diesel engine]
- Transport 2: 2/08/2016 (rec. time: 2hrs. 10mins) [Leaf spring with diesel engine]
- Transport 3: 3/08/2016 (rec. time: 3hrs. 55mins) [Leaf spring with diesel engine]

Specifications vibration measurements (truck):

- 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).

The authors of current research had the objective to measure the most extreme vibrations. Therefore, the measuring devices were located on top of a wooden pallet 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]).

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 order 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.

Specifications vibration measurements (train): Railcar: Max. 90 tons (of which 24 tons cargo), In total 15-25 wagons

Appendix 3 (Raw data on the chemical analysis of the beer flavor parameters of Part 5 Chapter 2 section 2.2.b)

Referred to in Part 5 Chapter 2 section 2.2.b

Table 29: Color measurements (absorption 430 nm) after the vibration experiments and after an additional aging of 30 days at 30°C

		Color (fresh beer) – absorption 430 nm	Color (Aged after vibration experiment for 30 days at 30°C) – absorption 430 nm
Reference samples	LB	7.5 EBC	8.1 EBC
	BSWithout	13.5 EBC	13.9 EBC
	BSWith	21.4 EBC	22.1 EBC
	DSWith	73.4 EBC	75.5 EBC
Setup 1: vibrations of 5 Hz and 15 m/s^2 during 4 days	LB	7.7 EBC	8.1 EBC
	BSWithout	13.7 EBC	13.9 EBC
	BSWith	21.5 EBC	21.9 EBC
	DSWith	57.1 EBC	58.0 EBC
Setup 2: vibrations of 15 Hz and 15 m/s^2 during 4 days	LB	7.6 EBC	8.1 EBC
	BSWithout	13.6 EBC	13.9 EBC
	BSWith	21.4 EBC	21.7 EBC
	DSWith	59.4 EBC	59.3 EBC
Setup 3: vibrations of 30 Hz and 15 m/s^2 during 4 days	LB	7.6 EBC	8.1 EBC
	BSWithout	13.6 EBC	14.2 EBC
	BSWith	21.4 EBC	21.9 EBC
	DSWith	59.4 EBC	68.0 EBC
Setup 4: vibrations of 50 Hz and 15 m/s^2 during 4 days	LB	7.6 EBC	8.1 EBC
	BSWithout	13.6 EBC	14.2 EBC
	BSWith	21.4 EBC	21.9 EBC
	DSWith	58.0 EBC	59.5 EBC

Source: Own measurements

Table 30: Iso-α-acids measurements (absorption 430 nm) after the vibration experiments and after an additional aging of 30 days at 30°C (raw data)

	10^{-3} g/l	*Trans-* isocohumulone	*Cis-* isocohumulone	*Trans-* isohumulone	*Cis-* isohumulone	*Trans-* isoadhumulone	*Cis-* isoadhumulone
Reference samples	LB	1.09 / 1.08 **0.88 / 0.9**	5.39 / 5.32 **5.2 / 5.23**	1.19 / 1.16 **0.93 / 0.95**	5.58 / 5.57 **5.51 / 5.64**	0.2 / 0.18 **0.14 / 0.16**	1.21 / 1.19 **1.1 / 1.1**
	BSWithout	0.56 / 0.56 **0.47 / 0.46**	3.44 / 3.45 **3.42 / 3.42**	0.74 / 0.73 **0.6 / 0.6**	4.86 / 4.87 **4.75 / 4.75**	0.11 / 0.12 **0.1 / 0.1**	0.97 / 0.96 **0.99 / 1.0**
	BSWith	2.82 / 2.81 **2.43 / 2.47**	8.17 / 8.17 **8.17 / 8.18**	3.11 / 3.09 **2.8 / 2.8**	11.16 / 11.11 **11.17 / 11.15**	0.62 / 0.61 **0.6 / 0.59**	2.04 / 2.11 **2.11 / 2.1**
	DSWith	1.88 / 1.87 **1.41 / 1.42**	4.2 / 4.17 **3.85 / 3.87**	1.91 / 1.92 **1.51 / 1.5**	5.26 / 5.28 **4.65 / 4.6**	0.52 / 0.53 **0.39 / 0.40**	1.13 / 1.08 **1.02 / 1.0**
Setup 1: vibrations of 5 Hz and 15 m/s² during 4 days	LB	1.07 / 1.07 **0.95 / 0.94**	5.29 / 5.31 **5.3 / 5.29**	1.09 / 1.08 **1.01 / 1.0**	5.52 / 5.52 **5.5 / 5.51**	0.19 / 0.19 **0.15 / 0.12**	1.12 / 1.11 **1.13 / 1.1**
	BSWithout	0.57 / 0.57 **0.47 / 0.47**	3.48 / 3.45 **3.42 / 3.4**	0.73 / 0.74 **0.65 / 0.63**	4.88 / 4.94 **4.78 / 4.62**	0.13 / 0.12 **0.1 / 0.1**	0.99 / 0.99 **0.96 / 0.96**
	BSWith	2.83 / 2.82 **2.46 / 2.45**	8.07 / 8.05 **8.3 / 8.27**	3.15 / 3.1 **2.81 / 2.87**	10.93 / 11.02 **11.2 / 11.25**	0.66 / 0.68 **0.57 / 0.57**	2.07 / 2.11 **2.1 / 2.11**
	DSWith	2.05 / 2.06 **1.65 / 1.66**	4.46 / 4.48 **4.28 / 4.24**	2.11 / 2.15 **1.82 / 1.79**	5.64 / 5.64 **5.56 / 5.58**	0.54 / 0.58 **0.52 / 0.48**	1.21 / 1.25 **1.23 / 1.2**
Setup 2: vibrations of 15 Hz and 15 m/s² during 4 days	LB	1.06 / 1.07 **0.9 / 0.9**	5.3 / 5.33 **5.17 / 5.16**	1.09 / 1.1 **0.89 / 0.87**	5.56 / 5.53 **5.43 / 5.3**	0.19 / 0.19 **0.14 / 0.13**	1.12 / 1.12 **1.05 / 1.06**
	BSWithout	0.55 / 0.55 **0.46 / 0.44**	3.4 / 3.37 **3.43 / 3.42**	0.68 / 0.65 **0.56 / 0.59**	4.49 / 4.43 **4.5 / 4.5**	0.15 / 0.14 **0.1 / 0.1**	1.0 / 1.0 **0.95 / 0.98**
	BSWith	2.78 / 2.76 **2.32 / 2.34**	8.1 / 8.08 **8.06 / 8.12**	3.01 / 3.01 **2.56 / 2.6**	10.88 / 10.83 **10.73 / 10.91**	0.64 / 0.67 **0.59 / 0.59**	1.97 / 1.96 **1.93 / 1.95**
	DSWith	1.76 / 1.77 **1.54 / 1.56**	3.89 / 3.89 **4.15 / 4.19**	1.8 / 1.78 **1.72 / 1.72**	4.9 / 4.86 **5.43 / 5.44**	0.45 / 0.45 **0.5 / 0.5**	1.1 / 1.09 **1.18 / 1.16**
Setup 3: vibrations of 30 Hz and 15 m/s² during 4 days	LB	1.1 / 1.1 **0.9 / 0.93**	5.44 / 5.4 **5.2 / 5.22**	1.15 / 1.13 **0.91 / 0.94**	5.92 / 5.89 **5.55 / 5.66**	0.19 / 0.17 **0.17 / 0.17**	1.18 / 1.17 **1.06 / 1.12**
	BSWithout	0.57 / 0.57 **0.47 / 0.47**	3.52 / 3.47 **3.4 / 3.42**	0.78 / 0.74 **0.57 / 0.63**	5.1 / 4.89 **4.59 / 4.59**	0.12 / 0.12 **0.1 / 0.1**	0.98 / 0.99 **0.97 / 1.0**
	BSWith	2.75 / 2.76 **2.24 / 2.33**	8.22 / 8.21 **7.99 / 8.21**	3.06 / 3.03 **2.43 / 2.6**	11.26 / 11.23 **10.99 / 11.0**	0.67 / 0.66 **0.54 / 0.59**	2.14 / 2.13 **1.88 / 1.99**
	DSWith	1.89 / 1.88 **1.31 / 1.29**	4.27 / 4.22 **3.79 / 3.8**	1.92 / 1.95 **1.41 / 1.4**	5.27 / 5.24 **4.82 / 3.78**	0.51 / 0.5 **0.39 / 0.38**	1.18 / 1.18 **0.94 / 0.92**
Setup 4: vibrations of 50 Hz and 15 m/s² during 4 days	LB	1.06 / 1.05 **0.92 / 0.91**	5.4 / 5.36 **5.21 / 5.14**	1.13 / 1.11 **0.92 / 0.9**	5.82 / 5.79 **5.58 / 5.44**	0.2 / 0.18 **0.12 / 0.13**	1.18 / 1.16 **1.13 / 1.15**
	BSWithout	0.57 / 0.57 **0.48 / 0.49**	3.5 / 3.53 **3.44 / 3.42**	0.76 / 0.75 **0.58 / 0.62**	4.99 / 5.01 **4.79 / 4.76**	0.1 / 0.1 **0.1 / 0.11**	1.0 / 1.02 **1.02 / 1.0**
	BSWith	2.88 / 2.89 **2.32 / 2.31**	8.28 / 8.32 **7.91 / 7.9**	3.24 / 3.23 **2.41 / 2.4**	11.44 / 11.44 **9.98 / 10**	0.68 / 0.7 **0.54 / 0.57**	2.1 / 2.1 **1.8 / 1.8**
	DSWith	1.82 / 1.83 **1.51 / 1.53**	4.07 / 4.1 **4.1 / 4.12**	1.92 / 1.99 **1.74 / 1.72**	5.28 / 5.3 **5.4 / 5.34**	0.53 / 0.54 **0.48 / 0.48**	1.01 / 1.05 **1.1 / 1.08**
Legend: Fresh beer (normal fond) - Aged beer after vibration experiment for 30 days at 30°C (**Bold fond**)							

Source: Own measurements

Table 31: Measured aldehyde concentrations after the vibration experiment and after an additional aging of 30 days at 30°C

	10^{-6} g/l	*2-methylpropanal*	*2-methylbutanal*	*3-methylbutanal*	*hexanal*	*furfural*	*methional*	*benzaldehyde*	*phenylacetaldehyde*	*(E)-2-nonenal*
Reference samples	LB	13.3 / 13.7 / 14.2 / 14.7 **36.2 / 41.4**	0.8 / 0.9 / 0.9 / 1.0 **2.0 / 2.0**	2.7 / 3.0 / 3.0 / 3.3 **9.0 / 9.7**	0.3 / 0.3 / 0.2 / 0.3 **0.4 / 0.4**	44.2 / 48.1 / 46.8 / 50.8 **113.9 / 116.4**	2.3 / 3.2 / 4.1 / 4.0 **12.2 / 9.8**	0.6 / 0.6 / 0.6 / 0.6 **0.8 / 0.8**	9.2 / 9.6 / 18.6 / 18.9 **14.3 / 13.3**	0.2 / 0.2 / 0.2 / 0.2 **0.06 / 0.06**
	BSWithout	9.1 / 9.4 / 9.8 / 9.9 **25.5 / 26.1**	2.1 / 2.3 / 2.5 / 2.6 **3.9 / 4.0**	7.6 / 8.3 / 7.9 / 8.5 **16.3 / 17.9**	0.5 / 0.5 / 0.5 / 0.5 **0.7 / 0.7**	117.3 / 123.6 / 134.8 / 139.0 **169.1 / 163.5**	7.5 / 7.0 / 12.5 / 11.3 **7.8 / 11.7**	1.2 / 1.2 / 1.0 / 1.2 **1.3 / 1.4**	11.9 / 13.2 / 27.5 / 26.4 **13.3 / 17.2**	0.08 / 0.09 / 0.11 / 0.11 **0.14 / 0.14**
	BSWith	2.5 / 2.8 / 1.7 / 1.8 **18.3 / 19.0**	0.6 / 0.8 / 0.5 / 0.6 **1.7 / 1.7**	3.2 / 3.9 / 2.3 / 2.8 **9.1 / 9.6**	0.2 / 0.2 / 0.1 / 0.1 **0.2 / 0.2**	10.5 / 10.5 / 5.8 / 5.6 **37.3 / 40.7**	3.7 / 4.1 / 6.9 / 8.9 **3.8 / 5.1**	0.8 / 0.7 / 0.7 / 0.7 **0.9 / 0.9**	10.0 / 10.0 / 28.7 / 27.9 **11.3 / 11.2**	0.01 / 0.01 / 0.01 / 0.02 **0.03 / 0.03**
Setup 1: vibr. 5 Hz and 15 m/s² during 4 days	LB	14.3 / 15.1 **37.8 / 42.8**	0.9 / 0.9 **2.0 / 2.1**	3.1 / 3.4 **9.5 / 10.0**	0.3 / 0.3 **0.5 / 0.5**	51.3 / 53.8 **112.0 / 114.4**	4.2 / 3.3 **11.1 / 10.3**	0.7 / 0.6 **0.8 / 0.8**	12.1 / 10.0 **13.7 / 14.3**	0.02 / 0.02 **0.05 / 0.05**
	BSWithout	9.8 / 10.2 **25.3 / 28.4**	2.4 / 2.5 **4.0 / 4.1**	8.6 / 9.1 **16.9 / 18.2**	0.5 / 0.5 **0.7 / 0.7**	127.3 / 134.5 **165.0 / 187 /4**	7.5 / 7.4 **11.2 / 10.0**	1.3 / 1.3 **1.5 / 1.6**	13.6 / 13.3 **17.7 / 14.1**	0.09 / 0.08 **0.14 / 0.15**
	BSWith	2.7 / 2.7 **18.6 / 19.8**	0.6 / 0.8 **1.6 / 1.8**	3.2 / 3.7 **9.1 / 9.9**	0.2 / 0.2 **0.3 / 0.3**	10.4 / 10.7 **39.8 / 46.1**	3.2 / 3.5 **4.8 / 5.2**	0.6 / 0.7 **1.0 / 0.9**	9.8 / 8.7 **11.8 / 12.0**	0.01 / 0.01 **0.04 / 0.04**
Setup 2: vibr. 15 Hz and 15 m/s² during 4 days	LB	15.0 / 15.6 **40.6 / 44.7**	0.9 / 0.9 **2.1 / 2.1**	3.0 / 3.4 **9.6 / 10.2**	0.3 / 0.3 **0.6 / 0.5**	56.0 / 58.5 **123.4 / 128.3**	3.1 / 2.8 **10.9 / 10.0**	0.6 / 0.6 **0.9 / 0.9**	9.6 / 9.6 **13.7 / 14.3**	0.02 / 0.02 **0.06 / 0.05**
	BSWithout	9.5 / 10.1 **25.9 / 25.3**	2.2 / 2.4 **3.9 / 3.9**	8.0 / 8.8 **16.5 / 16.8**	0.5 / 0.5 **0.7 / 0.8**	132.9 / 141.1 **158.9 / 148.4**	7.1 / 7.2 **7.6 / 9.8**	1.1 / 1.2 **1.4 / 1.5**	13.3 / 13.0 **11.7 / 15.0**	0.09 / 0.09 **0.14 / 0.14**
	BSWith	2.7 / 3.0 **22.9 / 23.7**	0.7 / 0.8 **2.1 / 2.1**	3.2 / 4.0 **10.6 / 11.2**	0.2 / 0.3 **0.4 / 0.3**	12.0 / 12.1 **50.1 / 52.6**	2.9 / 3.5 **8.3 / 6.5**	0.7 / 0.6 **0.9 / 0.9**	8.0 / 10.2 **20.9 / 11.0**	0.02 / 0.02 **0.05 / 0.04**
Setup 3: vibr. 30 Hz and 15 m/s² during 4 days	LB	15.9 / 16.4 **39.3 / 45.8**	1.0 / 1.1 **2.1 / 2.1**	3.4 / 3.9 **9.5 / 10.4**	0.3 / 0.3 **0.5 / 0.4**	53.4 / 60.3 **124.4 / 140.4**	6.4 / 6.9 **13.4 / 16.5**	0.6 / 0.7 **0.8 / 0.8**	25.8 / 25.6 **15.5 / 17.8**	0.03 / 0.03 **0.05 / 0.05**
	BSWithout	10.1 / 10.3 **27.0 / 28.8**	2.7 / 2.8 **4.5 / 4.7**	8.5 / 8.9 **18.9 / 20.4**	0.5 / 0.5 **0.8 / 0.8**	137.5 / 141.0 **179.5 / 172.8**	15.9 / 10.0 **10.9 / 11.1**	1.4 / 1.3 **1.9 / 2.0**	33.5 / 25.4 **16.9 / 16.8**	0.11 / 0.12 **0.14 / 0.15**
	BSWith	2.2 / 2.5 **20.6 / 22.4**	0.7 / 0.8 **1.9 / 2.1**	2.6 / 3.2 **9.8 / 10.5**	0.1 / 0.1 **0.3 / 0.3**	8.0 / 8.7 **42.6 / 44.8**	5.2 / 4.9 **5.8 / 6.0**	0.7 / 0.7 **0.8 / 0.9**	24.6 / 18.2 **11.5 / 11.7**	0.02 / 0.02 **0.04 / 0.04**
Setup 4: vibr. 50 Hz and 15 m/s² during 4 days	LB	16.1 / 16.4 **39.7 / 44.8**	1.0 / 1.1 **2.1 / 2.1**	3.4 / 3.8 **9.5 / 10.4**	0.2 / 0.3 **0.5 / 0.4**	52.6 / 60.3 **124.4 / 140.4**	5.6 / 4.5 **9.8 / 10.4**	0.6 / 0.7 **0.8 / 0.8**	20.5 / 20.3 **13.4 / 13.9**	0.03 / 0.03 **0.09 / 0.05**
	BSWithout	9.9 / 10.6 **27.1 / 28.2**	2.5 / 2.8 **4.4 / 4.6**	8.0 / 9.2 **18.6 / 20.8**	0.5 / 0.5 **0.7 / 0.9**	140.3 / 150.5 **187.6 / 164.4**	13.2 / 16.6 **10.6 / 14.1**	1.1 / 1.4 **1.8 / 1.9**	23.9 / 37.3 **15.5 / 19.5**	0.12 / 0.13 **0.14 / 0.16**
	BSWith	2.3 / 2.5 **19.7 / 19.5**	0.6 / 0.8 **1.7 / 1.7**	2.9 / 3.6 **8.9 / 9.6**	0.2 / 0.2 **0.3 / 0.4**	10.0 / 9.7 **44.4 / 41.6**	4.0 / 5.7 **4.1 / 4.7**	0.7 / 0.7 **0.8 / 0.8**	17.8 / 22.8 **10.1 / 10.1**	0.02 / 0.02 **0.03 / 0.04**
Legend: Fresh beer (normal fond) - Aged beer after vibration experiment for 30 days at 30°C (**Bold fond**)										

Source: Own measurements

Appendix 4 (Raw data of haze measurements of Part 5 Chapter 2 section 2.2.c)

Referred to in Part 5 Chapter 2 section 2.2.c

Table 32: Raw data, permanent and cold haze of samples with high and low initial oxygen content (90 hours of shaking at 50 Hz and 15 m/s^2)

In EBC	Permanent haze (fresh beer – low initial oxygen content)	Permanent haze (fresh beer – high initial oxygen content)	Cold haze (fresh beer – low initial oxygen content)	Cold haze (fresh beer – high initial oxygen content)
90hrs. in 5°C	1.73	1.78	2.97	3.28
90hrs. in 5°C shaking	1.83	1.84	3.56	3.86
90hrs. in 30°C	1.35	1.41	2.43	2.55
90hrs. in 30°C shaking	1.38	1.36	3.14	2.8
90hrs. in 45°C	1.12 / 1.18	1.21 / 1.26	3.89 / 3.92	4.54 / 4.92
90hrs. in 45°C shaking	1.15 / 1.24	1.28 / 1.36	4.46 / 5.00	5.34 / 5.99

Source: Own measurements

Appendix 5 (Calibration measurements of the shock device)

Referred to in Part 5 Chapter 2 section 2.3

A shock device was manufactured in order to automatically and repetitively generate shocks on bottled beer. The device lifts and drops a standard plastic beer crate filled with 16 bottles of beer (2 rows of 4 bottles on each side). In the current section, the results of the calibration measurements that were performed are presented.

The accelerometers that measured the generated transient vibrations were mounted on the beer bottleneck (as performed in the measurements during beer transport presented in CHAPTER 1 section 1.4). At least 20 shocks were measured with interchanged bottle position in the crate. The measurements indicate limited difference between the measurements on bottles of 25cl and 33cl. Also, the position of the bottle in the crate is of minor influence on the measured shock. Measurements were performed on beer bottles packaged in plastic crates and corrugated boxes. However, due the shock devices' primary point of contact in the middle of the crate and the weight of the bottles in the crate the corrugated bended on the sides. This caused the measured accelerations on the beer bottles in the middle of the crate to be up to two times higher than the measured accelerations of the bottles on the sides of the crate. Therefore, simulating shocks on bottles in cardboard crates were not considered in current research.

In Table 33, and Figures 44a-d, an overview of the results of the calibration measurements are presented. From the figures can be derived that if the height of dropping the crate increases the variability of the measured acceleration of the highest peak also substantially rises. Furthermore, individual transient vibrations were analyzed and benchmarked with the shocks measured during beer transport. The researcher acknowledges that the simulated shocks may diverge from the shocks observed during transport, but current experimental set-up is favored due to the consistent nature of the measured signals.

Table 33: Calibration of the measured shocks, generated by the shock device, on bottled beer in a standard plastic crate (bottles 33cl - Vichy)

Height of dropping the plastic beer crate	Measured acceleration of the highest peak (m/s^2) AVG (STD)*	Frequency of the damped oscillation ($\boldsymbol{\omega_d} - \mathbf{Hz}$) AVG (STD)*	The damping ratio (β) AVG (STD)*
2 mm	15.67 (1.08)	143.82 (12.62)	0.26 (0.03)
4 mm	34.69 (4.75)	153.74 (34.05)	0.19 (0.05)
10 mm	103.63 (41.19)	119.17 (13.78)	0.14 (0.03)
15 mm	156.04 (60.65)	111.08 (24.33)	0.11 (0.06)
*Beer bottles are interchanged in order to also study the impact of the position of the beer bottle in the beer crate			

The aim of current research was to approximate the measured shocks on beer bottles during truck transport. These shocks can be characterized by the frequency of the damped oscillation (ω_d): 321.29 Hz ± 296.68 Hz, and the damping ratio (β): 0.08 ± 0.03). The researcher acknowledges that the simulated shocks may diverge from the shocks observed during transport, but current experimental set-up is favored due to the consistent nature of the measured signals.

Source: Own measurements

Figure 44a: Calibration curve of the measured shocks, generated by the shock device, on bottled beer in a plastic crate (bottles 33cl - Vichy)
Figure 44b: Calibration curve of the measured shocks, generated by the shock device, on bottled beer in a plastic crate (bottles 33cl - Vichy) (zoomed in)
Figure 44c: Vibrations in time-domain of shocks, generated by the shock device, on bottled beer in a plastic crate (bottles 33cl - Vichy)
Figure 44d: Vibrations in time-domain of shocks, generated by the shock device, on bottled beer in a plastic crate (bottles 33cl - Vichy) (zoomed in)

Figure 44a

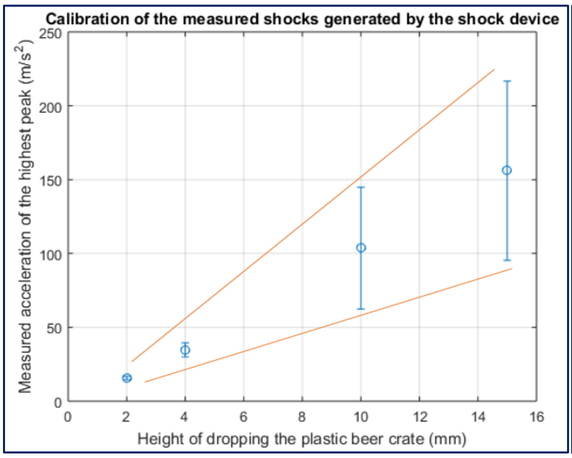


Figure 44b

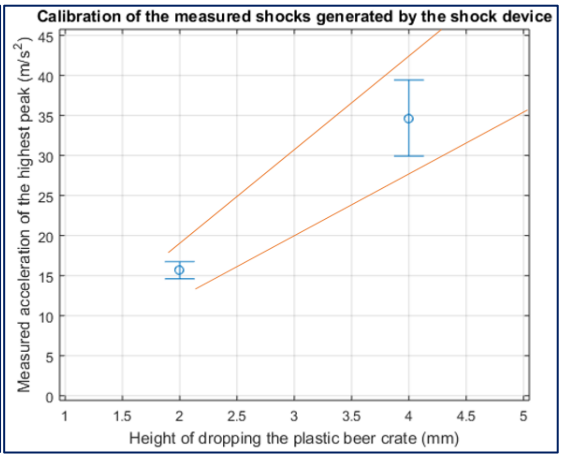


Figure 44c

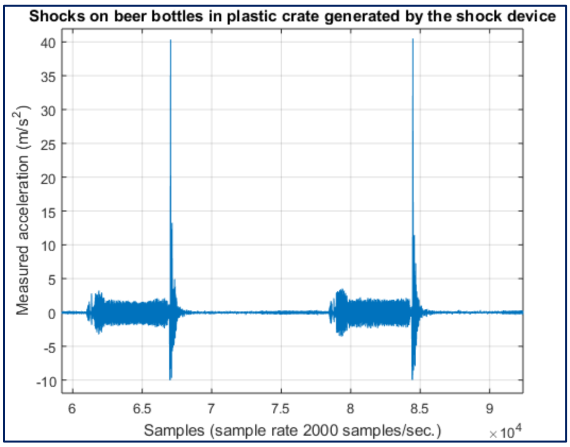


Figure 44d

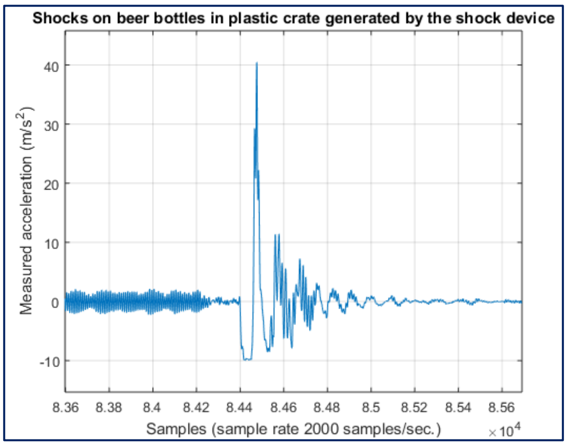


Fig. 44a-b: The measured acceleration of the highest peak of shocks was plotted against the height of dropping the plastic beer crate in order to study the variability in the responses. The results indicate the average, the upper and lower boundary (STD) of the measured response for drop heights of 2, 4, 10 and 15 mm. The variability in the measured response significantly rises by increasing drop height.

Fig. 44c-d: A time-domain plot of the measured shocks is presented. Prior to the shock response, vibrations were measured of the engine lifting up the beer crate. Subsequently, the gravitational acceleration of -10m/s² is observed and, afterwards, the measured peak and the damping phenomenon.

Source: Own measurements

Appendix 6 (Survey filled in by the respondents of the taste experiments)

Referred to in Part 5 Chapter 3 section 3.1-3.3

Degustation Form

TRIANGLE TEST – DUO TEST

General information ***PLEASE WRITE IN CAPITAL LETTERS***

Gender:

- ☐ Male
- ☐ Female

Age: ☐☐

Home country: ☐☐☐☐☐☐☐☐☐☐☐☐

How long have you been in Belgium?
(Fill in if Belgium is not your home country)

☐☐ Years and ☐☐ months

Highest certificate, diploma or degree:

- ☐ Secondary school
- ☐ Bachelor's
- ☐ Master's
- ☐ PhD

What is your current profession/job?

- ☐ Student
- ☐ Company-employee
- ☐ Governmental institution-employee
- ☐ Other:

Do you frequently drink lager beers?
(Lager beers = pilsener e.g. Stella, Jupiler, Carlsberg, Heiniken, etc.)

- ☐ No, never
- ☐ Less than 1 beer per month
- ☐ 1 to 2 beers per month
- ☐ 3 to 4 beers per month
- ☐ > 4 beers per month

Where do you consume lager beers most frequently?

- ☐ Buying in the supermarket, and consuming at home/at friends place
- ☐ Consuming in the pub
- ☐ Both above mentioned options occur with similar frequency

Do you frequently drink blond specialty beers?
(Blond specialty beers = all blond beers other than pilsener e.g. Hoegaarden, Duvel, Leffe blond, etc.)

- ☐ No, never
- ☐ Less than 1 beer per month
- ☐ 1 to 2 beers per month
- ☐ 3 to 4 beers per month
- ☐ > 4 beers per month

Where do you consume blond beers most frequently?

- ☐ Buying in the supermarket, and consuming at home/at friends place
- ☐ Consuming in the pub
- ☐ Both above mentioned options occur with similar frequency

Do you frequently drink dark specialty beers?
(Dark specialty beers = all dark beers other than pilsener e.g. Westmalle, St.-Bernardus, Petrus, etc.)

- ☐ No, never
- ☐ Less than 1 beer per month
- ☐ 1 to 2 beers per month
- ☐ 3 to 4 beers per month
- ☐ > 4 beers per month

Where do you consume dark beers most frequently?

- ☐ Buying in the supermarket, and consuming at home/at friends place
- ☐ Consuming in the pub
- ☐ Both above mentioned options occur with similar frequency

Triangletest A: Lager beer

Codes of the three beer samples:	Code of Sample 1	Code of Sample 2	Code of Sample 3
	. . .	. . .	. . .

QUESTION 1: Which sample is *different* from the two other samples?
(You must fill in a code)

Code of Sample …
. . .

QUESTION 2: What made you decide to choose the beer(s) you preferred over the other(s)?
(Fill in one or more of the categories)

- ☐ Aroma [= relates specifically to our sense of smell]
- ☐ Taste [= refers to the senses inside our mouth including our tongue]
- ☐ After taste [= the taste after the beer is swallowed]

QUESTION 3: Would you be willing to buy the current beer?
(Fill in one of the categories)

- ☐ Yes
- ☐ No

Duotest A: Lager beer

Please fill in the codes of the two beer samples	Code Sample 1	Code Sample 2
	. . .	. . .

You just received two beer samples. These beer samples can be identical or different.

QUESTION 1: Are the beer samples *identical* or *different*?
(Difference are possible in Aroma [= relates specifically to our sense of smell], Taste [= refers to the senses inside our mouth including our tongue] and after taste [= the taste after the beer is swallowed])

- ☐ The beer samples are *DIFFERENT*
- ☐ The beer samples are *IDENTICAL*

QUESTION 2: Which sample do you *prefer* over the other(s)?
(You must fill in a code – in case of two preferred samples, fill in one sample code)

Code of Sample …
. . .

QUESTION 3: Would you be willing to buy the beer (of your preference – refers to question 2 –)?
(Fill in one of the categories)

- ☐ Yes
- ☐ No

[Fill in Question 4 if 'Yes' on Question 3]

QUESTION 4: What are you willing to pay MORE for the beer sample of your choice (the beer you prefer – refers to question 2 –) over the other beer sample? (Indicate one of the categories)

Percentage you are willing to pay extra	SUPERMARKET – new price (old price: € 0,50)	PUB – new price (old price: € 2,00)
☐ It is not worth it to pay extra for my preferred beer (minimal differences in taste)		
☐ 1% - 10%	€ 0,51 - € 0,55	€ 2,02 - € 2,20
☐ 11% - 20%	€ 0,56 - € 0,60	€ 2,22 - € 2,40
☐ 21% - 30%	€ 0,61 - € 0,65	€ 2,42 - € 2,60
☐ 31% - 40%	€ 0,66 - € 0,70	€ 2,62 - € 2,80
☐ 41% - 50%	€ 0,71 - € 0,75	€ 2,82 - € 3,00
☐ I am willing to pay more than 50% of the initial price for the beer I prefer over the other beer(s)		

Degustation Form
DRINKABILITY TEST

General information ***PLEASE WRITE IN CAPITAL LETTERS***

Gender:
- ☐ Male
- ☐ Female

Age: ☐☐

Home country: ☐☐☐☐☐☐☐☐☐☐☐☐

How long have you been in Belgium?
(Fill in if Belgium is not your home country)

☐☐ Years and ☐☐ months

Do you smoke?
(Fill in one of the categories)
- ☐ Yes
- ☐ No

Do you frequently drink lager beers?
(Lager beers = pilsener e.g. Stella, Jupiler, Carlsberg, Heiniken, etc.)
- ☐ No, never
- ☐ Less than 1 beer per month
- ☐ 1 to 2 beers per month
- ☐ 3 to 4 beers per month
- ☐ > 4 beers per month

Where do you consume lager beers most frequently?
- ☐ Buying in the supermarket, and consuming at home/at friends place
- ☐ Consuming in the pub
- ☐ Both above mentioned options occur with similar frequency

Do you frequently drink specialty beers?
(Specialty beers = all beers other than pilsener e.g. Hoegaarden, Duvel, Leffe blond, etc.)
- ☐ No, never
- ☐ Less than 1 beer per month
- ☐ 1 to 2 beers per month
- ☐ 3 to 4 beers per month
- ☐ > 4 beers per month

Where do you consume blond beers most frequently?
- ☐ Buying in the supermarket, and consuming at home/at friends place
- ☐ Consuming in the pub
- ☐ Both above mentioned options occur with similar frequency

Appendix 7 (Extra information on the chemical analysis of the beer samples)

Referred to in Part 5 Chapter 3 section 3.1 and 3.2

Table 34: Color measurements beer samples tasting experiment triangle and duotest (raw data)

In EBC	Color (fresh beer) – absorption 430 nm	Color (Aged for 90/120 days at 30°C) – absorption 430 nm
Beer A (Pilsner)	6.67 / 6.65	7.75 / 7.78
Beer B (Blond specialty beer)	11.4 / 11.45	12.75 / 12.79
Beer C (Dark specialty beer)	87.43 / 87.26	92.73 / 92.68

Source: Own measurements

Table 35: Iso-α-acids measurements beer samples tasting experiment triangle and duotest (raw data)

10^{-3} g/l	*Trans-isocohumulone*	*Cis-isocohumulone*	*Trans-isohumulone*	*Cis-isohumulone*	*Trans-isoadhumulone*	*Cis-isoadhumulone*
Beer A (Pilsner) FRESH	2.14 / 2.11	4.42 / 4.4	2.18 / 2.18	5.73 / 5.72	0.61 / 0.6	1.56 / 1.53
Beer A (Pilsner) AGED	1.03 / 1.06	4.16 / 4.2	1.08 / 1.08	5.48 / 5.46	0.26 / 0.27	1.4 / 1.4
Beer B (Blond) FRESH	1.65 / 1.66	4.2 / 4.2	1.8 / 1.8	5.62 / 5.62	0.38 / 0.4	1.16 / 1.19
Beer B (Blond) AGED	0.74 / 0.74	3.75 / 3.75	0.69 / 0.7	4.53 / 4.51	0.18 / 0. 15	1.03 / 0.98
Beer C (Dark) FRESH	1.15 / 1.2	2.72 / 2.79	0.93 / 0.98	2.94 / 2.97	0.25 / 0.26	0.81 / 0.8
Beer C (Dark) AGED	0.62 / 0.64	2.69 / 2.69	0.49 / 0.5	2.92 / 2.99	0.14 / 0.15	0.85 / 0.82

Source: Own measurements

Table 36: Aldehyde measurements beer samples tasting experiment triangle and duotest (raw data)

Avg. x 10^{-6} g/l (STD)	*2-methylpropanal*	*2-methylbutanal*	*3-methylbutanal*	*hexanal*	*furfural*
Beer A (Pilsner) - FRESH	3.1 (0)	0.8 (0)	2.3 (0)	0.1 (0)	6.3 (0)
Beer A (Pilsner) - AGED	32.4 (0.8)	3.5 (0.1)	8.6 (0.4)	0.6 (0.1)	149.8 (0.3)
Beer B (Blond) - FRESH	16.2 (0.2)	2.6 (0)	12.5 (0.2)	0.6 (0)	24 (0.5)
Beer B (Blond) - AGED	48.7 (5.4)	6.2 (0.2)	19.8 (0.6)	1.1 (0)	190 (10.6)
Beer C (Dark) - FRESH	11 (0.3)	4.9 (0)	8.1 (0)	0.4 (0)	1781.9 (78)
Beer C (Dark) - AGED	76.2 (3.2)	19.1 (1.3)	46.1 (5.4)	1.1 (0)	1914.9 (84.8)

10^{-6} g/l	*methional*	*benzaldehyde*	*phenylacetaldehyde*	*(E)-2-nonenal*
Beer A (Pilsner) - FRESH	1.1 (0.1)	0.7 (0)	9.2 (1.4)	0.01 (0)
Beer A (Pilsner) - AGED	9.4 (1)	1.4 (0)	29.5 (4.1)	0.04 (0)
Beer B (Blond) - FRESH	17.1 (4.7)	1.5 (0.1)	27.2 (5.2)	0.12 (0.02)
Beer B (Blond) - AGED	18.9 (3.8)	2.1 (0)	32.7 (4.1)	0.18 (0.01)
Beer C (Dark) - FRESH	22.9 (1.1)	1.5 (0.1)	17 (2.6)	0.02 (0)
Beer C (Dark) - AGED	36.1 (3.6)	2.2 (0.1)	28.5 (2.1)	0.07 (0)

Source: Own measurements

Appendix 8 (Information on the preference of fresh over aged beer (non-)Belgians >27y.)

Referred to in Part 5 Chapter 3 section 3.2 and 3.3

From both the results from the duotest (Part 5 Chapter 3 section 3.2) and the drinkability experiment (first consumption after performing the duotest Part 5 Chapter 3 section 3.3) can be derived that there are strong indications that Belgians older than 27 years significantly prefer fresh over aged beer. The latter finding is not found for foreigners of the same age category.

Table 37: Results of the performed duo tests (preference test Part 5 Chapter 3 section 3.2) – Participants: Belgians and non-Belgians, > 27y.

Belgians > 27y. (11p)	**Percentage of the respondents that indicate to be capable to distinguish fresh from aged beer**	**Percentage of the respondents that prefer fresh over aged beer**
Beer A [Lager beer] (Number of respondents in category)	90.9% (10/11)	70.0% (7/10)
Beer B [Blond beer] (Number of respondents in category)	72.7% (8/11)	37.5% (3/8)
Beer C [Dark beer] (Number of respondents in category)	81.8% (9/11)	66.7% (6/9)
Non-Belgians > 27y. (63p)	**Percentage of the respondents that indicate to be capable to distinguish fresh from aged beer**	**Percentage of the respondents that prefer fresh over aged beer**
Beer A [Lager beer] (Number of respondents in category)	92.1% (58/63)	53.4% (31/58)
Beer B [Blond beer] (Number of respondents in category)	71.2% (42/59*)	50.0% (21/42)
Beer C [Dark beer] (Number of respondents in category)	79.7% (47/59*)	57.4% (27/47)
* 4 respondents only took part in the tasting of Beer A (the lager beer)		

Source: Own measurements

Table 38: Results of the performed drinkability experiment (preference test Part 5 Chapter 3 section 3.2) – Participants: Belgians and non-Belgians, > 27y.

Belgians > 27y. (16p)	**Percentage of the respondents that prefer fresh over aged beer (first consumption after performing the duotest)**
Beer drinkability experiment [Lager beer] (Number of respondents in category)	93.8% (15/16)
Non-Belgians > 27y. (13p)	**Percentage of the respondents that prefer fresh over aged beer (first consumption after performing the duotest)**
Beer drinkability experiment [Lager beer] (Number of respondents in category)	61.5% (8/13)

Source: Own measurements

Appendix 9 (Extra information on the chemical analysis of the beer samples)

Referred to in Part 5 Chapter 3 section 3.3

Table 39: Chemical characteristics beer samples

Density (g/cm3)	*1.006*	*SG 20/20*	*1.008*
Alc. (V/V%)	*4.92*	*RDF (%)*	*67.52*
Alc. (m/m%)	*3.86*	*ADF (%)*	*81.96*
Er (g/100ml)	*3.89*	*Cal. (kJ/100 ml)*	*170.52*
Ea (g/100ml)	*2.06*	*P (g/100ml)*	*11.84*
Legend: pH (acidity), Alc. (Alcoholic volume or weight in %), Er (realistic extract), Ea (Apparent extract), RDF (Realistic degree of fermentation), ADF (Apparent degree of fermentation), Cal. (Caloric content)			

Source: Own measurements

Table 40: A more detailed investigation of the permanent haze, cold haze and color (raw data)

EBC	*Permanent Haze (H90)*	*Permanent Haze (H25)*	*Cold Haze (H90)*	*Cold Haze (H25)*	*Color*
Fresh beer	0.38 / 0.39	0.2 / 0.12	0.89 / 0.92	1.05 / 1.58	7.25 / 7.63
Aged beer	1.31 / 1.31	0.5 / 0.38	3.88 / 3.55	2.09 / 1.92	8.08 / 8.02

Source: Own measurements

Table 41: A more detailed investigation of the individual *trans*- and *cis*-iso-α-acids (raw data)

Conc. x 10-3 g/L	*Trans*-isoco-humulone	*Cis*-isoco-humulone	*Trans*-iso-humulone	*Cis*-iso-humulone	*Trans*-isoad-humulone	*Cis*-isoad-humulone	*Total*	*TC-ratio (%)*
Fresh beer	2.59 / 2.48	5.98 / 6.00	2.95 / 2.86	6.27 / 6.34	0.62 / 0.59	1.43 / 1.39	19.84 / 19.66	45.22 / 43.27
Aged beer	1.85 / 1.79	5.79 / 5.81	2.06 / 1.99	6.12 / 6.26	0.39 / 0.35	1.38 / 1.36	17.59 / 17.56	32.83 / 31.32

Source: Own measurements

Table 42: A more detailed investigation of the individual aldehydes (raw data)

Conc. x 10-6 g/L	2-methyl-propanal	2-methyl-butanal	3-methyl-butanal	hexanal	furfural	methional	*Benz-aldehyde*	*Phenyl-acet-aldehyde*	*(E)-2-nonenal*
Fresh beer	1.5 / 1.5 / 1.7	0.8 / 0.8 / 0.9	3.6 / 3.5 / 3.7	0.4 / 0.3	18.3 / 16.1 / 19.5	0.8 / 0.6 / 0.8	0.9 / 0.7 / 0.8	6.4 / 6.8 / 7.5	0.07 / 0.06 / 0.10
Aged beer	8.7 / 8.7 / 8.7	2.4 / 2.4 / 2.5	7.2 / 7.2 / 7.5	1.0 / 1.1	338.4 / 338.5/ 336.7	2.2 / 1.2 / 1.6	1.5 / 1.4 / 1.5	9.4 / 9.4 / 11.1	0.13 / 0.16 / 0.012

Source: Own measurements

Appendix 10 (Information on the nominal homogeneity index (nHi) of the different tables)

Referred to in Part 5 Chapter 3 section 3.3

The nominal homogeneity index (nHi) = $\frac{1-\sum_{i=1}^{k}(F(i))^2}{\frac{k-1}{k}}$

With
K= the number of categories
F= the relative percentages

Since the current analysis is performed with two categories (fresh and aged beer), the prior described formula can be simplified.

The nominal homogeneity index (nHi) = $4 * p1 * (1 - p1)$

With
p1= the percentage of consumed fresh beer (per table)
p2 = (1 – p1) = the percentage of consumed aged beer (per table)

If
nHi = 0, then there is a clear preference for fresh or aged beer
nHi = 1, then there is a 50% preference for / consumption of fresh and a 50% preference / consumption of aged beer

When the nHi of all respondents was calculated the number 0.98 was found. This number indicates there was a close to 50-50% consumption of fresh and aged beer (in the experiment, 57.5% of the consumed beer was fresh beer). The nHi calculated by table is mostly considerably different from 0.98. We expect the variation in nHi for small tables to be large and larger tables to be smaller. There are no statistics tests available to test this hypothesis.

Table 43: The nominal homogeneity index (nHi) for fresh and aged beer segmented by table

Table size	nHi	Table size	nHi	Table size	nHi	Table size	nHi
1 p.	0	2 p.	1	3 p.	0	4 p.	0.78
1 p.	0.64	2 p.	1	3 p.	0.98	5 p.	0.94
2 p.	0	2 p.	1	3 p.	0.69	5 p.	0.78
2 p.	0.31	2 p.	0.88	3 p.	0.75	5 p.	0.75
2 p.	0	2 p.	0.31	4 p.	0.99	6 p.	0.68
2 p.	0.64	2 p.	1	4 p.	0.89	7 p.	0.13
2 p.	0.82	3 p.	0.75	4 p.	1	9 p.	0.92

Legend:

0.64	The background color is green: The most consumed type of beer at the current table was fresh beer
0.31	The background color is orange: The most consumed type of beer at the current table was aged beer
1	The background color is grey: There is a 50% preference for / consumption of fresh and a 50% preference / consumption of aged beer

Source: Own measurements

Appendix 11 (Extra information on ISO specifications of transport containers)

Referred to in Part 6 Chapter 1

Figure 45: 40 ft. Container dimensions

Table 41: ISO specifications (40 ft. containers)

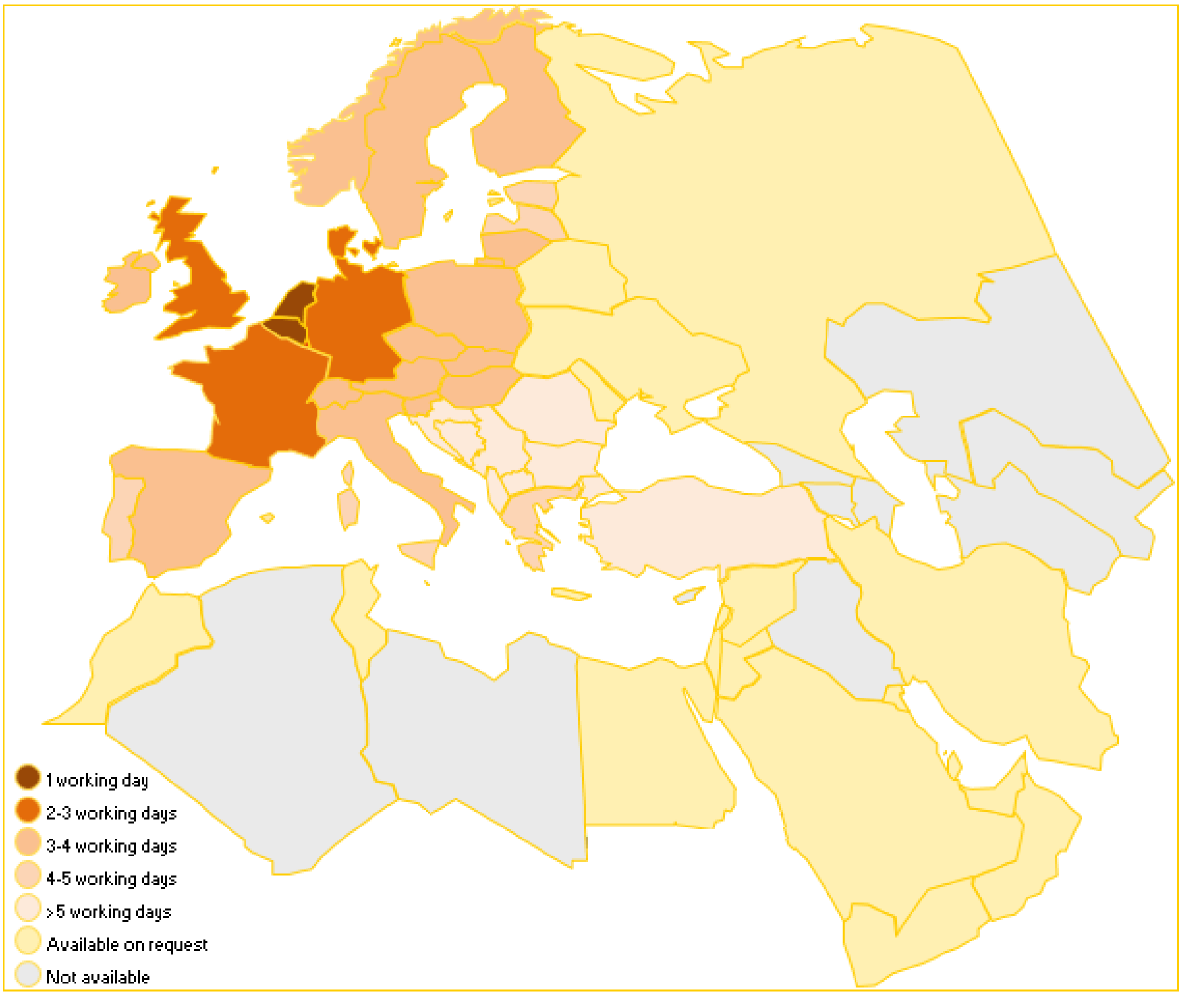
	40 ft. Dry container	40 ft. Reefer container
Dimensions (external) [m]	12.192 x 2.438 x 2.591	12.192 x 2.438 x 2.591
Dimensions (internal) [m]	12.014 x 2.337 x 2.362	11.557 x 2.286 x 2.286
Maximum Payload [kg]	28,860	28,600
Door Opening (W x h) [m]	2,337 x 2,286	2.286 x 2.286
Inside Cubic Capacity (CBM) [m^3]	66.3	60.4

Source: ISO specifications, 2017[100]

Appendix 12 (Information on the truck transport lead times and prices)

Referred to in Part 6 Chapter 1

Figure 46: Map of Europe (truck transport lead times [Country of origin: Belgium/Netherlands])



Leadtimes from departure day:

Austria	2-3 days	Hungary	2-3 days	Russia (Nizny Novgorad)	10 days
Bulgaria	4-6 days	Republic of Ireland	3-4 days	Serbia and Montenegro	4-5 days
Croatia	3-4 days	Italy	2-4 days	Slovenia	2-3 days
Czech Republic	2 days	Latvia	4 days	Slovakia	2-3 days
Denmark	2 days	Lithuania	3-4 days	Spain	3-4 days
Estonia	3-4 days	Malta	6 days	Sweden	2-4 days
Finland	3-4 days	Norway	3-5 days	Switzerland	2 days
France	2-3 days	Poland	2-3 days	Turkey (IST)	5-7 days
Germany	1-2 days	Portugal	3-4 days	United Kingdom	2-3 days
Greece	5-6 days	Romania	4-5 days		

Source: Logistics provider F, 2017[70]

Table 44: Dry container pricing – truck transport

Destination country (Country of origin: Belgium / The Netherlands)	**Postal code/ Country code**	**Avg. transport price (€)**	**Std. transport price (€)**	**Transit time**
Federal Republic of Germany	DE	707,71	218,02	1-2 days
Czech Republic	CZ	991,16	137,80	2 days
Republic of Poland	PL	1.146,35	148,43	2-3 days
Kingdom of Denmark	DK	1.200,05	173,47	2 days
French Republic	FR	1.257,55	371,67	2-3 days
Republic of Austria	AT	1.258,97	29,58	2-3 days
Republic of Lithuania	LT	1.328,09	44,17	3-4 days
Slovak Republic	SK	1.328,27	115,34	2-3 days
Republic of Slovenia	SI	1.370,31	26,61	2-3 days
Switzerland	CH	1.376,01	114,05	2 days
Hungary	HU	1.627,90	94,65	2-3 days
Republic of Latvia	LV	1.683,11	125,29	4 days
United Kingdom of Great Britain	GB/UK	1.797,31	211,63	2-3 days
Kingdom of Spain	ES	1.880,79	309,32	3-4 days
Republic of Estonia	EE	1.894,79	89,84	3-4 days
Kingdom of Sweden	SE	1.957,00	414,44	2-4 days
Republic of Croatia	HR	1.992,43	272,65	3-4 days
Italian Republic	IT	2.005,13	844,84	2-4 days
Portuguese Republic	PT	2.156,29	225,92	3-4 days
Ireland	IE	2.352,05	156,05	3-4 days
Romania	RO	2.353,02	38,37	4-5 days
Russia	RS	2.530,39	42,38	5-7 days
Republic of Bulgaria	BG	2.599,12	78,08	4-6 days
Turkey	TR	3.013,00	0,00*	5-7 days
Republic of Finland	FI	3.086,23	364,46	3-4 days
Greece	GR	3.523,47	110,20	5-6 days
Norway	NO	3.586,10	1.542,26	3-5 days
*Only one location/area offered as destination by the logistics provider				

Source: Logistics provider F, 2017[70]

Appendix 13 (Raw data of the survey 1 filled in by the Belgian breweries)

Referred to in Part 6 Chapter 2 and 3

The survey was performed in Dutch and afterwards translated in English.

Question 1: How many hectoliters beer does your brewery produce?

Responses:

145,000 hl	1.4 M hl	6000 hl	1500 hl	1000 hl
(confidential info)	32,369 hl	850,000 hl	23 hl	3300 hl
849,019 hl	40,000 hl	(confidential info)	5500 hl	700 hl
4000 hl	120 hl	5000 hl	1200 hl	180 hl
731 hl	3000 hl	1250 hl		

Question 2: How many hectoliters beer is destined for export?

Responses:

90,000 hl	0.5 M hl	0 hl	1000 hl	750 hl
700 hl	(confidential info)	17,800 hl	364,000 hl	0 hl
1485 hl	362,354 hl	20,000 hl	(confidential info)	3300 hl
300 hl	3000 hl	20 hl	2000 hl	400 hl
50 hl	183 hl	2000 hl	1000 hl	

Question 3: What is the percentage of transports that are refrigerated (reefer containers)?

Responses:

Answer 1	The brewery does not have cooled transports	10 responses	42% of the responses
Answer 2	1-20% of all transports are cooled	9 responses	38% of the responses
Answer 3	20-40% of all transports are cooled	3 responses	13% of the responses
Answer 4	40-60% of all transports are cooled	2 responses	8% of the responses
Answer 5	60-80% of all transports are cooled	0 responses	0% of the responses
Answer 6	80-100% of all transports are cooled	0 responses	0% of the responses
	TOTAL	24 responses	

Question 4: What is the average degree of loading of your truck transports?

Responses:

Answer 1	Degree of loading between 0-20%	0 responses	0% of the responses
Answer 2	Degree of loading between 20-40%	4 responses	17% of the responses
Answer 3	Degree of loading between 40-60%	4 responses	17% of the responses
Answer 4	Degree of loading between 60-80%	3 responses	13% of the responses
Answer 5	Degree of loading between 80-100%	13 responses	54% of the responses
	TOTAL	24 responses	

Question 5: How are the breweries transports within Belgium organized?

Responses:

Answer 1	Own logistics	1 responses	4% of the responses
Answer 2	Third Party logistics [3PL] (paid by the brewery)	6 responses	25% of the responses
Answer 3	Ex-works (clients organize transport)	3 responses	13% of the responses
Answer 4	Combination of own logistics and 3PL	1 responses	4% of the responses
Answer 5	Combination of own logistics and ex-works	3 responses	13% of the responses
Answer 6	Combination of 3PL and ex-works	3 responses	13% of the responses
Answer 7	Combination of own logistics, 3PL and ex-works	7 responses	29% of the responses
Answer 8	Other (please describe)	0 responses	0% of the responses
	TOTAL	24 responses	

Question 6: How are the breweries transports to foreign markets organized?

Responses:

Answer 1	Own logistics	0 responses	0% of the responses
Answer 2	Third Party logistics [3PL] (paid by the brewery)	3 responses	13% of the responses
Answer 3	Ex-works (clients organize transport)	15 responses	63% of the responses
Answer 4	Combination of own logistics and 3PL	0 responses	0% of the responses
Answer 5	Combination of own logistics and ex-works	1 responses	4% of the responses
Answer 6	Combination of 3PL and ex-works	3 responses	13% of the responses
Answer 7	Combination of own logistics, 3PL and ex-works	0 responses	0% of the responses
Answer 8	The brewery does not export beer	2 responses	8% of the responses
Answer 9	Other (please describe)	0 responses	0% of the responses
	TOTAL	24 responses	

Question 7: Did your brewery organize transport in collaboration with other breweries in the past?

Responses:

Answer 1	Yes	10 responses	42% of the responses
Answer 2	No	24 responses	58% of the responses
	TOTAL	24 responses	

(if 'No' on question 7)
Question 8: Do you believe there is added value for the brewery if transport is organized in collaboration with other breweries?

Responses:

Answer 1	Yes	4 responses	29% of the responses
Answer 2	No	10 responses	71% of the responses
	TOTAL	14 responses	

(if 'No' on question 8)

Question 9: What would be the predominant reasoning not to start a collaboration initiative with other breweries with respect to transport?

Responses:

Answer 1	No need	2 responses	20% of the responses
Answer 2	The practical feasibility is limited	2 responses	20% of the responses
Answer 3	Confidential information will be shared	1 responses	10% of the responses
Answer 4	Difficulties in dividing the costs	0 responses	0% of the responses
Answer 5	Anti-trust laws	0 responses	0% of the responses
Answer 6	The time needed to organize	0 responses	0% of the responses
Answer 7	Other (please describe)	5 responses	50% of the responses
	TOTAL	10 responses	

Other:

Transport within Belgium is outsourced to a third Party, which can optimize transport: the company can bundle cargo and, therefore, a pallet of beer can be transported (together with other goods) in an efficient fashion across Belgium.
Close to all transports occur with completely filled containers.
Collaboration in logistics is possibly only beneficial with respect to export. However, in rare cases the breweries have similar importers.
Horizontal collaboration is important to optimize transport, limit the environmental footprint and to reduce costs. However, I believe there are better collaborations with other fast moving consumer goods.
All transport is ex-works. As a consequence, the client is required to bundle cargo of different breweries.

(if 'Yes' on question 7)
Question 10: Did your brewery positively evaluate the collaboration in logistics with other breweries?

Responses:

Answer 1	Yes	10 responses	100% of the responses
Answer 2	No	0 responses	0% of the responses
	TOTAL	10 responses	

(if 'Yes' on question 10)
Question 11: What would be the largest advantage for the collaboration in logistics with other breweries?

Responses:

Answer 1	Cost advantages	3 responses	33% of the responses
Answer 2	More efficient transports	2 responses	22% of the responses
Answer 3	Better customer service	1 responses	11% of the responses
Answer 4	Strengthening the market position	0 responses	0% of the responses
Answer 5	Other (please describe)	3 responses	33% of the responses
	TOTAL	9 responses	

Other:

The cost advantage for the small befriended brewery we worked together with.

Breweries deliver us their beer and we load them into the container. The advantage is that all products are loaded as good and safe as it is possible.
We did organize a collaboration in transport in the past, but we also experienced that there were difficulties in dividing the costs.

Question 12: The brewery can describe additional concerns or considerations about the survey and the collaboration in logistics between breweries?

Responses:

Our brewery is small, but grows rapidly and, therefore, collaboration in logistics between breweries might be interesting.
Our company is a concern of breweries and, as a consequence, we ‘internally’ share transport and warehousing between the different breweries.
60% of the distribution within Belgium is first transported to the distributor ‘Prik & Tik’ and ‘Districo’. The distributor picks up an order (and the orders at other breweries at full loading) and distributes the beer to its customers.
The clients organize transport, and the brewery does not require its own logistics chain.

Appendix 14 (Raw data of the survey 2 filled in by the Belgian breweries)

Referred to in Part 6 Chapter 2 and 3

The survey was performed in Dutch and afterwards translated in English.

Question 1: Can you identify the location of your brewery/moutery?

Responses:

Vlaams-Brabant	Oost-Vlaanderen	Antwerpen	Vlaams-Brabant	Vlaams-Brabant
West-Vlaanderen	Vlaams-Brabant	Antwerpen	Limburg	Vlaams-Brabant
West-Vlaanderen	Limburg	/	/	West-Vlaanderen
Vlaams-Brabant	Oost-Vlaanderen	Antwerpen	/	Antwerpen

Question 2: What is the number of beers your brewery produces (portfolio of the brewery)?

Responses:

15 beers	5 beers	2 beers	14 beers	6 beers
12 beers	7 beers	/	20 beers	28 beers
7 beers	>40 beers	9 beers	15 beers	29 beers
15 beers	12 beers			

Question 3: How many hectoliters beer does your brewery produce?

Responses:

800,000 hl	3,900 hl	130,000 hl	220 hl	5,000 hl
100,000 hl	1,500 hl	36,672 hl	45,000 hl	240,000 hl
50,000 hl	1,600,000 hl	6,200 hl	2,500 hl	100,000 hl
20,000 hl	7,500 hl			

Question 4: How many hectoliters beer is destined for export?

Responses:

250,000 hl	800 hl	45,000 hl	0 hl	100 hl
5 to 10,000 hl	750 hl	13,208 hl	5,000 hl	40,000 hl
20,000 hl	640,000 hl	4,000 hl	875 hl	55,000 hl
2,000 hl	3,000 hl			

Question 5: Are you aware of the profile of the average consumer of your beer in the export markets?

Responses:

Answer 1	Yes	7 responses	41% of the responses
Answer 2	No	9 responses	53% of the responses
Answer 3	No export	1 responses	6% of the responses
	TOTAL	17 responses	

(if 'Yes' on question 5)

Question 6: Is the average consumer of your beer in the export markets loyal?

Responses:

Answer 1	Yes	2 responses	29% of the responses
Answer 2	No	3 responses	42% of the responses
Answer 3	Other (please describe)	2 responses	29% of the responses
	TOTAL	7 responses	

Other:

Sometimes customers are loyal; in other countries customers 'try' different beers and, therefore, there is not a fixed consumer group/fixed basis
The consumer loyalty is difficult to assess, there is little information available.

(if 'Yes' on question 5)
Question 7: Can you describe the profile of the average consumer of your beer in the export markets (some sentences/key words)?

Responses:

Curious and searching for new beers, discovering Belgian beer, not loyal, prefers German beers (in Italy) since they are cheaper
Prosperous, wealthy, interested in beer and quality
We assume that the foreign beer drinker tastes the difference between diverse beers in a similar segment and, as a consequence, adapts consumption based on previous experiences
Difficult to explain (our export manager has more information)
/
Loves drinking beer
Related to the craft beer trend

(if 'Yes' on question 5)
Question 8: Are the answers with respect to the profile of the average consumer of your beer in the export markets based on data or conjectures?

Responses:

Answer 1	I communicate with the importer	2 responses	29% of the responses
Answer 2	The answer is based on the public opinion/information available on the internet	2 responses	29% of the responses
Answer 3	Other (please describe)	3 responses	42% of the responses
	TOTAL	responses	

Other:

Own insights
/
There are also multiple foreign visitors in our bar

Question 9: Do you test the beer quality of your exported beer (after arrival in the foreign markets)?

Responses:

Answer 1	Yes	5 responses	29% of the responses
Answer 2	No	11 responses	65% of the responses
Answer 3	No export	1 responses	6% of the responses
Answer 4	Other (please describe)	0 responses	0% of the responses
	TOTAL	17 responses	

(if 'Yes' on question 9)
Question 10: How do you test the beer quality of your exported beer (after arrival in the foreign markets)? (e.g. on-site sensorial test, sending back beer to Belgium and testing)

Responses:

Feedback of our local agent, some beer samples are sent back to Belgium for a sensorial test
On-site sensorial test
Sensorial evaluation (recently tasted 'oer-beer' of 1 year old and 'ara-beer' for which the taste was a little bit different
On-site sensorial test, or beer samples are sent back to Belgium for a sensorial test
beer samples are sent back to Belgium for a sensorial test (VIS/brewers-project)

(if 'Yes' on question 9)
Question 11: What is the frequency of testing the beer quality of your exported beer (after arrival in the foreign markets)? (per month/per year)

Responses:

Not regularly, dependent on the feedback of the importer and the comments/complaints of the consumers
3 visits per year
We visit our importer, taste beer and check other (economical) data
Sensorial test on a yearly basis
1 time per year sending back beer samples

Question 12: Are new product introductions important for your brewery?
– Product introductions can be beers or malts –

Responses:

Answer 1	Yes	9 responses	56% of the responses
Answer 2	No	5 responses	31% of the responses
Answer 3	Other (please describe)	2 responses	13% of the responses
	TOTAL	16 responses	

Other:

/
We keep an eye on / focus on market trends

Question 13: What is the frequency of doing new product introductions for your brewery? (per month/per year)

Responses:

1-2 per year	1 per 5 years	0	2 per year	0

1 to 3 per year	0	0	1 per year	8 per year
Very few	15 per year	2 per year	1 per year	1 per year

Question 14: Will the frequency of doing new product introductions increase in the future?

Responses:

Yes	Perhaps	No	Yes	No
Probably	No	/	Yes	Yes
No	Yes	Probably	Yes	Possibly

Question 15: Do you frequently change processes (and/or chemical components) in order to brew beer of increased flavor stability? (per month/per year)

Responses:

Constantly on a monthly basis	Constantly	No idea	2 to 3 times per year	No
Constantly	Constantly	Continuous evaluation, few adaptations	Normally not	+/- 2 times per year
Constantly	+/- 1 time per year	+/- 2 times per year	Constantly on a monthly basis	Constantly

Question 16: Can you identify the R&D-budgets of the brewery related to improvements or research on beer flavor stability? (as a percentage of the total revenues)

Responses:

No fixed budget	Predominantly personnel and costs of material and resources	/	5 to 10%	Not applicable
Max 0.5%	Cost of a trial brew	No budget	No budget	/
/	No budget	0.50%	2%	Not defined

Question 17: Can you identify the importance of the flavor stability problem?

Responses:

Answer 1	Improving the flavor stability of beer is important and priority	13 responses	87% of the responses
Answer 2	Improving the flavor stability of beer is important but currently not priority	2 responses	13% of the responses
Answer 3	Improving the flavor stability of beer is not important for our brewery	0 responses	0% of the responses
Answer 4	Other (please describe)	0 responses	0% of the responses
	TOTAL	15 responses	

Question 18: Can you give further explanation your response of question 19?

Responses:

Export rises and the customer demands new beer types. The consumer compares with similar beers on the market (more often than it used to be), and, therefore, the ‘competition’ among brands becomes larger. As a consequence, there is a need for more stable beers.
We think it is more important to further develop our current beers, rather than to develop new beers. Quality is the single most important aspect. We brew traditionally (no filtration, no centrifugation, no pasteurization) and we do it ourselves, we also do yeasting, lagering, as well as bottling and stock control, and that distinguishes us from the competition.
We want to offer the consumer the best possible quality, even though the consumer might not be critical on the beer flavor or if he experience the degraded beer quality as the standard.
Flavor stability is important and not only for export but also for the domestic market. We are a small brewery and often people taste beer in the brewery, buy additional bottles and consume it elsewhere. As a consequence, it is important that flavors and the taste does not degrade.
Flavor stability is crucial for beers in the export and domestic market
Our export figures rise, but we only do export with the beers of which our production and quality deCHAPTERment indicates they are resistant against the external influences (e.g. temperature, etc.) of export. [We do export ‘complex beers’ of which slight oxidation is ‘allowed’.] Furthermore, achieving flavor stability is a continuous process that is important for both export as well as domestic distribution (e.g. transport of beer to warehouses in warm environments, storage at the wholesalers, etc.).
The consumer is critical and able to taste differences between beers, although he does not always communicates his experience of the beer taste. We do taste different beers with tasters. The consumer is sometimes mild/temperate with respect to the taste of beer; even a sharp beer taste (rated by the professional drinker) appears to have loyal fans.
The brewery is expanding and, therefore, priorities have shifted.
We try to achieve a longer shelf life of our brewed beers.
We try to make different beers, but we know from experience that some of our products are delicate and sensitive for flavor changes. We believe that a constant quality at the point of consumption is crucial to keep on growing as a brewery. Therefore, we focus on the flavor stability of our beers.
Our priority is beer of high quality and bottling.
The brewery should continuously work on beer flavor stability.
We strive for flavor stability and optimal flavors and aromas.
Export becomes increasingly important.
Working on flavor stability is a must (definitely for beers that are exposed to export conditions). We think it is important with respect to the purchase of raw materials, the investments and our working methods.

Question 19: Which of the following options is most harmful for a beer brand in your belief?

Responses:

Answer 1	A decrease in beer flavor and taste	4 responses	27% of the responses
Answer 2	Variations in the beer flavor and taste	1 responses	7% of the responses
Answer 3	Both problems are equally important	9 responses	60% of the responses
Answer 4	The mentioned options are no problems	0 responses	0% of the responses
Answer 5	Other (please describe)	1 responses	7% of the responses
	TOTAL	15 responses	

Other:

A decrease in beer flavor and taste is a major problem. Variations beyond the specifications in beers flavor may not occur if the processes are clearly described and the beers are released (from production) within certain specifications.

Question 20: Has your brewery received complaints or returns of beer in the past due to beer flavor stability problems?

Responses:

Answer 1	Yes	8 responses	53% of the responses
Answer 2	No	7 responses	47% of the responses
	TOTAL	15 responses	

Question 21: What is the frequency of the received complaints or returns of beer due to beer flavor stability problems? (per month/per year)

Responses:

Not frequently, less than 1 time per year	Turbidity: 2 times in 7 years Flavor: 1 time in 7 years	Returns of beer do not occur. 5-10 questions per year on the flavor of the beer (95% from Belgium or the Netherlands)	No complaints yet
Not frequently	No complaints yet	We brewed a batch that was ok for the USA but not for the Belgian market (complaints)	1 per month, frequently related to the hygiene conditions of the tap installation
No complaints yet	1 per month	No complaints yet	1 per month
No complaints yet	No complaints yet	No complaints yet	

Question 22: In which of the services with respect to beer transport and storage simulations of the KU Leuven campus Ghent are you interested as a brewery? (per month/per year)

Responses:

Standardized aging test for current beers (and process & chemical changes of beers)	Standardized aging test	/ (I am not interested)
I do not export beer (I am not interested)	/ (I am not interested)	We would like to send back samples and test the beer quality (normally within the VIS/brewers-project)
Our importer thinks that 'oer-beer' is at its best after 3 years of storage, 'beer X' after one year of storage. 'Arabeer' becomes less bitter. (I am not really interested)	Standardized aging test for new beers and to test process and chemical changes of beers	Interested in standardized aging test for current and new beers (and process & chemical changes of beers) and sending back beer samples and testing the quality
Standardized aging test for current beers (and process & chemical changes of beers)	/ (I am not interested)	Standardized aging test for current beers (and process & chemical changes of beers)

Standardized aging test for current beers	Interested in standardized aging test for current and new beers (and process & chemical changes of beers) and sending back beer samples and testing the quality	Interested in standardized aging test for current and new beers (and process & chemical changes of beers)

Question 23: Can you identify the countries your brewery exports beer to, the cargo load (amount of pallets) and an estimate of the degree of loading (DOL)?

Responses:

Brewery 1			
France	216 times/year	2.5 container	DOL: 80-100%
Italy	18 times/year	1 container	DOL: 80-100%
UK	18 times/year	1 container	DOL: 80-100%
Spain	12 times/year	2.5 containers	DOL: 80-100%
Japan	6 times/year	1 container	DOL: 80-100%
China	12 times/year	1 container	DOL: 80-100%
Russia	12 times/year	1 container	DOL: 80-100%

Brewery 2			
Italy	72 times/year	2 pallets	DOL: 40-60%
The Netherlands	24 times/year	1 pallet	DOL: 40-60%
Norway	3 times/year	4 pallets	DOL: 40-60%

Brewery 3			
The Netherlands	288 times/year	24 pallets	DOL: 80-100%
France	48 times/year	24 pallets	DOL: 80-100%
UK	24 times/year	12 pallets	DOL: 80-100%
USA	12 times/year	24 pallets	DOL: 80-100%
Italy	6 times/year	24 pallets	DOL: 60-80%

Brewery 4			
The Netherlands	96 times/year	12 pallets	DOL: 40-60%
France	48 times/year	22 pallets	DOL: 80-100%
Italy	12 times/year	12 pallets	DOL: 40-60%
USA	4 times/year	22 pallets	DOL: 80-100%
Scandinavia	4 times/year	8 pallets	DOL: 40-60%

Brewery 5			
USA	12 times/year	3 pallets	DOL: 80-100%
Italy	6 times/year	4 pallets	DOL: 40-60%
UK	4 times/year	4 pallets	DOL: 80-100%
Spain	24 times/year	2 pallets	DOL: 20-40%
Denmark	36 times/year	3 pallets	DOL: 20-40%

Appendix 15 (Horizontal collaboration in logistics calculations)

Referred to in Part 6 Chapter 2

Table 45: Estimation of logistics provider prices per pallet to Italy and USA

Export country	**Price 40ft. Container***	**Price per pallet**	**€/pal. (23 pal.)**	**€/pal. (22 pal.)**	**€/pal. (21 pal.)**	**€/pal. (20 pal.)**	**€/pal. (19 pal.)**	**€/pal. (18 pal.)**	**€/pal. (17 pal.)**	**€/pal. (16 pal.)**	**€/pal. (15 pal.)**	**€/pal. (14 pal.)**	**€/pal. (13 pal.)**
Italy	€ 2000	83	86	88	91	94	97	100	102	106	109	112	115
	Price 20ft. Container*	**Price per pallet**	**€/pal. (11 pal.)**	**€/pal. (10 pal.)**	**€/pal. (9 pal.)**	**€/pal. (8 pal.)**	**€/pal. (7 pal.)**	**€/pal. (6 pal.)**	**€/pal. (5 pal.)**	**€/pal. (4 pal.)**	**€/pal. (3 pal.)**	**€/pal. (2 pal.)**	**€/pal. (1 pal.)**
	€ 1400	117	120	124	127	131	135	139	143	148	152	157	161
Export country	**Price 40ft. Container***	**Price per pallet**	**€/pal. (23 pal.)**	**€/pal. (22 pal.)**	**€/pal. (21 pal.)**	**€/pal. (20 pal.)**	**€/pal. (19 pal.)**	**€/pal. (18 pal.)**	**€/pal. (17 pal.)**	**€/pal. (16 pal.)**	**€/pal. (15 pal.)**	**€/pal. (14 pal.)**	**€/pal. (13 pal.)**
USA	€ 1700	71	73	75	77	80	82	85	87	90	92	95	98
	Price 20ft. Container*	**Price per pallet**	**€/pal. (11 pal.)**	**€/pal. (10 pal.)**	**€/pal. (9 pal.)**	**€/pal. (8 pal.)**	**€/pal. (7 pal.)**	**€/pal. (6 pal.)**	**€/pal. (5 pal.)**	**€/pal. (4 pal.)**	**€/pal. (3 pal.)**	**€/pal. (2 pal.)**	**€/pal. (1 pal.)**
	€ 1190	99	102	105	108	112	115	118	122	126	129	133	137

*The price for 12 pallets in a 24ft. container should be equal to 12 pallets in a 12ft. container. Therefore, reducing the transported cargo by one pallet results in the price per pallet to increase by 3%. Calculation: € 2000 / 24 pallets = 83 €/pal. (24 pal.) => 1.03*83=86€/pal. (23 pal.), etc. Source of price quotes: Logistics provider A, C, D, E, F, 2017[61,66,68–70]

Table 46: Estimation of costs related to export to Italy and the USA (current situation based on the results from the survey by Paternoster, 2017[76])

Distributor 1 / Brewery 1	**Distributor 2 / Brewery 2**	**Distributor 3 / Brewery 3**	**Distributor 4 / Brewery 4**	**Distributor 5 / Brewery 5**
EXPORT ITALY				
18 times 24 pallets per year	72 times 2 pallets per year	6 times 24 pallets per year	12 times 12 pallets per year	6 times 4 pallets per year
Transport cost = **€ 35,856** (18tr.*24pal.*83€/pal) [+/-10% = € 32,270 – 39,442]	Transport cost = **€ 22,608** (72tr.*2pal.*157€/pal) [+/-10% = € 20,347 – 24,869]	Transport cost = **€ 11,952** (6tr.*24pal.* 83€/pal.) [+/-10% = € 10,757 – 13,147]	Transport cost = **€ 16,848** (12tr*12pal* 117€/pal) [+/-10% = € 15,163 – 18,533]	Transport cost = **€ 3,552** (6tr.*4pal.*148€/pal.) [+/-10% = € 3,197 –3,907]
Order cost = **€ 3,600-7,200** (2*18tr.* 100-200 €/tr.)	Order cost = **€ 14,400-28,800** (2*72tr.*100-200 €/tr.)	Order cost = **€ 1,200-2,400** (2*6tr.*100/200 €/tr.)	Order cost = **€ 2,400-4,800** (2*12tr.*100-200 €/tr.)	Order cost = **€ 1,200-2,400** (2*6tr.*100-200 €/tr.)
Storage cost = **€ 5,225-10,450** (25-50%*1,30€/l*670l/pal.*24pal.)	Storage cost = **€ 436-872** (25-50%*1,30€/l*670l/pal.*2pal.)	Storage cost = **€ 5,225-10,450** (25-50%*1,30€/l*670l/pal.*24pal.)	Storage cost = **€ 2,613-5,225** (25-50%*1,30€/l *670 l/pal*12pal)	Storage cost = **€ 871-1,742** (25-50%*1,30€/l *670l/pal.*4pal.)
EXPORT U.S.A.				
No export country	No export country	12 times 24 pallets per year	4 times 22 pallets per year	12 times 3 pallets per year
/	/	Transport cost = **€ 20,448** (12tr.*24pal.*71€/pal) [+/-10% = € 18,403 – 22,493]	Transport cost = **€ 6,600** (4tr.*22pal.*75€/pal.) [+/-10% = € 5,940 – 7,260]	Transport cost = **€ 4,644** (12tr.*3pal.*129€/pal.) [+/-10% = € 4,180 – 5,108]
/	/	Order cost = **€ 2,400-4,800** (2*12tr.*100-200 €/tr.)	Order cost = **€ 800-1,600** (2*4tr.*100-200 €/tr.)	Order cost = **€ 2,400-4,800** (2*12tr.*100-200 €/tr.)
/	/	Storage cost = **€ 5,225-10,450** (25-50%*1,30€/l*670l/pal.*24pal.)	Storage cost = **€ 4,790-9,579** (25-50%*1,30€/l*670l/pal.*22pal.)	Storage cost = **€ 653-1,307** (25-50%*1,30€/l *670l/pal.*3pal.)

The transport frequency and degree of loading per transport of breweries 1-5 were surveyed with respect to export to Italy and the USA, and the transport, order and storage costs were estimated: Transport cost = (# transports) x (# pallets per transport) x (price per pallet (Table 22)) // Order cost = 2 (brewery to logistics provider, and to distributor) x (# transports) x (assumption 100-200 €/transport) // Storage cost = 25-50% product value of 1 transport Source: Own content, based on Survey Paternoster, 2017[76]

Table 47: Overview of results - collaboration in logistics with respect to data of the breweries

<table>
<tr><td colspan="4">Italy - Scenario 1: bundling cargo</td></tr>
<tr><td colspan="4">6 transports with 18 pallets, 6 transports with 14 pallets and 60 (72-12) transports coming from brewery 2 with 2 pallets
[The transported beer from brewery 3 is not considered due to the optimal loading]</td></tr>
<tr><td colspan="4">TRANSPORT COST = € 39,048
(6tr.*18pal.*100€/pal. + 6tr.*14pal.*112€/pal. +60tr.*2pal.*157€/pal.) [+/- 10%: € 35,143 – 42,953]</td></tr>
<tr><td colspan="4">PROFIT from bundling = € 3,564 – 4,356 [comparison indiv. - bundled transport costs of brewery 2, 4 & 5 - Table 23]</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Italy - Scenario 2: bundling cargo + optimizing transportation frequency</td></tr>
<tr><td colspan="4">14 mutual transports with 24 pallets and 60 (72-2) transports coming from brewery 2 with 2 pallets</td></tr>
<tr><td colspan="4">TRANSPORT COST = € 46,728
(14tr.*24pal.*83€/pal. + 60tr.*2pal.*157€/pal.) [+/- 10%: € 42,055 – 51,401]</td></tr>
<tr><td>Brewery/wholesaler 2</td><td>Brewery/wholesaler 3</td><td>Brewery/wholesaler 4</td><td>Brewery/wholesaler 5</td></tr>
<tr><td>Order cost= 14,400-28,800
(2*72tr.* 100-200 €/tr.)</td><td>Order cost= € 2,800-5,600
(2*14tr.* 100-200 €/tr.)</td><td>Order cost= €2,800-5,600
(2*14tr.* 100-200 €/tr.)</td><td>Order cost= €2,400-4,800
(2*12tr.* 100-200 €/tr.)</td></tr>
<tr><td>Storage cost= € 436 – 871
(25-50%*871€/pal. *2pal.)</td><td>Storage cost= 2,395 – 4,791
(25-50%*871€/pal.*11pal.)</td><td>Storage cost= 2,395 – 4,791
(25-50%*871€/pal.*11pal.)</td><td>Storage cost= € 436 – 871
(25-50%*871€/pal.*2pal.)</td></tr>
<tr><td colspan="4">€ 2,855 - 3,956 Profit from bundling cargo (transport and order costs)
+ € 3,483 - 6,964 Profit from frequent transports (storage costs)</td></tr>
<tr><td colspan="4">TOTAL PROFIT from collaborating = € 6,338 – 10,920</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">USA - Scenario 1: bundling cargo</td></tr>
<tr><td colspan="4">4 transports with 24 pallets, 4 transports coming from brewery 5 with 4 pallets and 4 transports with 3 pallets
[The transported beer from brewery 3 are not considered due to the optimal loading]</td></tr>
<tr><td colspan="4">TRANSPORT COST = € 10,380
(4tr.*24pal.*71€/pal. + 4tr.*4pal.*126€/pal. + 4tr.*3pal.*129€/pal.) [+/- 10%: € 9,342 – 11,418]</td></tr>
<tr><td colspan="4">PROFIT from bundling = € 778 – 950 [comparison indiv. - bundled transport costs of brewery 4 & 5 - Table 23]</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">USA - Scenario 2: bundling cargo + optimizing transportation frequency</td></tr>
<tr><td colspan="4">16 mutual transports with 24 pallets and 2 transports with 12 pallets</td></tr>
<tr><td colspan="4">TRANSPORT COST = € 29,640
(16tr.*24pal.*71€/pal. + 2tr.*12pal.*99€/pal.) [+/- 10%: € 26,676 – 32,604]</td></tr>
<tr><td>Brewery/wholesaler 2</td><td>Brewery/wholesaler 3</td><td>Brewery/wholesaler 4</td><td>Brewery/wholesaler 5</td></tr>
<tr><td>/</td><td>Order cost= 3,200-6,400
(2*16tr.* 100-200 €/tr.)</td><td>Order cost= 3,600-7,200
(2*18tr.* 100-200 €/tr.)</td><td>Order cost= 3,600-7,200
(2*18tr.* 100-200 €/tr.)</td></tr>
<tr><td>/</td><td>Storage cost= 3,920 – 7,840
(25-50%*871€/pal.*18pal.)</td><td>Storage cost= 1,089 – 2,178
(25-50%*871€/pal.*5pal.)</td><td>Storage cost= € 436 – 871
(25-50%*871€/pal.*2pal.)</td></tr>
<tr><td colspan="4">€ -2,950 to -7,343 Profit from bundling cargo (transport and order costs)
+ € 5,224 to 10,447 Profit from frequent transports (storage costs)</td></tr>
<tr><td colspan="4">TOTAL PROFIT from collaborating = € 2,274 – 3,104</td></tr>
</table>

Two case-studies (for exporting beer to Italy and the USA) are presented: (scenario 1) bundling cargo, (scenario 2) bundling cargo and optimizing transport frequency. Substantial profits were reported. The costs should be compared to the costs of individual breweries/wholesalers of Table 46. Source: Own calculations

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