



GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Master Thesis

Multivariate modelling of the dependency
structure between article sales of a
sportswear manufacturer

Author

Petros Christanas

from Nuremberg

Matriculation Number

11604278

Applied Statistics M.Sc.

Chair of Statistics and Econometrics

Supervisors

Prof. Dr. Thomas Kneib

Dipl.-Vw. Quant. Fabian H. C. Raters

Submitted August 7, 2020

Processing time of 20 weeks

Confidentiality Clause

Acknowledgments

Contents

1	Introduction	1
1.1	adidas	2
1.2	Data Sources	3
2	Statistical Theory & Methods	7
2.1	Shapiro-Wilk Test of Normality	7
2.2	Generalized Linear Models	7
2.3	Additive Models	8
2.4	Generalized Additive Models for Location, Scale and Shape	10
3	Copulas & Dependence Structures	11
3.1	Introduction to Copulas	11
3.2	Copula Classes	14
3.2.1	Fundamental Copulas	14
3.2.2	Elliptical Copulas	15
3.2.3	Archimedean Copulas	17
3.3	Dependence Measures	20
3.3.1	Linear Correlation	20
3.3.2	Rank Correlation	21
3.3.3	Tail Dependence	22
3.4	Structured Additive Conditional Copulas	23
4	Data Exploration	25
4.1	Universal Sales Patterns	26
4.2	Grouped Patterns - Key Category Cluster	31
5	Modelling	35
5.1	Key Category Cluster - Marginals	35
5.1.1	Key Category Cluster 2	36
5.1.2	Key Category Cluster 6	41
5.1.3	Key Category Cluster 8	45
5.2	Key Category Cluster - Pairwise Copulas	49
5.2.1	Key Category Clusters 2 & 6	51
5.2.2	Key Category Clusters 2 & 8	55

5.2.3 Key Category Clusters 6 & 8	58
6 Conclusion	59
List of Abbreviations	61
List of Figures	63
List of Tables	67
References	69

1 Introduction

Nowadays, online shopping is gradually becoming people's favourite purchasing standard. As designer and fashion brands adjust to this new way of shopping, they are not only promoting their products via third party providers, but also have their own e-Commerce websites. Likewise, *adidas* has grown its eCom channel tremendously over the past few years and has gained a large pool of casual and regular customers.

The aim of some use cases of the adidas Advanced Analytics Hub is to generate sales¹ forecasts for individual articles, usually on a weekly or monthly level. This is not always trivial since industrial big data are quite noisy, e.g. different types of campaigns and promotions influence the demand quantity dramatically over time. The purpose of this thesis is to capture a dependence structure between article demand quantities over time, applied to transactional eCom data. Primary modelling focus will be on particular clusters of article demand quantities and extensions on individual articles, will be outlined.

Another latent effect is sales cannibalization between newer and older articles or articles of similar traits. To identify this effect in a quantifiable way, there will be suggestions for further methodologies towards the end.

In the remaining of Chapter 1, a brief overview of the sports brand adidas is given in Section 1.1 and in Section 1.2 we will have a first look into our data sources and a data dictionary. Chapter 2 introduces some notions on relevant statistical methodology. In Chapter 3, we will have a closer look into the copula framework which comprises the major ingredient of the modelling part of this thesis. In Chapter 4 we perform some exploratory data analysis to deep dive into the behaviour of article sales and to step-wise investigate some hierarchical properties of our data. Chapter 5 analyses based on some preliminary work the results of modelling copulas to the data and we will examine some diagnostics using different approaches. A final conclusion will be summarized in Chapter 6, where we point out the main findings of this thesis and further potential study directions.

¹By sales we actually mean sale quantities in units throughout this thesis.

1.1 adidas

After World War II, the "*Dassler Brothers Shoe Factory*" (German: "*Gebrüder Dassler Schuhfabrik*"), which was led by *Adolf Dassler* (aka *Adi Dassler*) and his brother Rudolph, was dissolved. The brothers split up and formed their own firms. As a result, the sports shoe factory "*Adi Dassler adidas Sportschuhfabrik*" was founded on August 18th 1949 by Adolf Dassler in Herzogenaurach, a small town in Germany [adidas-group.com].



(a) adidas Performance



(b) adidas Originals

Figure 1.1: Two of the adidas-group logos: Performance (left) & Originals (right)
[adidas.com media-center]

Today, just over 70 years later, the sportswear designer and manufacturer is known as the "*adidas AG*" (short: *adidas*) and is one of the world's biggest sports and fashion brands. The global headquarters of are located in the birthplace Herzogenaurach and the company is employing over 59,000 people worldwide, with *Kasper Rørsted* leading the brand as CEO since October 1st 2016. In 2019, adidas produced over 1.1 billion sports and sports lifestyle products and is nowadays sponsoring a vast range of athletes, artists and organizations across the globe (e.g. the FIFA World Cup™).

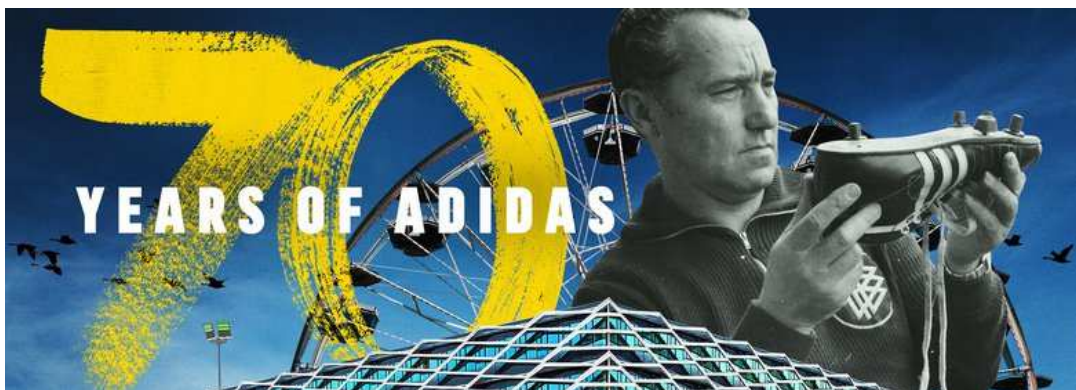


Figure 1.2: adidas celebrates its 70th anniversary and the opening of the ARENA building [adidas 70 years, 2019]

With the company's rapid growth, the data produced and acquired from social media, e-Commerce (eCom), transactions, demographics and other channels require suitable instruments and stuff to generate business relevant insights. As the need for data-driven decision making keeps increasing, "*Data and Analytics (DNA)*" became a sub-department of IT. Within DNA, the "*Data Science & AI Solutions*" team consisting of data scientists, analysts, engineers and other roles is responsible for carrying out analytical tasks, for the most part in the context of various DNA use cases.

1.2 Data Sources

Throughout each season, transactional data are collected from online purchases of the sports brand's e-Commerce website. Specifically, weekly sales data for western European countries consisting of 109 observed weeks in total are provided. A short description is depicted in Table 1.1.

Column	Description	Values
week_id	Calendar week of a specific year (YYYYWW)	Factors: 201648, ..., 201852
article_number	Unique article identification number (article ID)	Factors: 10669, 10, ...
min_date_of_week	Minimum date of the respective week; always a Monday (YYYY-MM-DD)	Dates: 2016-11-28, ..., 2018-12-24
art_min_price	Minimal recorded price of the article	Non-negative (integer) value
month_id	Calendar month of a specific year (YYYYMM)	Factors: 201612, ..., 201812
season	Season of year (format: SSYY) (Spring-Summer [SS]: December - May) Fall-Winter [FW]: June - November)	Factors: SS17, FW17, SS18, FW18, SS19
bf_w	Weekly "Black Friday" promotion intensity of the article	Between 0 and 1
ff_w	Weekly "Friends & Family" promotion intensity of the article	Between 0 and 1
ot_w	Weekly article promotion intensity of "Other" type	Between 0 and 1
gross_demand_quantity	Weekly amount of added articles to shopping cart	Non-negative (integer) value
base_price_locf	Retail price of the article without any discounts	Non-negative (integer) value
total_markdown_pct	Total markdown percentage of the article	Non-negative
day_of_month	Day of the month	Integers: 1 - 31
month_of_year	Month of the year	Factors: January, ..., December
year	Year	Integers: 2016, 2017, 2018
week_of_year	Week of the year	Integers: 1 - 52

Table 1.1: Transactional raw data description from online purchases of western European countries

Due to legal regulations of the company, some columns had to undergo anonymization in order for the data to be released. To ensure data protection and confidentiality, numeric variables (with exception of time-indicating columns) were transformed. As a consequence for the analysis part, most integer values were converted to float numbers. This fact should be kept in mind by the reader, since the above table serves as a reminder and

reference point for the data documentation.

Another peculiarity of this setup is to be considered, too. We will often refer to the variable *gross demand quantity* as *sales*, even though it is obviously not exactly the same. In the e-Commerce environment, there are several stages before the purchase is complete, e.g. addition to cart, removal from cart, proceeding to checkout & even the return of bought articles. Targeting the articles added to cart, i.e. the (gross) demand quantity, provides the optimal data extraction for analytical purposes and is the closest to adequately model the dependence structure between net sales of articles.²

Besides the transactional data, attributes of the articles are provided and described in Table 1.2. Some attributes of special importance will be explained in more detail later on in Chapter 4.

Column	Description	Values (all Factors)
article_number	Unique article identification number (article ID)	10669, 10, ...
gender	Gender type of the article (Men, Women, Unisex)	M, W, U
age_group	Age group of the article (Adult, Infant, Junior, Kids)	A, I, J, K
key_category_descr	Key category of the article	KC_1, ..., KC_15
key_category_cluster_descr	Key category cluster of the article	KCC_1, ..., KCC_9
product_division_descr	Product division of the article	Apparel, Footwear, Hardware
product_group_descr	Product group of the article	Bags, Balls, Footwear Accessories, Shoes, ...
color	Consolidated color group of the article	Beige, Black, Brown, Orange, Pink, Red, ...
sports_category_descr	Sports category of the article	encoded: SC_1, ..., SC_22
sales_line_descr	Sales line of the article	encoded: SL_1, ..., SL_379
business_unit_descr	The article's Business Unit membership	encoded: BU_1, ..., BU_18
business_segment_descr	The article's Business Segment membership	encoded: BS_1, ..., BS_49
sub_brand_descr	Sub-brand of the article	encoded: sub-brand_1, ..., sub-brand_4
item_type	Item type of the article	encoded: IT_1, ..., IT_171
brand_element	Brand element of the article	encoded: BE_1, ..., BE_131
product_franchise_descr	Product franchise of the article	encoded: franchise_1, ..., franchise_72
product_line_descr	Product line of the article	encoded: PL_1, ..., PL_105
franchise_bin	Franchise indicator of the article	Franchise, Non-Franchise
category	Category of the article	encoded: category_1, category_2

Table 1.2: Article attribute data

Overall, these are the primary data sources and we will be working with data collected over two years, namely the years 2017 and 2018, while some transactions of late 2016 are attached marginally. In summary, after joining the transactional observations to the

²Gross demand quantity will be our target as we follow the adidas norm

article attributes by the article ID, this translates to a dataset of over 587,000 instances and over 30 variables.

2 Statistical Theory & Methods

This chapter introduces some statistical methods used during the conduction of this thesis. Basic notations regarding mathematical foundations of statistics (such as linear algebra, probability theory, hypothesis testing etc) are skipped. Theoretical aspects regarding copulas and dependence structures will be introduced separately in Chapter 3.

2.1 Shapiro-Wilk Test of Normality

The *Shapiro-Wilk test* is a method used to test the hypothesis whether a sample of observations $\mathbf{x} = x_1, \dots, x_n$ was drawn from a normal distribution, i.e.

$$H_0 : \mathbf{x} \sim \mathcal{N}(\mu, \sigma) \quad \text{vs} \quad H_1 : \mathbf{x} \not\sim \mathcal{N}(\mu, \sigma)$$

and the test statistic is

$$W = \frac{\left(\sum_{i=1}^n a_i x_{(i)}\right)^2}{\sum_{i=1}^n (x_i - \bar{x})^2},$$

where the coefficients a_i are given by

$$(a_1, \dots, a_n) = \frac{\mathbf{m}^\top \mathbf{V}^{-1}}{(\mathbf{m}^\top \mathbf{V}^{-1} \mathbf{V}^{-1} \mathbf{m})^{1/2}}.$$

The expected values of the order statistics of independent and identically distributed (iid) random variables (RV), which are sampled from a standard normal distribution $\mathcal{N}(0, 1)$, are represented by the vector $\mathbf{m} = (m_1, \dots, m_n)^\top$ and \mathbf{V} is the covariance matrix of those order statistics.

The Shapiro-Wilk test of normality was first introduced in Shapiro and Wilk [1965] and more details can be found in this paper.

2.2 Generalized Linear Models

Generalized Linear Models (GLMs) are an extension of the classical *Linear Regression Model (LM)*

$$y_i = \beta_0 + \beta_1 x_{i1} + \dots + \beta_k x_{ik} + \varepsilon_i, \quad i = 1, \dots, n$$

which in matrix notation can be written as

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon}$$

where the response variable y_i can take values from several probability distributions (e.g. Poisson, Binomial, Gamma, ...), which are members of the exponential family [Fahrmeir

et al., 2003]. The linear predictor

$$\eta_i = \beta_0 + \beta_1 x_{i1} + \dots + \beta_k x_{ik} + \varepsilon_i = \mathbf{x}_i' \boldsymbol{\beta} \quad (2.1)$$

is passed through a *response function* h (a one-to-one, twice differentiable transformation), such that

$$E(y_i) = h(\eta_i) \quad (2.2)$$

i.e. h ensures that the expected value of the response variable belongs to the appropriate value range. The inverse of the response function, i.e.

$$g = h^{-1}, \quad (2.3)$$

is called the *link function* and transforms the mean of the response's distribution to an unbounded continuous scale.

2.3 Additive Models

Additive Models expand models with just a linear predictor

$$\eta_i^{lin} = \beta_0 + \beta_1 x_{i1} + \dots + \beta_k x_{ik}$$

(such as the LM) to

$$y_i = \eta_i^{add} + \varepsilon_i, \quad (2.4)$$

where

$$\eta_i^{add} = f_1(z_{i1}) + \dots + f_q(z_{iq}) + \eta_i^{lin}, \quad i = 1, \dots, n. \quad (2.5)$$

The functions $f_1(z_1), \dots, f_q(z_q)$ are non-linear univariate *smooth effects* of the *continuous* covariates z_1, \dots, z_q and are defined as

$$f_j(z_j) = \sum_{l=1}^{d_j} \gamma_{jl} B_l(z_j) \quad (2.6)$$

with $B_l(z_j)$ being *basis functions* for $j = 1, \dots, q$ and d_j the number of basis functions for covariate z_j . The regression coefficients of the basis functions $B_l(z_j)$ are labeled as γ_{jl} . There is a wide variety of basis functions which can be used to flexibly model the data in a non-parametric manner. For more content on basis functions the reader can refer to Wood [2017] and Fahrmeir et al. [2003]. The basis functions evaluated at the observed covariate values are summarized in the design matrices $\mathbf{Z}_1, \dots, \mathbf{Z}_q$ and the additive model 2.4 can be written in matrix notation as

$$\mathbf{y} = \mathbf{Z}_1 \boldsymbol{\gamma}_1 + \dots + \mathbf{Z}_q \boldsymbol{\gamma}_q + \mathbf{X} \boldsymbol{\beta} + \boldsymbol{\varepsilon}. \quad (2.7)$$

Accordingly, the vector of function values evaluated at the observed covariate values z_{1j}, \dots, z_{nj} is denoted by $\mathbf{f}_j = (f_j(z_{1j}), \dots, f_j(z_{nj}))'$ and therefore $\mathbf{f}_j = \mathbf{Z}_j \boldsymbol{\gamma}_j$. To ensure identifiability of the additive model, the smooth functions $f_j(z_j)$ are centered around zero, such that

$$\sum_{i=1}^n f_1(z_{i1}) = \dots = \sum_{i=1}^n f_q(z_{iq}) = 0.$$

A convenient trait of additive models is that they also support the incorporation of random effects. Random coefficient terms can straightforwardly be added to the model. Data are considered to be measured in a longitudinal setting with individuals $i = 1, \dots, m$ observed at times $t_{i1} < \dots < t_{ij} < \dots < t_{in_i}$ or clustered data with subjects $j = 1, \dots, n_i$ in clusters $i = 1, \dots, m$. Without loss of generality,³ we can simply add to Equation 2.7 the terms $\mathbf{Z}_0 \boldsymbol{\gamma}_0$ and $\mathbf{Z}_1 \boldsymbol{\gamma}_1$ representing the design matrices and coefficients of the random intercepts and random slopes respectively. Explicitly, the coefficients are formulated as $\boldsymbol{\gamma}_0 = (\gamma_{01}, \dots, \gamma_{0i}, \dots, \gamma_{0m})'$ and $\boldsymbol{\gamma}_1 = (\gamma_{11}, \dots, \gamma_{1i}, \dots, \gamma_{1m})'$, whereas the design matrices are expressed as

$$\mathbf{Z}_0 = \begin{pmatrix} \mathbf{1}_1 & & & \mathbf{0} \\ & \ddots & & \\ & & \mathbf{1}_i & \\ & & & \ddots \\ & & & & \mathbf{1}_m \end{pmatrix} \quad \mathbf{Z}_1 = \begin{pmatrix} \mathbf{x}_1 & & & \mathbf{0} \\ & \ddots & & \\ & & \mathbf{x}_i & \\ & & & \ddots \\ & & & & \mathbf{x}_m \end{pmatrix}.$$

More details and technicalities regarding mixed effects in additive models can be found in the respective literature.

Extensions of additive models to non-normal responses are consequently called *Generalized Additive Models (GAMs)*, which were first introduced by Hastie and Tibshirani [1986]. If additionally random effects are included, they are called *Generalized Additive Mixed Models (GAMMs)*.

Thus far, models with main effects and conceivably random effects have been introduced. Accordingly, these types of effects can likewise be combined with covariate interactions and/or spatial effects. Such models can be described in a unified framework and are titled as (possibly *Generalized*) *Structured Additive Regression Models (STARs)*,

$$y = f_1(\nu_1) + \dots + f_q(\nu_q) + \beta_0 + \beta_1 x_1 + \dots + \beta_k x_k + \varepsilon.$$

³for the indexes

The covariates ν_1, \dots, ν_q can be one- or multidimensional and the functions can be of different structure determining the type of effect.

2.4 Generalized Additive Models for Location, Scale and Shape

Generalized Additive Models for Location, Scale & Shape (GAMLSS) [Rigby and Stasinopoulos, 2001, 2005] are a framework which surpass the limitations that come with GLMs and GAMs. Particularly, in GAMLSS the assumption that the response variable y belongs to a distribution of the exponential family is relaxed and a more general distribution family is permissible, including highly skewed and/or kurtotic distributions. In addition, other parameters besides the mean (or location) of the response's distribution can be modelled flexibly incorporating linear, non-linear and/or additive functions of covariates as well as random effects. By modelling the scale and shape parameters also, the issue of heteroscedasticity in the response is being handled. The models are fitted using maximum (penalised) likelihood estimation. Two algorithms can be used to fit the models, namely the CG and the RS algorithms, which can be looked upon in more detail in Rigby and Stasinopoulos [2005].

Independent observations y_i for $i = 1, 2, \dots, n$ with probability (density) function $f(y_i | \theta^i)$, where $\theta^i = (\theta_{i1}, \theta_{i2}, \dots, \theta_{ip})$ are assumed. Without loss of generality, p is at most 4 and the parameters are denoted as $(\mu_i, \sigma_i, \nu_i, \tau_i)$, where the parameter μ_i is the location parameter, σ_i is the scale parameter, and ν_i and τ_i are characterized as shape parameters. The model can be of course applied to distributions of any kind of parametric nature. Let $\mathbf{y} = (y_1, y_2, \dots, y_n)^\top$ be the vector of the response variable and $g_k(\cdot)$, $k = 1, 2, 3, 4$ be known monotonic link functions. Then

$$\begin{aligned} g_1(\boldsymbol{\mu}) &= \eta_1 = \mathbf{X}_1\boldsymbol{\beta}_1 + \sum_{j=1}^{J_1} h_{j1}(\mathbf{x}_{j1}) \\ g_2(\boldsymbol{\sigma}) &= \eta_2 = \mathbf{X}_2\boldsymbol{\beta}_2 + \sum_{j=1}^{J_2} h_{j2}(\mathbf{x}_{j2}) \\ g_3(\boldsymbol{\nu}) &= \eta_3 = \mathbf{X}_3\boldsymbol{\beta}_3 + \sum_{j=1}^{J_3} h_{j3}(\mathbf{x}_{j3}) \\ g_4(\boldsymbol{\tau}) &= \eta_4 = \mathbf{X}_4\boldsymbol{\beta}_4 + \sum_{j=1}^{J_4} h_{j4}(\mathbf{x}_{j4}), \end{aligned} \tag{2.8}$$

where $\boldsymbol{\mu}, \boldsymbol{\sigma}, \boldsymbol{\nu}, \boldsymbol{\tau}$ and $\boldsymbol{\eta}_k$ and \mathbf{x}_{jk} , for $j = 1, \dots, J_k$ and $k = 1, 2, 3, 4$ are vectors of length n . The explanatory variable X_{jk} evaluated at x_{jk} is described by the additive function h_{jk} .

X_k are fixed design matrices and β_k are the parameter vectors.⁴

Note that the model 2.8, also known as *semi-parametric GAMLSS* model, can be extended to allow random effect terms to be included for any parameter (more details can be found in the mentioned literature for this section).

⁴According to Stasinopoulos et al. [2007], in typical applications a constant is often adequate for each of the two shape parameters.

3 Copulas & Dependence Structures

Multivariate distributions consist of the marginal distributions and the dependence structure between those marginals. These components can be specified separately in a single framework with the help of copula functions. This chapter introduces the concept of modelling such dependence structures with copulas, which is the main focus of this thesis. The core elements on this subject were picked up from McNeil et al. [2015] and Ruppert and Matteson [2015].

3.1 Introduction to Copulas

A d -dimensional function $C : [0, 1]^d \rightarrow [0, 1]$ is called a *copula*, if it is a Cumulative Distribution Function (CDF) with uniform margins, i.e.

$$P(U_1 \leq u_1, \dots, U_d \leq u_d) = C(u_1, \dots, u_d)$$

where U_i , $i = 1, \dots, d$ are uniformly distributed Random Variables (RVs) in $[0, 1]$.

Since C is a CDF, following properties emerge:

- $C(\mathbf{u}) = C(u_1, \dots, u_d)$ is increasing in each component u_i , $i = 1, \dots, d$.
- The i^{th} marginal distribution is obtained by setting $u_j = 1$ for $j \neq i$ and it has to be uniformly distributed

$$C(1, \dots, 1, u_i, 1, \dots, 1) = u_i$$

- For $a_i \leq b_i$, the probability $P(U_1 \in [a_1, b_1], \dots, U_d \in [a_d, b_d])$ must be non-negative, so we obtain the *rectangle inequality*

$$\sum_{i_1=1}^2 \dots \sum_{i_d=1}^2 (-1)^{i_1 + \dots + i_d} C(u_{1,i_1}, \dots, u_{d,i_d}) \geq 0, \quad (3.1)$$

where $u_{j,1} = a_j$ and $u_{j,2} = b_j$.

The reverse is also true, i.e. any function C that satisfies the above properties is a copula. Furthermore, $C(1, u_1, \dots, u_{d-1})$ is also a $(d-1)$ -dimensional copula and thus all k -dimensional marginals with $2 < k < d$ are copulas.

Generalized Inverse

For a CDF, the *generalized inverse* is defined by

$$F^{\leftarrow}(y) := \inf\{x : F(x) \geq y\}$$

(similar to the definition of a *quantile function*).

□

Probability Transformation

If a RV Y has a continuous CDF F , then

$$F(Y) \sim U[0, 1]. \quad (3.2)$$

□

The reverse of the *probability transformation* is the *quantile transformation*.

Quantile Transformation

If $U \sim U[0, 1]$ and F be a CDF, then

$$P(F^{\leftarrow}(U) \leq x) = F(x) \quad (3.3)$$

□

The above two transformations allow us to move back and forth between \mathbb{R}^d and $[0, 1]^d$ and are the primary building blocks when it comes to copulas. Against this backdrop, *Sklar's theorem* is introduced, which is considered the foundation of all copula related applications.

Sklar's Theorem [Sklar, 1959]

Let F be a d -dimensional CDF with marginal distributions F_i , $i = 1, \dots, d$. Then there exists a copula C such that

$$F(x_1, \dots, x_d) = C(F_1(x_1), \dots, F_d(x_d)) \quad (3.4)$$

for all $x_i \in \mathbb{R}$, $i = 1, \dots, d$.

The copula C is unique, if $\forall i = 1, \dots, d$, F_i is continuous. Otherwise C is uniquely determined only on $\text{Ran}(F_1) \times \dots \times \text{Ran}(F_d)$, where $\text{Ran}(F_i)$ is the range of F_i .

Conversely, if C is a d -dimensional copula and F_1, \dots, F_d are univariate CDF's, then F as defined in Equation 3.4 is a d -dimensional CDF.

□

If the copula has a Probability Density Function (PDF), then the *copula density* is defined as

$$c(\mathbf{u}) = \frac{\partial^d C(u_1, \dots, u_d)}{\partial u_1 \dots \partial u_d} \quad (3.5)$$

for a differentiable copula function C and the realization of a random vector $\mathbf{u} = (u_1, \dots, u_d)$.

By virtue of Equation 3.4 in Sklar's theorem and given that

$$C(\mathbf{u}) = F(F_1^{\leftarrow}(u_1), \dots, F_d^{\leftarrow}(u_d)), \quad (3.6)$$

i.e. invertible CDFs F_i , $i = 1, \dots, d$, we can rewrite the copula density to

$$c(u_1, \dots, u_d) = \frac{f(F_1^{\leftarrow}(u_1), \dots, F_d^{\leftarrow}(u_d))}{\prod_{i=1}^d f_i(F_i^{\leftarrow}(u_i))} \quad (3.7)$$

for densities f of F and f_1, \dots, f_d of the corresponding marginals.

Invariance Principal

Suppose the RVs X_1, \dots, X_d have continuous marginals and copula C . For strictly increasing functions $T_i : \mathbb{R} \rightarrow \mathbb{R}$, $i = 1, \dots, d$, the RVs $T_1(X_1), \dots, T_d(X_d)$ also have copula C .

□

Fréchet-Hoeffding Bounds

Let $C(\mathbf{u}) = C(u_1, \dots, u_d)$ be any d -dimensional copula.

Then, for

$$W(\mathbf{u}) = \max \left\{ \sum_{i=1}^d u_i - d + 1, 0 \right\} \quad (3.8)$$

as well as

$$M(\mathbf{u}) = \min_{1 \leq i \leq d} \{u_i\}, \quad (3.9)$$

it holds that

$$W(\mathbf{u}) \leq C(\mathbf{u}) \leq M(\mathbf{u}), \quad \mathbf{u} \in [0, 1]^d. \quad (3.10)$$

W is called the *lower Fréchet-Hoeffding bound* and M the *upper Fréchet-Hoeffding bound*.

Note that W is a copula if and only if $d = 2$, whereas M is a copula for all $d \geq 2$ (more on this later in Section 3.2.1).

□

3.2 Copula Classes

In this section we will take a look at three very popular *copula classes*, namely *fundamental*, *elliptical* and *archimedean copulas*. For each class, a few (parametric) *copula families*, which are widely used, will be presented.

3.2.1 Fundamental Copulas

Fundamental copulas are a basic class of copulas, which emerge directly from the copula framework and do not depend on any parametric components.

Independence Copula

It is well known that the joint CDF of a finite set of RVs $X_i, i = 1, \dots, n$, is equal to the product of the marginals if and only if the RVs X_i are mutually independent, i.e.

$$F_{X_1, \dots, X_n}(x_1, \dots, x_n) = \prod_{i=1}^n F_{X_i}(x_i)$$

$\forall x_1, \dots, x_n$.

Equally, the exact same concept applies when we talk about the *independence copula*

$$\Pi(\mathbf{u}) = \prod_{i=1}^d u_i. \quad (3.11)$$

As a result of Sklar's theorem the RVs u_i are independent if and only if their copula is the independence copula, i.e.

$$C(\mathbf{u}) = \Pi(\mathbf{u})$$

and thus the copula density would be

$$c(\mathbf{u}) = 1, \quad \mathbf{u} \in [0, 1]^d.$$

□

From Equation 3.10, it is obvious that the Fréchet-Hoeffding bounds correspond to the extreme cases of perfect dependence between the RVs $X_i, i = 1, \dots, d$.

Comonotonicity Copula

Consider the RVs X_1, \dots, X_d and strictly increasing transformations T_1, \dots, T_d and $X_i = T(X_i)$ for $i = 2, \dots, d$. Making use of the *invariance principle*, it can be shown that these RVs have as copula the upper Fréchet-Hoeffding bound

$$M(\mathbf{u}) = \min\{u_1, \dots, u_d\}.$$

Since there is perfect positive dependence between those RVs, M is called the *comonotonicity copula*. The number of dimensions d can be any finite number greater than or equal to 2 for M to be a copula, as the minimum remains well defined.

□

Countermonotonicity Copula

Similar to the comonotonic case, it can be shown that if two RVs X_1 and X_2 are perfectly negatively dependent, their copula is the lower Fréchet-Hoeffding bound

$$W(\mathbf{u}) = \max \left\{ \sum_{i=1}^d u_i - d + 1, 0 \right\}.$$

Therefore, W is known as the *countermonotonicity copula*. Because of the fact that countermonotonicity is not valid for a dimension greater than 2, we end up with the restriction $d = 2$ for W to be indeed a copula.

□

3.2.2 Elliptical Copulas

Copulas which can be derived from known multivariate distributions like for example the *Multivariate Normal (or Gaussian) Distribution* or the *Multivariate Student's t-Distribution* are called *implicit copulas*. *Elliptical copulas* are implicit copulas which arise via Sklar's theorem from elliptical distributions like the mentioned examples.

Gaussian Copula

Without loss of generality, for a random vector $\mathbf{X} \sim \mathcal{N}_d(\mathbf{0}, \mathbf{P})$ and *correlation matrix* \mathbf{P} , the *Gaussian copula (family)* is given by

$$C_{\mathbf{P}}^{Ga}(\mathbf{u}) = \Phi_{\mathbf{P}}(\Phi^{-1}(u_1), \dots, \Phi^{-1}(u_d)), \quad (3.12)$$

where Φ is the CDF of $\mathcal{N}(0, \sigma^2)$ and $\Phi_{\mathbf{P}}$ is the CDF of $\mathcal{N}_d(\mathbf{0}, \mathbf{P})$.

There are special cases to this copula family, namely for $d = 2$ and correlation ρ , the *bivariate Gaussian copula* C_{ρ}^{Ga} is equivalent to

- the independence copula Π if $\rho = 0$,
- the comonotonicity copula M if $\rho = 1$ and
- the countermonotonicity copula W if $\rho = -1$

The density of the Gaussian copula is given by

$$c_{\mathbf{P}}^{\text{Ga}}(\mathbf{u}) = \frac{1}{\sqrt{\det \mathbf{P}}} \exp \left(-\frac{1}{2} \mathbf{x}' (\mathbf{P}^{-1} - \mathbf{I}_d) \mathbf{x} \right), \quad (3.13)$$

where $\mathbf{x} = (\Phi^{-1}(u_1), \dots, \Phi^{-1}(u_d))$.

□

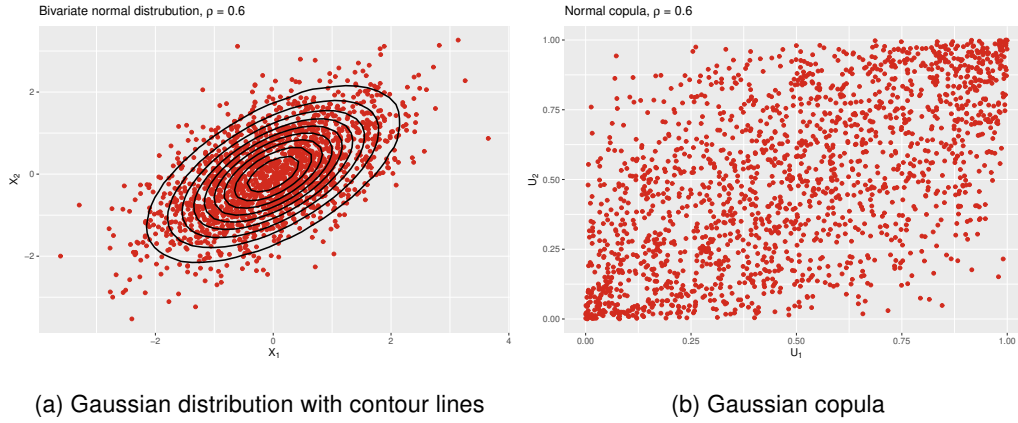


Figure 3.1: Bivariate Gaussian distribution and Gaussian copula for Pearson's $\rho = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals

t-Copula

Consider without loss of generality $\mathbf{X} \sim t_d(\nu, \mathbf{0}, \mathbf{P})$ (multivariate Student's t-distribution) with ν Degrees of Freedom (d.o.f.) and \mathbf{P} a correlation matrix, then the *t-copula (family)* is given by

$$C_{\nu, \mathbf{P}}^t(\mathbf{u}) = t_{\nu, \mathbf{P}}(t_{\nu}^{-1}(u_1), \dots, t_{\nu}^{-1}(u_d)), \quad (3.14)$$

where t_{ν} is the CDF of the univariate Student's t-distribution and $t_{\nu, \mathbf{P}}$ is the CDF of the multivariate Student's t-distribution (both with ν d.o.f.).

For the *bivariate t-copula* ($d = 2$), the special cases are the same as for the Gaussian copula except that $d = 0$ does not yield the independence copula (unless $\nu \rightarrow \infty$ in which case $C_{\nu, \rho}^t = C_{\rho}^{\text{Ga}}$).

The density of $C_{\nu, \mathbf{P}}^t$ is given by

$$c_{\nu, \mathbf{P}}^t(\mathbf{u}) = \frac{\Gamma((\nu + d)/2)}{\Gamma(\nu/2)\sqrt{\det \mathbf{P}}} \left(\frac{\Gamma(\nu/2)}{\Gamma((\nu + 1)/2)} \right)^d \frac{(1 + \mathbf{x}' \mathbf{P}^{-1} \mathbf{x} / \nu)^{-(\nu + d)/2}}{\prod_{j=1}^d (1 + x_j^2 / \nu)^{-(\nu + 1)/2}}, \quad (3.15)$$

where $\mathbf{x} = (t_{\nu}^{-1}(u_1), \dots, t_{\nu}^{-1}(u_d))$.

□

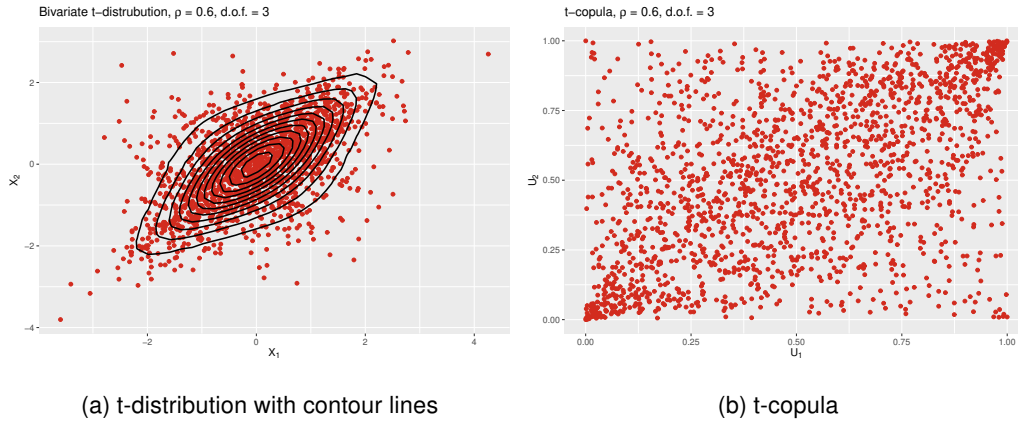


Figure 3.2: Bivariate t-distribution and t-copula with 3 degrees of freedom for Pearson's $\rho = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals

3.2.3 Archimedean Copulas

Unlike implicit copulas, *explicit copulas* can be specified directly by taking into account certain constructional principles. The most important aspects of a such explicit copulas, in particular *archimedean copulas*, are showcased in this subsection. Archimedean copulas are of the general form

$$C(\mathbf{u}) = \phi^{-1}(\phi(u_1) + \cdots + \phi(u_d)), \quad (3.16)$$

where the function $\phi : [0, 1] \rightarrow [0, \infty)$ is the (*archimedean*) *generator* and satisfies the following properties:

- ϕ is strictly decreasing in the entire domain $[0, 1]$
- We set $\phi(1) = 0$
- If $\phi(0) = \lim_{u \rightarrow 0^-} \phi(u) = \infty$, then ϕ is called *strict*.

Based on Equation 3.16 and according to the form of the generator, we can construct several copula families. Three of the most popular ones are the *Gumbel*, the *Clayton* and the *Frank copula*, which will be discussed.⁵ The advantage of such copulas lies in the fact that they interpolate between certain fundamental dependence structures.

⁵We will look into these copulas for the bivariate case ($d = 2$) only.

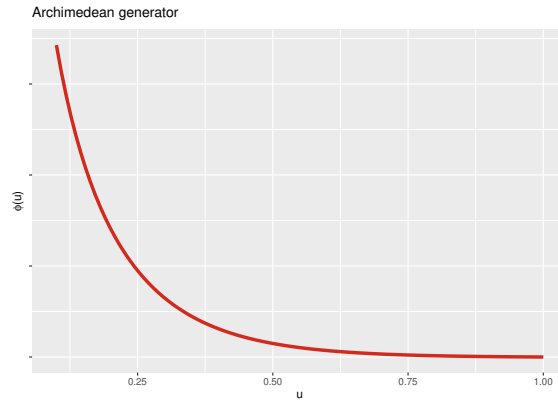


Figure 3.3: Shape of a generator function

Clayton Copula

If the generator takes on the form

$$\phi_{Cl}(u) = \frac{1}{\theta} (u^{-\theta} - 1) \quad (3.17)$$

then we obtain the *Clayton copula* given by

$$C_{\theta}^{Cl}(u_1, u_2) = \left(\max \left\{ u_1^{-\theta} + u_2^{-\theta} - 1, 0 \right\} \right)^{-\frac{1}{\theta}}, \quad (3.18)$$

where $\theta \in [-1, \infty) \setminus \{0\}$.

For $\theta > 0$ the generator of the Clayton copula is strict and we arrive at

$$C_{\theta}^{Cl}(u_1, u_2) = (u_1^{-\theta} + u_2^{-\theta} - 1)^{-\frac{1}{\theta}}. \quad (3.19)$$

Note that for $\theta = -1$, we obtain the lower Fréchet-Hoeffding bound W , whereas for the limits $\theta \rightarrow 0$ and $\theta \rightarrow \infty$ we arrive at the independence copula Π and the comonotonicity copula M respectively.

□

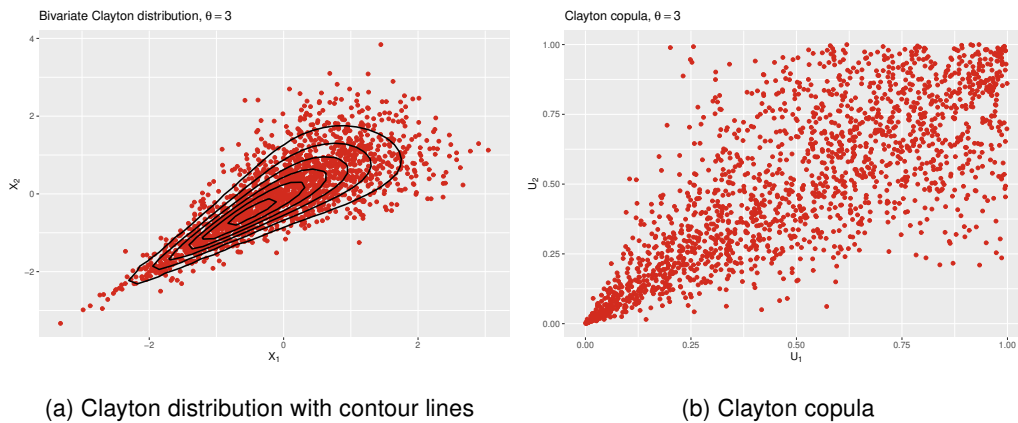


Figure 3.4: Bivariate Clayton distribution and Clayton copula for Kendall's $\tau = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals

Gumbel Copula

If the generator takes on the form

$$\phi_{Gu}(u) = (-\ln u)^\theta, \quad \theta \in [1, \infty), \quad (3.20)$$

then we arrive at the *Gumbel copula* given by

$$C_\theta^{Gu}(u_1, u_2) = \exp \left[- \left((-\ln u_1)^\theta + (-\ln u_2)^\theta \right)^{\frac{1}{\theta}} \right]. \quad (3.21)$$

Note that for $\theta = 1$, we obtain the independence copula Π , while for $\theta \rightarrow \infty$ the Gumbel copula converges to the comonotonicity copula M . Strictness holds for the entire parameter range of θ .

□

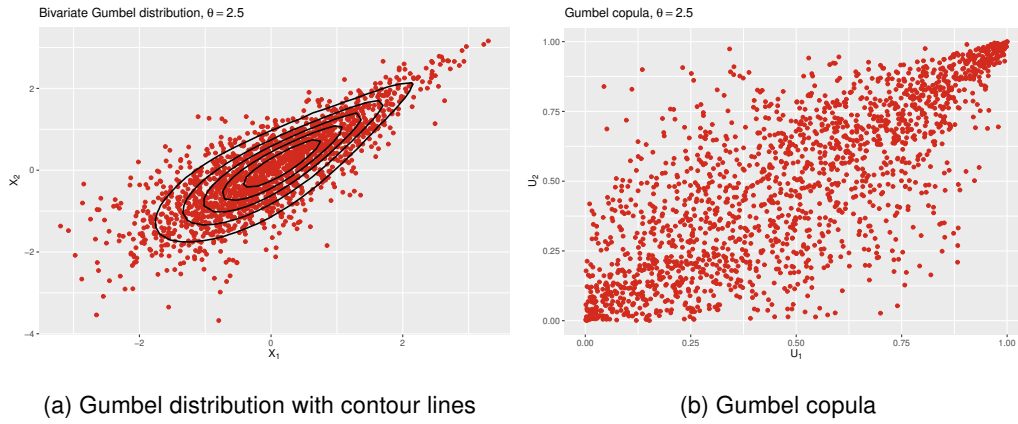


Figure 3.5: Bivariate Gumbel distribution and Gumbel copula for Kendall's $\tau = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals

Frank Copula

If the generator takes on the form

$$-\ln \left(\frac{e^{-\theta u} - 1}{e^{-\theta} - 1} \right), \quad \theta \in \mathbb{R} \setminus \{0\}, \quad (3.22)$$

we obtain the *Frank copula* given by

$$C_\theta^{Fr}(u_1, u_2) = -\frac{1}{\theta} \ln \left(1 + \frac{(e^{-\theta u_1} - 1) \cdot (e^{-\theta u_2} - 1)}{e^{-\theta} - 1} \right). \quad (3.23)$$

The Frank copula is strict in the parameter range of θ and interpolates between W ($\theta \rightarrow -\infty$), Π ($\theta \rightarrow 0$) and M ($\theta \rightarrow \infty$).

□

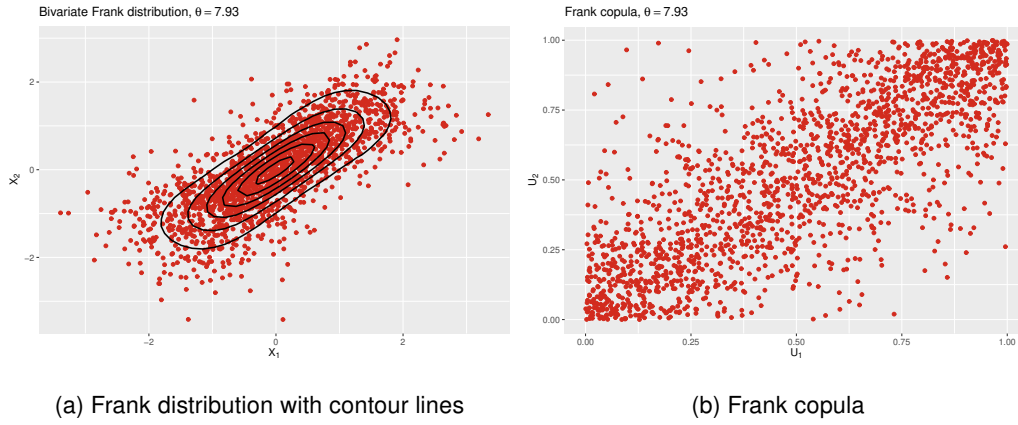


Figure 3.6: Bivariate Frank distribution and Frank copula for Kendall's $\tau = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals

3.3 Dependence Measures

Dependence measures allow us to summarize a particular kind of dependence into a single number.⁶ Recall the Fréchet-Hoeffding bounds (Equation 3.8 and Equation 3.9). They are an example of such kind of dependence measures. After all, they represent perfect negative or positive dependence. In this section, we will take a closer look into three classes of dependence measures along with appropriate association metrics.

3.3.1 Linear Correlation

Undoubtedly, the most famous association metric for two RVs X_1 and X_2 is the *Linear or Pearson's correlation coefficient*

$$\rho(X_1, X_2) = \frac{\text{Cov}(X_1, X_2)}{\sqrt{\text{Var}(X_1)}\sqrt{\text{Var}(X_2)}} \in [-1, 1]. \quad (3.24)$$

Note that $E(X_1) < \infty$ and $E(X_2) < \infty$ have to hold, i.e. the first two moments have to exist for ρ to be defined.

The Pearson correlation coefficient is interpretable for RVs which have (approximately) a linear relationship, where $\rho = -1$ indicates perfect negative linear correlation, $\rho = 1$ indicates perfect positive linear correlation and $\rho = 0$ indicates no correlation between X_1 and X_2 . However, comprehensibility of this measure comes along with some drawbacks:

- A correlation of 0 is in general not equivalent to independence. This property holds only for normally distributed RVs.⁷

⁶In the bivariate case

⁷e.g. $X_2 = X_1^2$ implies perfect dependence, yet $\rho(X_1, X_2) = 0$. Conversely though, independence always yields $\rho = 0$.

- ρ is invariant only under linear transformations, but not under transformations in general.
- Given the marginals and correlation ρ , one is able to construct a joint distribution only for the class of elliptical distributions.
- Given the marginals, only for elliptically distributed RVs any $\rho \in [-1, 1]$ is attainable.

3.3.2 Rank Correlation

To compensate some of the drawbacks of linear correlation, we can take advantage of correlation measures based on the ranks of data. *Rank correlation coefficients*, like the ones presented below, are always defined and obey to the invariance principal. This means that these coefficients only depend on the underlying copula and they can thereof be directly derived.

Spearman's Rho

Consider two RVs X_1 and X_2 with continuous CDFs F_1 and F_2 , then the *Spearman's rho correlation coefficient* is simply the linear correlation between the CDFs

$$\rho_S = \rho(F_1(X_1), F_2(X_2)). \quad (3.25)$$

The reason being is that by applying the CDF to data, naturally a multiple of the ranks of the data are obtained, which essentially is equivalent to

$$\rho_S = \rho(\text{Ran}(X_1), \text{Ran}(X_2)) \quad (3.26)$$

Due to the invariance principle, we also obtain Spearman's rho directly from the unique copula via

$$\rho_S = 12 \int_0^1 \int_0^1 C(u_1, u_2) du_1 du_2 - 3. \quad (3.27)$$

□

Kendall's Tau

Let $X_1 \sim F_1$ and $X_2 \sim F_2$ be two RV and let $(\tilde{X}_1, \tilde{X}_2)$ be an independent copy⁸ of (X_1, X_2) . Then *Kendall's tau* is defined by

$$\begin{aligned} \rho_\tau &= E [\text{sign}((X_1 - X'_1)(X_2 - X'_2))] \\ &= P((X_1 - X'_1)(X_2 - X'_2) > 0) - P((X_1 - X'_1)(X_2 - X'_2) < 0). \end{aligned} \quad (3.28)$$

⁸An independent copy \tilde{X} of a RV X is a RV that inherits from the same distribution as X and is independent of X .

Similarly to Spearman's rho, using the invariance principal, we can directly derive Kendall's tau from the unique copula by

$$\rho_\tau(X_1, X_2) = 4 \int_0^1 \int_0^1 C(u_1, u_2) dC(u_1, u_2) - 1. \quad (3.29)$$

□

Both $\rho_S, \rho_\tau \in [-1, 1]$ and any value within this interval is attainable for an arbitrary copula class in contrast to the Pearson coefficient. If any of these rank correlations is -1 (or 1), we are in the countermonotonic (or comonotonic) case. If ρ_S (or ρ_τ) $= 0$, this does not necessarily imply independence between X_1 and X_2 , although the opposite direction holds. Furthermore, they are not limited to be invariant just under linear transformations.

3.3.3 Tail Dependence

Coefficients of tail dependence express the strength of the dependence in the extremes of distributions, i.e. the joint tails. We distinguish between *lower* and *upper tail dependence* between $X_j \sim F_j, j = 1, 2$ and provided that the below limits exist, they are given by

$$\lambda_l = \lim_{q \rightarrow 0^+} P(X_2 \leq F_2^{\leftarrow}(q) | X_1 \leq F_1^{\leftarrow}(q)) \quad (3.30)$$

and

$$\lambda_u = \lim_{q \rightarrow 1^-} P(X_2 > F_2^{\leftarrow}(q) | X_1 > F_1^{\leftarrow}(q)). \quad (3.31)$$

If λ_l (or λ_u) $= 0$, then we say that X_1 and X_2 are *asymptotically independent* in the lower (or upper) tail,⁹ otherwise we have lower (or upper) tail dependence.

For continuous CDFs and by using Bayes' theorem, these expressions can be re-written to

$$\begin{aligned} \lambda_l &= \lim_{q \rightarrow 0^+} \frac{P(X_2 \leq F_2^{\leftarrow}(q), X_1 \leq F_1^{\leftarrow}(q))}{P(X_1 \leq F_1^{\leftarrow}(q))} \\ &= \lim_{q \rightarrow 0^+} \frac{C(q, q)}{q} \end{aligned}$$

and similarly

$$\lambda_u = 2 - \lim_{q \rightarrow 1^-} \frac{1 - C(q, q)}{1 - q}.$$

Therefore, tail dependencies can be assessed by means of the copula itself when approaching the points $(0, 0)$ and $(1, 1)$. In addition, for all radially symmetric copulas (e.g. the bivariate Gaussian or the t-copula) we have $\lambda_l = \lambda_u = \lambda$.

Some examples are:

- Clayton: $\lambda_l = 2^{-1/\theta}, \lambda_u = 0$ (only lower tail dependence, see Figure 3.4)

⁹Not necessarily true for the other way around

- Gumbel: $\lambda_l = 0$, $\lambda_u = 2 - 2^{1/\theta}$ (only upper tail dependence, see Figure 3.5)
- Frank: $\lambda_l = 0$, $\lambda_u = 0$ (no tail dependence, see Figure 3.6)

Following such guidelines, the choice of a practicable copula can be facilitated. Table 3.1 displays an overview of the relationships between dependence measures and θ parameters of various copulas.

Copula \ Measure	τ	ρ_s	λ_l	λ_u
Gaussian	$\frac{2}{\pi} \arcsin(\rho)$	$\frac{6}{\pi} \arcsin(\rho)$	0	0
Student's t	$\frac{2}{\pi} \arcsin(\rho)$	-	$2T_{\nu+1}(\sqrt{\frac{(\nu+1)(1-\rho)}{1+\rho}})$	$2T_{\nu+1}(\sqrt{\frac{(\nu+1)(1-\rho)}{1+\rho}})$
Clayton	$\frac{\theta}{\theta+2}$	-	$2^{-1/\theta}$	0
Gumbel	$\frac{\theta-1}{\theta}$	-	0	$2 - 2^{1/\theta}$
Frank	$1 - \frac{4}{\theta} (4 - D_1(\theta))$	$1 - \frac{12}{\theta} (D_1(\theta) - D_2(\theta))$	0	0

Table 3.1: Bivariate relationships in copula families, with T_ν being the Student's t-distribution function with ν degrees of freedom and $D_k(x) = \frac{k}{x^k} \int_0^x \frac{t^k}{e^t - 1} dt$ being the Debye function [stanfordphd]

3.4 Structured Additive Conditional Copulas

Modelling of the marginal response distributions along with their dependence structure has been studied so far in a strictly parametric context, not considering any potentially available covariate information. In this section, the copula framework will be broadened by adding conditions given possible covariates for all model parameters, i.e. both for the parameters of the marginals as well as the copula parameter. All involved model parameters will receive *structured additive predictors* (see Section 2.3) to account for possible non-linear or random effects. We will summarily explore *Structured Additive Conditional Copulas* and for extensive literature, good references to view are Klein and Kneib [2016], Vatter and Nagler [2019] and Marra and Radice [2016].

To get started, we define $(Y_1, Y_2)'$ to be independent bivariate responses and ν being the information contained in covariates. Ergo, Equation 3.4 of Sklar's theorem can be extended to the conditional case

$$F_{1,2}(Y_1, Y_2 | \nu) = C(F_1(Y_1 | \nu), F_2(Y_2 | \nu) | \nu) \quad (3.32)$$

in conjunction with all facets of Section 3.1 [Patton, 2006].

The marginal CDFs $F_d(y_{id} | \nu_i)$ for observations $i = 1, \dots, n$ can also be stated as

$$F_d(y_{id} | \nu_{i1}^{(d)}, \dots, \nu_{iK_d}^{(d)}), \quad d = 1, 2, \quad (3.33)$$

i.e. the distribution F_d has a total of K_d parameters, denoted as $\vartheta_{i1}^{(d)}, \dots, \vartheta_{iK_d}^{(d)}$. To relate all parameters of the marginals to structured additive predictors $\eta_i^{\vartheta_k^{(d)}}$, $k = 1, \dots, K_d$ consisting of the covariates ν_i (see Section 2.3), we employ strictly increasing response mappings $h_k^{(d)}$ to ensure proper domain allocation, i.e.

$$\vartheta_{ik}^{(d)} = h_k^{(d)}(\eta_i^{\vartheta_k^{(d)}}). \quad (3.34)$$

Assuming that the parameters of the copula can also depend on covariates ν_i while Sklar's theorem applies as usual, the left-hand side of Equation 3.32 can equivalently be stated as

$$F_{1,2}(y_{i1}, y_{i2} | v_i) = F_{1,2}(y_{i1}, y_{i2} | \vartheta_{i1}^{(1)}, \dots, \vartheta_{iK_1}^{(1)}, \vartheta_{i1}^{(2)}, \dots, \vartheta_{iK_2}^{(2)}, \vartheta_{i1}^{(c)}, \dots, \vartheta_{iK_c}^{(c)}),$$

where the last share of parameters $\vartheta_{i1}^{(c)}, \dots, \vartheta_{iK_c}^{(c)}$ belong to the copula. Similar to Equation 3.34, the copula parameters are modelled as $\vartheta_{ik}^{(c)} = h_k^{(c)}(\eta_i^{\vartheta_k^{(c)}})$ with K_c being the number of parameters.

4 Data Exploration

In Section 1.2 the setup of the data to be treated was introduced. As can be seen in Table 1.2, each article can be assigned to a set of attributes. Besides some elemental attributes like *color*, *age group* or *gender*, the data exhibit a "natural" company-specific hierarchical structure. In Figure 4.1, we can see an example of such a hierarchy for the attributes *Key Category Cluster (KCC)* and *Business Segment (BS)* (See Table 1.2). The bottom level consists of the individual articles and at the top level we have the brand. It is important to mention that there are more inner levels between the brand and the articles than depicted in Figure 4.1 below. For example, Key Category (KC) would be the level below KCC. KCCs are aggregated sport/fashion categories and KCs add an additional layer to KCCs, namely the *Product Division* covering Footwear, Apparel and Accessories/Hardware. The BS supplements the KC with a consumer driven "gender" perception. Within the scope of this thesis, we will be concerned with the hierarchical structure of Figure 4.1 and in particular our KCCs of interest are "KCC 2", "KCC 6" and "KCC 8".

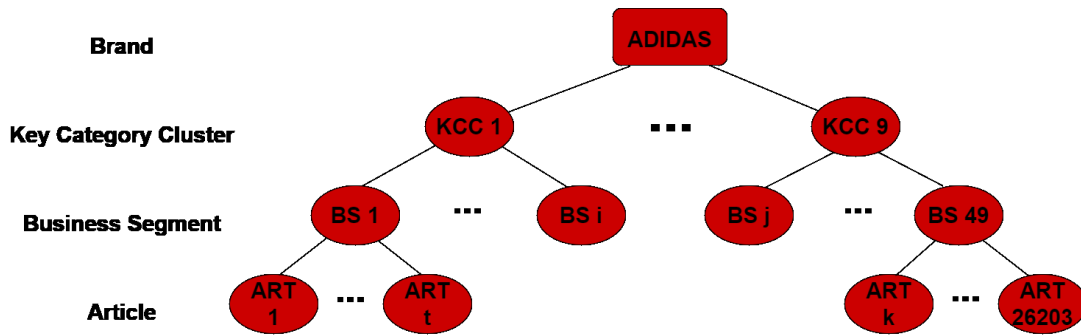


Figure 4.1: Illustration of a hierarchical article structure

Worth mentioning is that it is possible that some individual nodes might have only one single child node, meaning that the hierarchy level can stay consistent across multiple nodes. This phenomenon however is very rare and when it occurs, it affects usually two consecutive nodes only. For example, *Sub-Brand 4* has only one child node *KCC 6* (See Figure 4.2). Sub-Brands are visible for consumers through an own, not shared logo (See Figure 1.1).

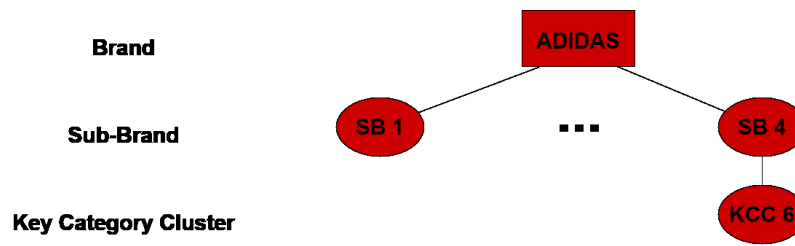


Figure 4.2: Example of a single child node

4.1 Universal Sales Patterns

As mentioned in Section subsection 1.2, our data contains the information about sold articles over the years 2017 and 2018. Figure 4.3 shows the weekly course for the quantities over those two years, highlighting active promotion weeks as vertical lines. We can undoubtedly recognize that *"Black Friday"* weeks (black lines) have an exceptional impact on sales, as they stand internationally for the most busy shopping periods. During these days in mid- to late November each year, large amounts of different products are heavily discounted.

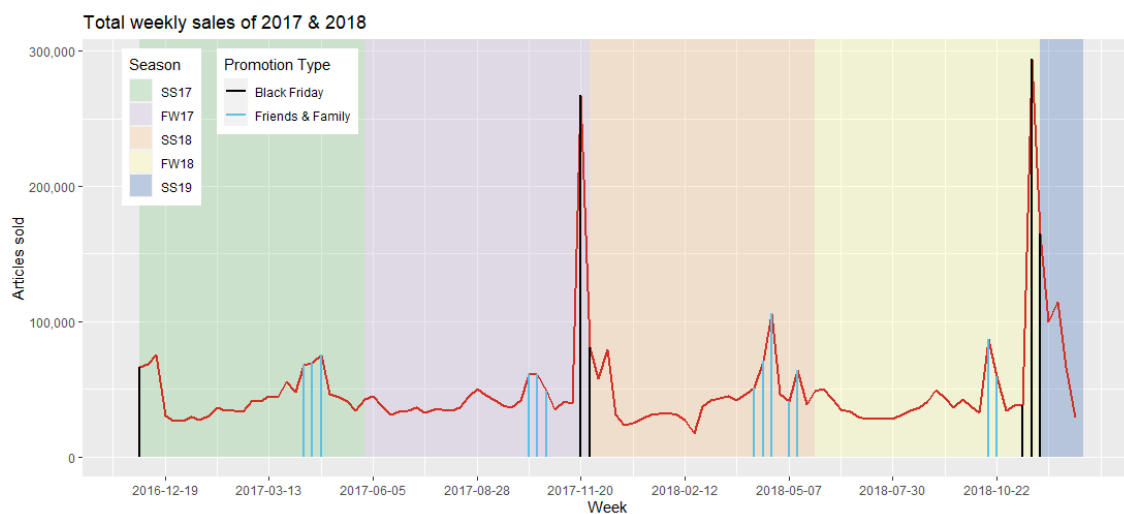


Figure 4.3: Course of article unit sales

Another promotion type we are interested in is *"Friends & Family"*, occurring yearly around April-May and October, where on the eCom website plenty of articles are on offer. On these weeks, we have elevated numbers of sold articles as well (Figure 4.3, blue lines). Tables 4.1 and 4.2 show the weeks where Black Friday and Friends & Family took place respectively. The dates indicate always the Monday of the respective week (according to European standards, a week starts on Monday).

Black Friday weeks	2016-11-28	2017-11-20	2017-11-27	2018-11-12	2018-11-19	2018-11-26
--------------------	------------	------------	------------	------------	------------	------------

Table 4.1: Black Friday weeks

Friends & Family weeks	2017-04-10	2017-04-17	2017-04-24	2017-10-09	2017-10-16	2017-10-23	2018-04-09
	2018-04-16	2018-04-23	2018-05-07	2018-05-14	2018-10-15	2018-10-22	

Table 4.2: Friends & Family weeks

Figure 4.4 depicts scatterplots of 10,000 randomly chosen observations in the dataset, where the two main promotion intensities are plotted against article unit sales. A positive relationship is visible as we would expect. Due to the high noise persisting in these relationships however, Pearson’s correlation coefficient for Black Friday against sales and Friends & Family against sales take on values of 0.32 and 0.11 respectively. Similar behavioural conclusions can made about the total markdown percentage, with a correlation coefficient of 0.27 (see Figure 4.5). The type of season (Fall-Winter (FW) or Spring-Summer (SS)) doesn’t seem to make an overall difference in the sale quantities, as can be seen in Figure 4.6.

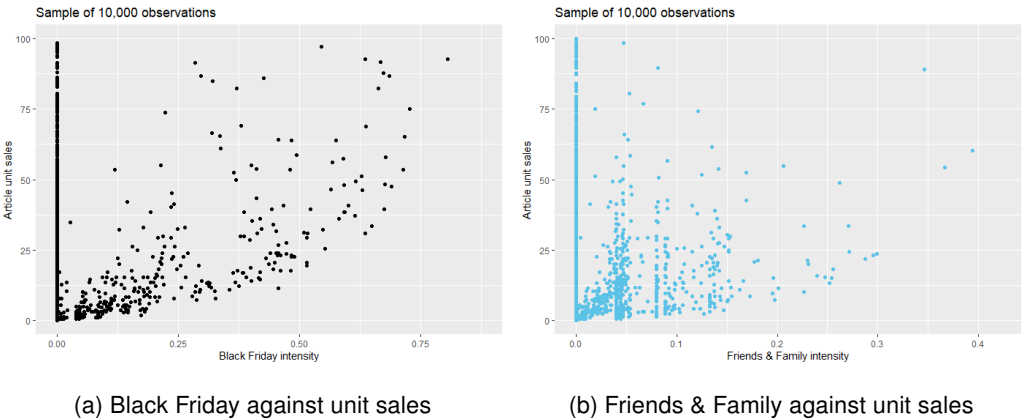


Figure 4.4: Scatterplots of promotion intensities against article unit sales; The y-axes are cut at 100

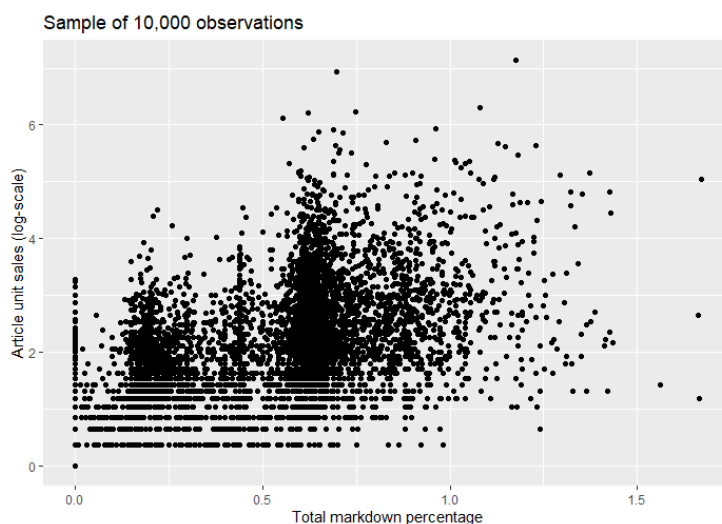


Figure 4.5: Unit sales in log-scale against total markdown percentage

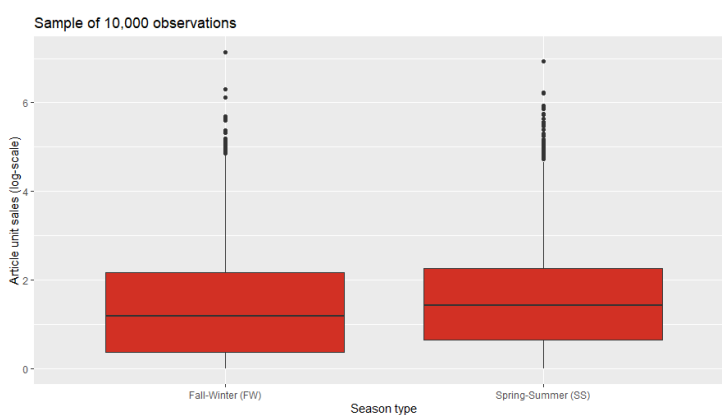
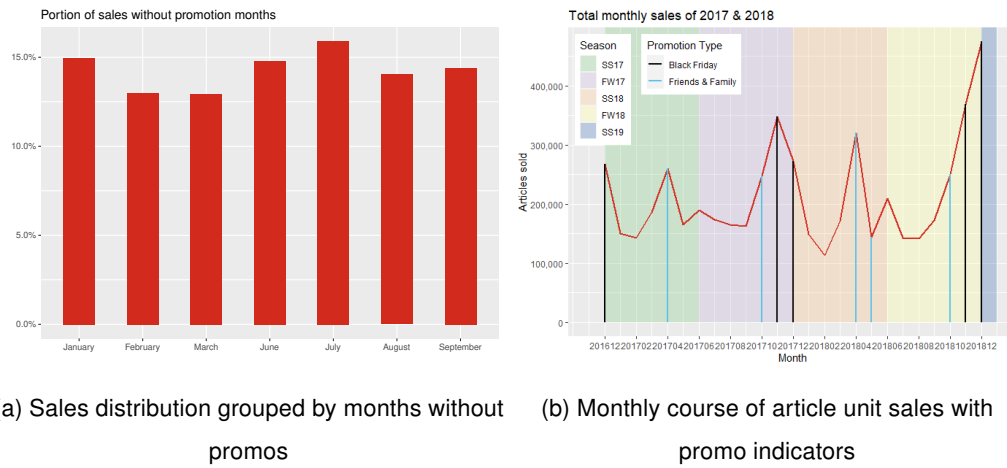


Figure 4.6: Unit sales in log-scale against season type

Regarding the months, they don't seem to differ generally in their sale quantities, that is of course excluding the months of the two mentioned promotion types. The monthly sales portions for those months can be observed in Figure 4.7a. We have slightly higher sales portions on January, June and July. Most probably this is due to Christmas and "end of the year" shopping habits, which are carried forward from December to the very next month January. Regarding June and July, they indicate summer periods and frequent occurrence of big sports events, which may drive sales. Notice that, despite the fact that December is not explicitly present in Table 4.1, it is nonetheless a Black Friday month as the promotion is still activated moving from November to December (see Figure 4.7b).



(a) Sales distribution grouped by months without promos (b) Monthly course of article unit sales with promo indicators

Figure 4.7: Monthly patterns of article unit sales

Moving forward, reviewing some sales summary statistics along with the findings so far, we detect a very high overdispersion in our data. The first two rows in Table 4.3 give as a first impression of the sales distribution. Considering the sold units of one article at a time within a week, there are lots of weeks where no single unit was sold. The median is at 2.71 units,¹⁰ 75% of the "article-week" combinations take on a value of at most 20 and the minority exceeds 100 pieces (99%-quantile). The third row of the table shows how many distinct articles fall under the respective quantile of sales and there is a visible anti-proportional behaviour towards the number of sold units, which is of course intuitive. Remarkable though is the quantity of affected articles even for incredibly large quantiles.

Quantile	Min	25%	50%	75%	90%	95%	99%	99.9%	Max
# Sold units / week	0	0.45	2.71	8.14	19.45	34.39	102.71	360.12	6,816.74
# Affected articles	26,203	26,195	23,797	17,014	10,275	6,458	1,800	273	1

Table 4.3: Number of sold units per week & number of affected articles for various quantiles of sales

Conscientiously, we want to inspect the number of weekly sold units above and below a certain (large) threshold to find out how promotions influence these vast sales numbers. In Figure 4.8a we can see how the sales are distributed over Black Friday, Friends & Family and regular weeks for below a threshold of 200 units. Most high sales occurrences are not attached to any of the two big promotions. They might be due to other events or unrelated to any campaigns altogether. Observations above that threshold of 200 can be seen in Figure 4.8b and we can clearly see a change from Figure 4.8a. As expected, Black Friday is the dominating promotion type, although the majority remains

¹⁰Reminder from Section 1.2: the values are in reality discrete, but due to anonymization they were transformed into real numbers.

in not promoted sales.

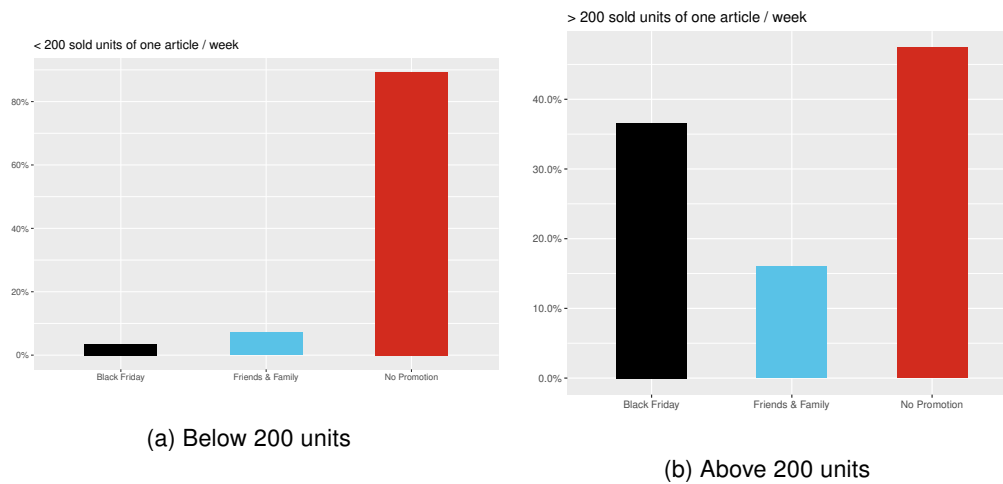


Figure 4.8: Distribution of sold units of articles per week split at 200 units

To validate the exploration on this, we may look at the empirical CDF in Figure 4.9 using all observations now. Instances with no promotions have a steeper curve (red line) and reach their maximum faster compared to articles tagged with a promotion in a certain week. The less concave curve of Friends & Family promoted sales (blue line) implies that there are more instances with a larger amount of sold units overall. The same behaviour is even more pronounced for Black Friday (black line), having considerably more high quantity instances. Along these lines, promotions might somewhat explain this pattern better.

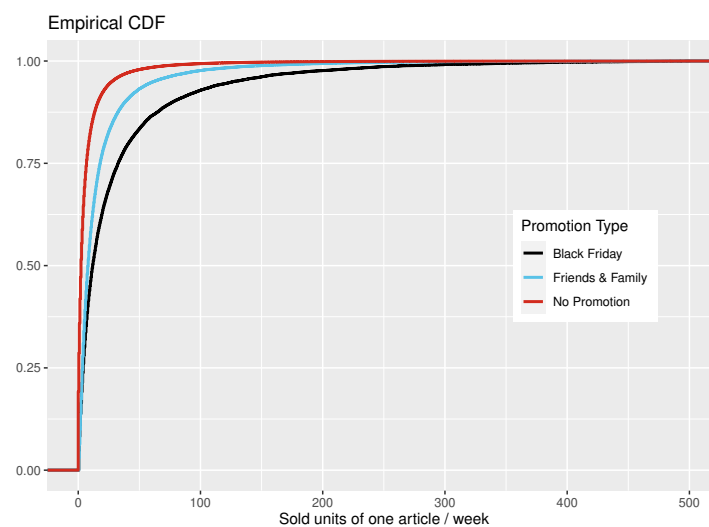


Figure 4.9: Empirical CDF of all sold units per week; x-axis cut at 500

Unfortunately, we cannot just remove such outliers with extreme sale numbers from the

dataset, as it would produce gaps in the time series of some specific articles. Removing entire articles from the analysis is also not an option at this point, since we would be forced to remove a lot of articles. There will be a data delimitation process down the line to deal with this issue (see Subsection ??). For example, 273 articles alone would have to be removed to get rid of the highest 0.01% of quantities (see Table 4.3). Besides, these extreme values might be too informative for the underlying data generating process, so we decide to keep them all.

4.2 Grouped Patterns - Key Category Cluster

To gain some insights on the hierarchical levels of interest, we perform some quick analysis on different groups of the upper levels of the tree in Figure 4.1. We start out with a broad picture on the key category clusters and eventually reach a better understanding for the the article behaviour.

By viewing the sales trends separately for each key category cluster, we can observe in Figure 4.10a that, among the weekly noise, they climax similarly. Just like in the previous section, those peaks come about primarily during the big promotions weeks. To put it into perspective, we can see logarithmic sales behaviour in Figure 4.10b, where patterns are quite similar although they differ strongly in volume.

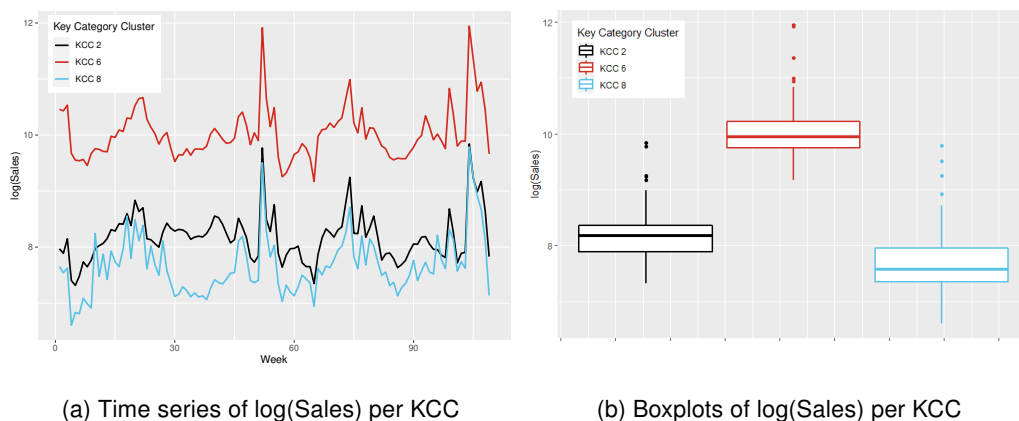


Figure 4.10: Time series and boxplot showing logarithmized sales of the key category clusters

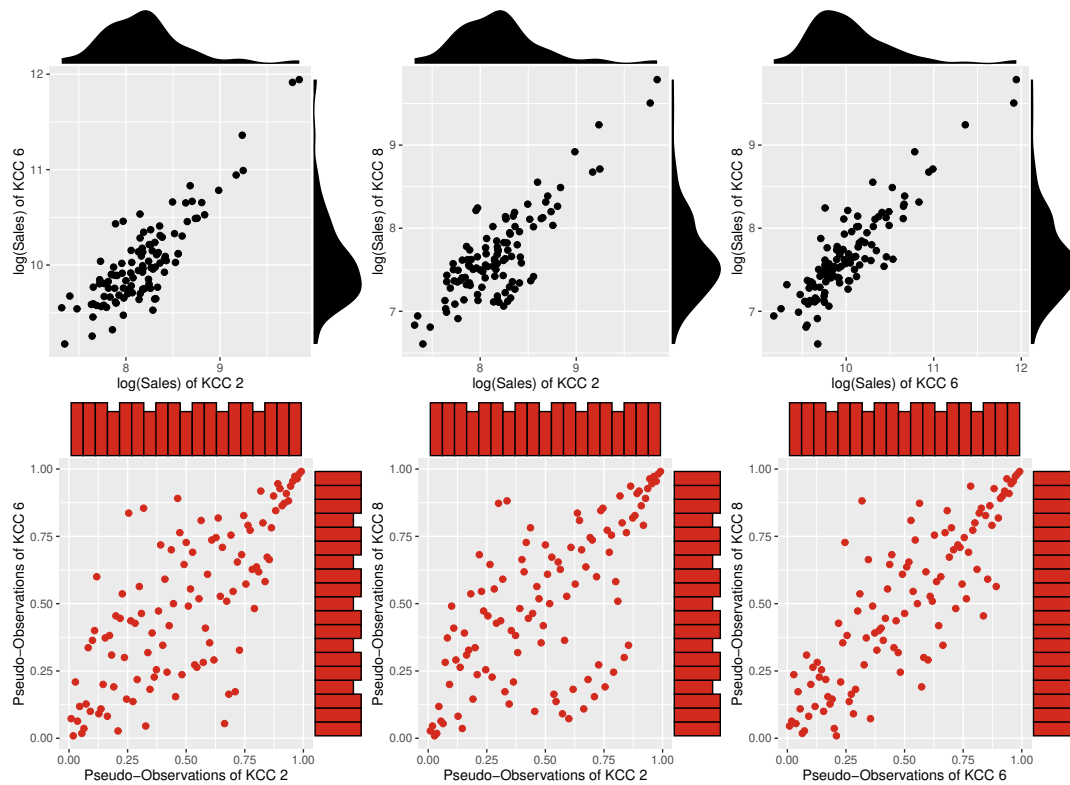


Figure 4.11: Pairwise scatterplots of sales on KCC level. First row: Logarithmic sales with marginal densities, Second row: Pseudo sales observation with marginal histograms

All the more interesting are the joint distributions of our KCCs. Figure 4.11 shows scatterplots of KCC pairs. In the first row we can see some isolated points on the upper tails representing outliers. We took the logarithmized sales to spot differences that would be otherwise hard to see. The outliers produced by the promotions still remain outliers in the log-scale. Also, by checking the densities for the marginals, pertinent marginal distributions are hardly determined but not to be ruled out.

The second row displays the pairs of the according *pseudo observations*. Pseudo observations are calculated by taking the data ranks and dividing them by $(1 + \text{number of observations})$, which makes them robust against outliers and restricts the value range to $(0, 1)$. Here we are faced with a strange behaviour of the histograms. They practically look uniformly distributed, however there are seemingly regular step patterns in the pseudo data. This might be traced back to the fact that we are dealing in reality with discrete data of not necessarily unique occurrence.

For the above reasons, on KCC level we will attempt modelling parametric distributions to the marginals as well as directly use the pseudo data. In addition, looking at both rows of Figure 4.11, we suspect tail dependence and there is an obvious strong positive corre-

lation among all three pairs, which is confirmed by viewing Figure 4.12.

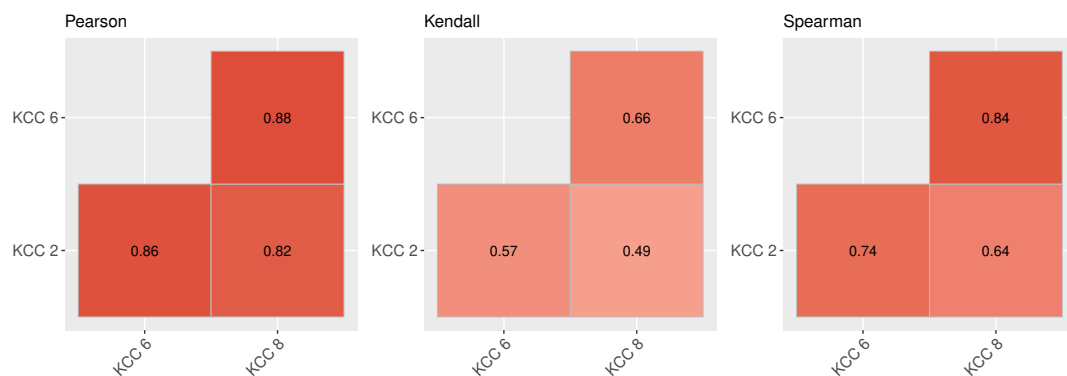


Figure 4.12: Correlation plots of the three KCC log-sales with different correlation coefficients. Left: Pearson's rho, Middle: Kendall's tau, Right: Spearman's rho

One side note on the promotion intensities of Black Friday and Friends & Family (see Table 1.1) is that on higher levels such as key category cluster, as we aggregate our data, promotion intensities become binary values indicating whether the respective promotion took place in those respective weeks. Also note that Black Friday and Friends & Family weeks do not overlap. The boxplots of the two promotion types depicted in Figure 4.13 and Figure 4.14 point out how they affect the sales. Though, one shall keep in mind that, out of 109 weeks, only the minority include promo activation. Precisely, Black Friday is activated over 6 weeks out of 109 and Friends & Family is activated over 13 weeks¹¹ (see Tables 4.1 and 4.2). In Figure 4.14, one shall also be aware of large outliers being present during no Friends & Family weeks.

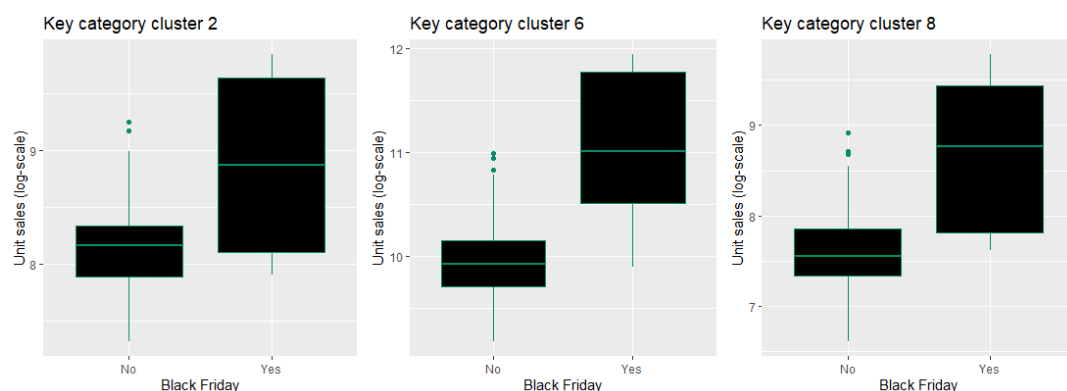


Figure 4.13: Boxplots showing log-sales of KCCs against presence of Black Friday

¹¹And of course not in a row, as can be clearly observed in Figure 4.3.

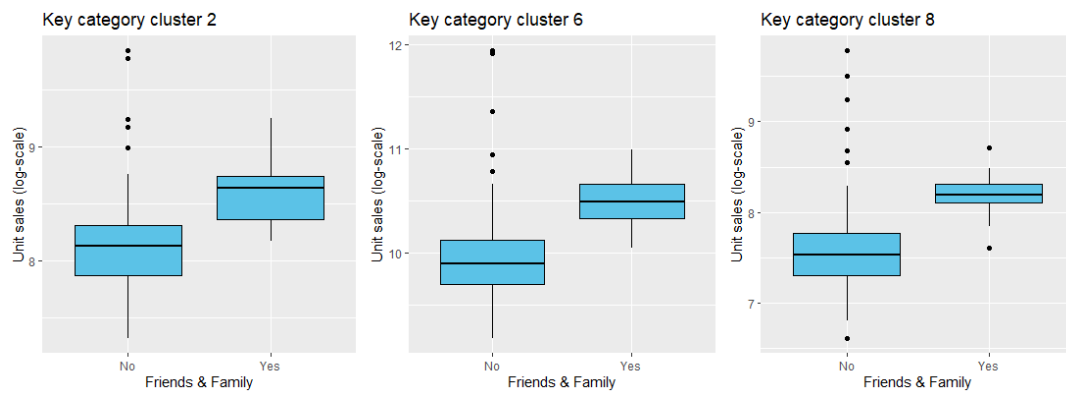


Figure 4.14: Boxplots showing log-sales of KCCs against presence of Friends & Family

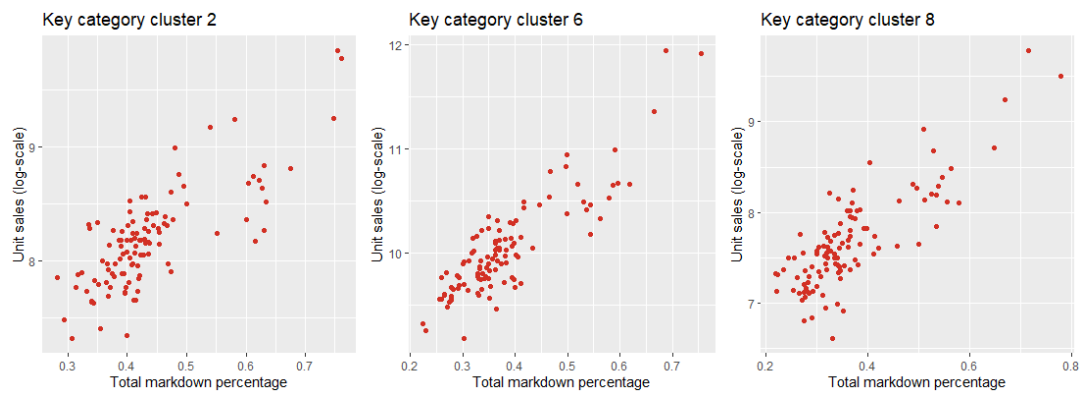


Figure 4.15: Scatterplots of KCC log-sales against total markdown percentage



Figure 4.16: Boxplots of KCC log-sales against the two season types

The scatterplots in Figure 4.15 clearly reveal the strong positive relationship between the log-sales and the KCCs' respective total markdown percentages.

Regarding the season type (SS vs FW), visual exploration is not sufficient to conclude existence of effects on the unit sales. The effect of season type as well as other features on the unit sales shall be discussed in Chapter 5.

5 Modelling

In this chapter, we will explore various ways on how to model, evaluate and interpret the dependence structure of unit sales.

An important aspect of the modelling part is that usually, continuous responses are implied in the literature. Nevertheless, discrete responses (like in our "real" case) are also justified when explanatory variables are involved. A detailed explanation can be found in Trivedi and Zimmer [2017].

As the observation period is only 109 weeks and the highest peaks occur during Black Friday twice, the second time being very late (104th week, see e.g. Figure 4.3), all of the modelling will be performed in-sample. Thus, evaluation and diagnostics will be based on the entire observation period so that both extreme peaks can be included in model trainings.

5.1 Key Category Cluster - Marginals

Figure 4.11 (Section 4.2) is hinting that the marginal distributions come with a noticeable skewness, which are best to take into account. The logarithmic scale is the preferred transformation due to variance stabilization of the marginals. Among a pool of possible parametric distributions, we pick an appropriate one for each marginal. Several distributions would theoretically be justifying the shape of our data, e.g. Weibull, Gamma, Box-Cox-Cole-Green or Dagum distribution. After screening those parametric distributions, we find that the exponentially modified Gaussian distribution (or ex-Gaussian distribution which will be used from here on) fits all three marginals fairly well [Grushka, 1972].¹² Before entering the dependence structures between the three KCC pairs, the marginal distribution of each cluster will be analyzed individually in the next three subsections. First, the ex-Gaussian distribution will be fitted to the marginals and in a second step covariate effects will be included to obtain flexible estimations on the distribution parameters.

¹²Another appropriate distribution would be the Dagum distribution [Dagum, 1975], however interpretability of the parameters is difficult to comprehend.

5.1.1 Key Category Cluster 2

Simple maximum likelihood estimation based on the log-sales of the marginals allow us to estimate the ex-Gaussian distribution parameters. Figure 5.1a describes how the histogram of the data match to the theoretical density of an ex-Gaussian distribution considering the estimated parameter values represented in Table 5.1.

$\hat{\mu}$	$\hat{\sigma}$	$\hat{\nu}$
7.85	0.26	0.33

Table 5.1: Estimated parameters for log-sales of KCC 2 fitted to ex-Gaussian distribution with no covariate effects

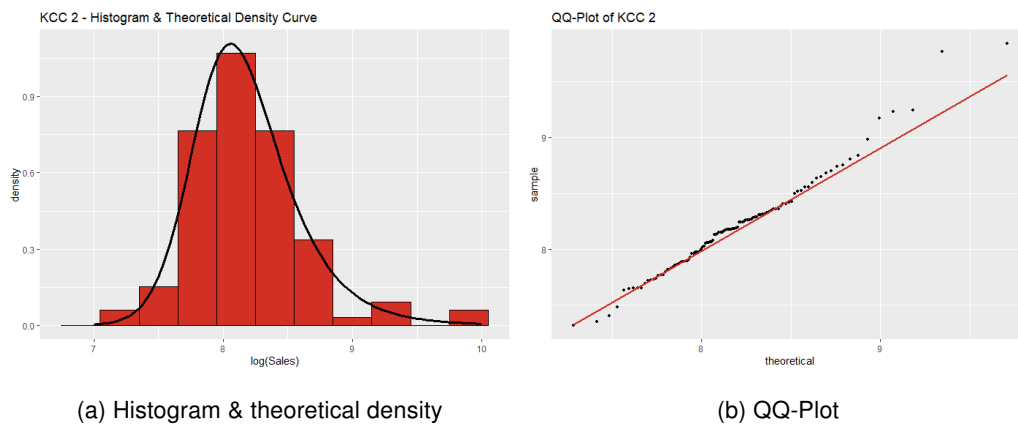


Figure 5.1: ex-Gaussian distribution fitted to log-sales of KCC 2

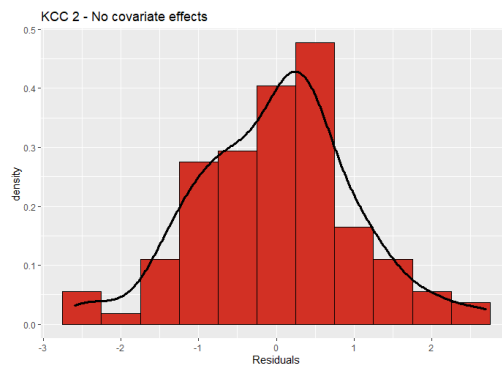


Figure 5.2: Residuals of KCC 2 log-sales fitted to an ex-Gaussian distribution with no covariate effects together with their density curve

As can be seen in Figure 5.2, the residuals of the fitted distribution are not too far from a normal distribution. In fact, a Shapiro-Wilk normality test (see Section 2.1) will fail to reject the null hypothesis, returning a p-value of 0.6645. There still exist skewness in the

distribution of the residuals and correction will be attempted in the following.

The findings so far indicate that the overall fit for this cluster is quite satisfiable and also supports interpretability of the estimated parameters.

To make the estimation more precise and to get a better understanding of what is driving sales, flexible estimation of the distribution parameters is required and thus covariate effects shall be included.

After multiple equation setups for the marginal distribution of KCC 2, the chosen GAMLSS model specification (see Section 2.4) is as follows:

$$\begin{aligned}\mu &= \beta_{01} + f_{11}(\text{time}) + f_{12}(\text{total_markdown_pct}) + \text{promo_type} * \text{total_markdown_pct} \\ \log(\sigma) &= \beta_{02} + f_{21}(\text{time}) \\ \log(\nu) &= \beta_{03},\end{aligned}\tag{5.1}$$

where *promo_type* is a factor variable with levels "No Promotion" (reference category), "Black Friday" and "Friends & Family". The smooth functions f_{11} , f_{21} and f_{12} are build upon P-Splines with 40 knots each. For the scale and shape parameters (σ and ν respectively) the logarithmic link function is used to ensure that they are mapped to the real positive line as the ex-Gaussian distribution family can only capture positive skewness (ν). For σ we just use time as the only regressor and we set the skewness ν as a constant.

The estimated location and scale parameters over time are depicted in Figure 5.3 and in Table 5.2 the estimated skewness parameter value with its 95% confidence interval is shown. The fitted values approximate the actual values quite adequately given the present limitations. The sale peaks are also well captured, especially for Black Friday. The scale parameter has an increasing trend up until roughly mid-January (60th observation) and then decreases again. However, the overall range of deviation is kept to a minimum, ranging from 0.05 to 0.20. The estimated skewness parameter is closer to zero than in the maximum likelihood approach without any covariate effects.

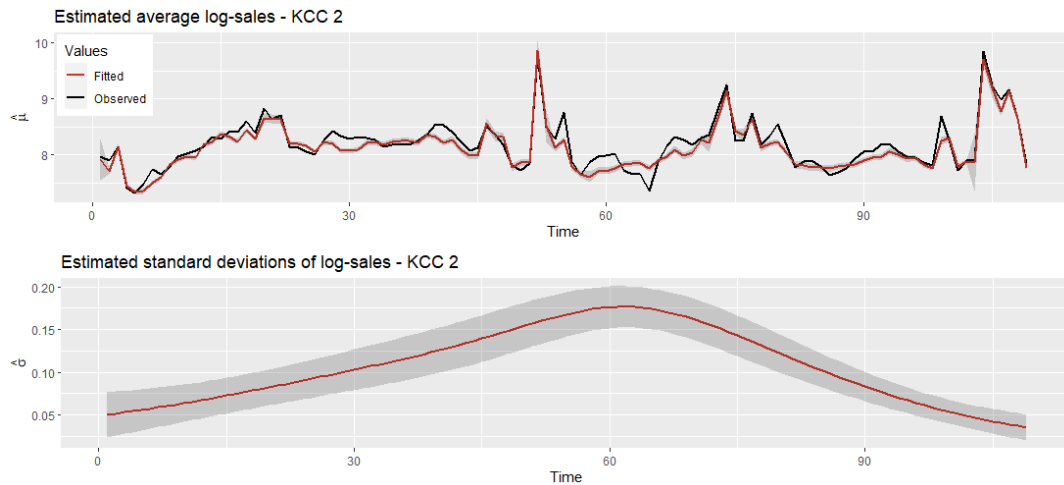


Figure 5.3: Estimated location parameter $\hat{\mu}$ compared to the observed values and scale parameter $\hat{\sigma}$ with confidence bands of GAMLSS fit - KCC 2

Lower	$\hat{\nu}$	Upper
0.067	0.058	0.076

Table 5.2: Estimated skewness parameter $\hat{\nu}$ of GAMLSS fit with 95% confidence interval bounds - KCC 2

Below we can observe the summary output from the R console (R output 5.1 as well as the visual covariate effects on the expected value (Figure 5.4).

R output 5.1: GAMLSS Fit on KCC 2

```

1 *****
2 Family:  c("exGAUS", "ex-Gaussian")
3
4 Call:  gamlss(formula = logsales_kcc_2 ~ pb(time_obs) + pb(total_markdown_pct) +
5         promo_type * total_markdown_pct, sigma.formula = ~pb(time_obs),      nu.formula = ~1, family = "exGAUS",
6         data = data_agg_KCC)
7
8 Fitting method: RS()
9
10 Mu link function:  identity
11 Mu Coefficients:
12
13             Estimate Std. Error t value Pr(>|t|)
14 pb(time_obs)      0.0010396  0.0002714   3.831 0.000251 ***
15 pb(total_markdown_pct)  6.7884739  0.1846136  36.771 < 2e-16 ***
16 promo_typeBlack Friday  1.3325479  0.1897891   7.021 6.22e-10 ***
17 promo_typeFriends & Family  2.3073358  0.4146677   5.564 3.33e-07 ***
18 promo_typeBlack Friday:total_markdown_pct -3.8745823  0.3674925 -10.543 < 2e-16 ***
19 promo_typeFriends & Family:total_markdown_pct -6.0992694  0.7498619  -8.134 4.18e-12 ***
20 ---
21 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
22
23 -----
24 Sigma link function:  log
25 Sigma Coefficients:
26             Estimate Std. Error t value Pr(>|t|)
27 (Intercept)  -2.838160  0.232620 -12.201 < 2e-16 ***

```



```

28 pb(time_obs) 0.032702 0.003654 8.949 1.03e-13 ***
29 ---
30 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
31
32 -----
33 Nu link function: log
34 Nu Coefficients:
35      Estimate Std. Error t value Pr(>|t|)
36 (Intercept) -2.7038      0.2471  -10.94  <2e-16 ***
37 ---
38 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
39
40 -----
41 NOTE: Additive smoothing terms exist in the formulas:
42 i) Std. Error for smoothers are for the linear effect only.
43 ii) Std. Error for the linear terms maybe are not accurate.
44 -----
45 No. of observations in the fit: 109
46 Degrees of Freedom for the fit: 28.27367
47      Residual Deg. of Freedom: 80.72633
48      at cycle: 20
49
50 Global Deviance: -148.3187
51      AIC: -91.77135
52      SBC: -15.67708
53 *****

```

From the visual representation of the covariate effects in (Figure 5.4, we can see that the temporal effect on log-sales varies within a certain range. Higher total markdown percentages enhance higher response values, which can also be observed when looking at the R output. The estimated coefficient for the markdown obtains a value of 6.79 (without considering promotions). The log-sales increase by 1.33 and 2.31 units on average when Black Friday and Friends & Family respectively is activated, assuming no total markdown percentages exist. That is of course counterintuitive, as promotion go hand in hand with markdowns. The summary in R output 5.1 reveals such kind of peculiar effects when we look at the interaction coefficients of promotions and total markdown percentage. When any promo type is activated, the total markdown percentage has a negative effect on the log-sales. Interpretation of the results shall be expressed with caution. Season type (SS & FW) was not included in the model as it had no significant effect and distorts the output and the effect plots. All curves of smooth effects are centered around zero due to identifiability constraints (see Section 2.3).

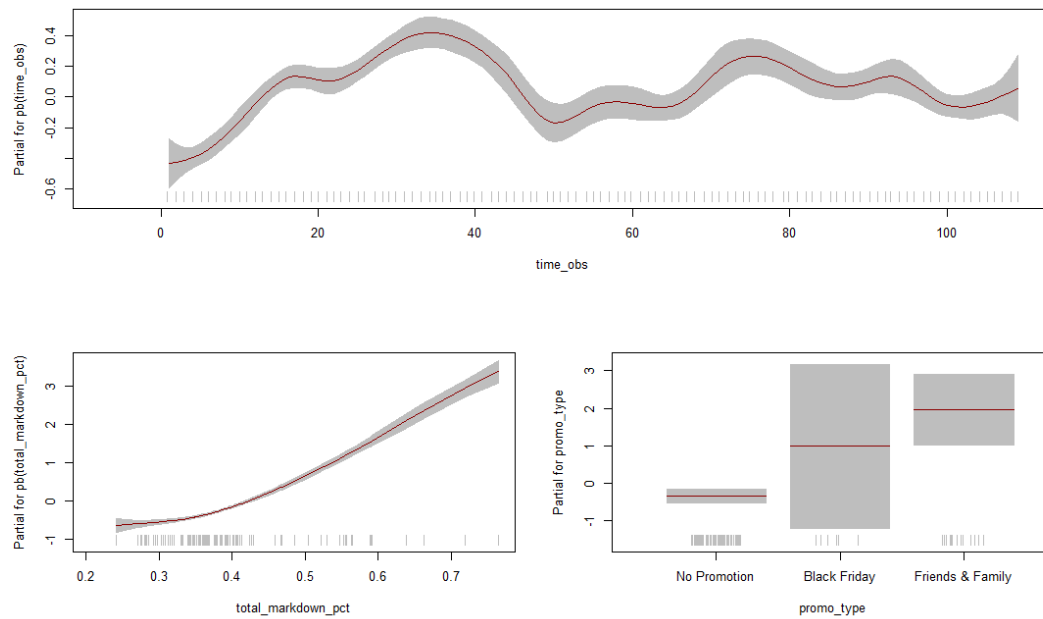


Figure 5.4: Covariate effects on the expected response variable (log-sales) of GAMLSS fit - KCC 2

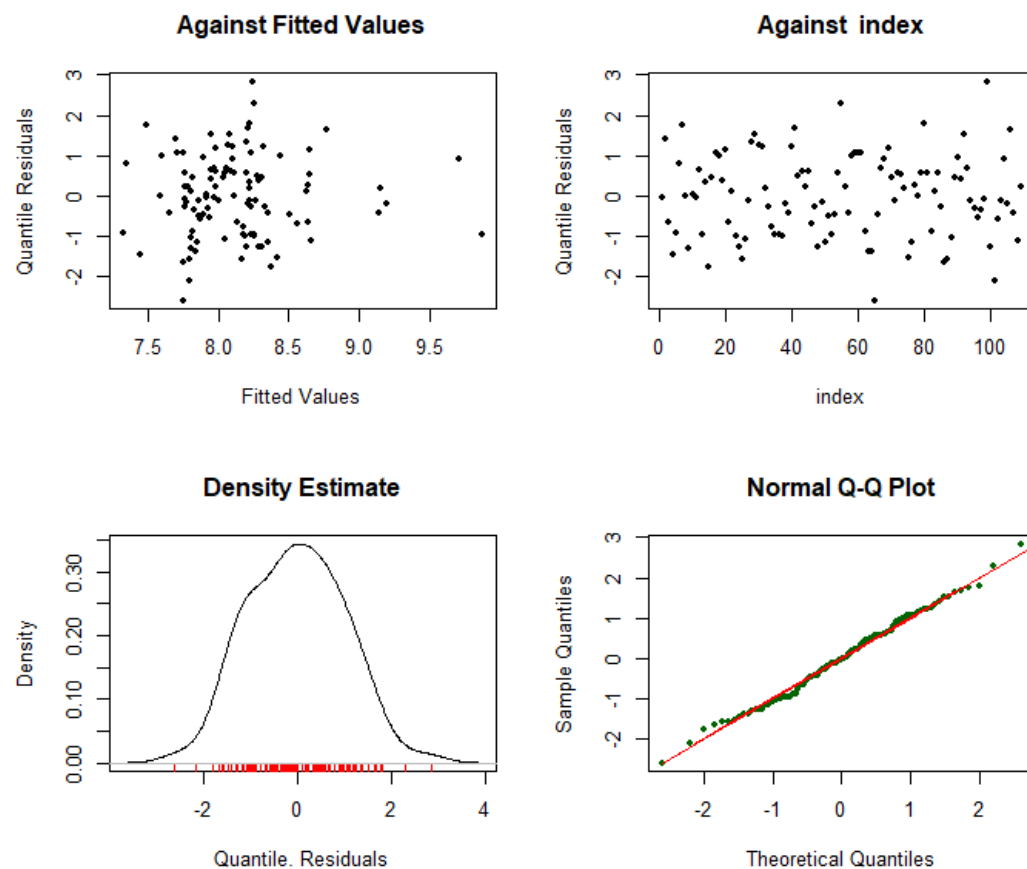


Figure 5.5: Residuals of GAMLSS fit - KCC 2

Fitting the data to a GAMLSS model like this can be considered favourable. The emerged residuals are closer to a standard normal distribution than the maximum likelihood esti-

mation without any covariate effects. Diagnostic plots of quantile residuals in Figure 5.5 confirm this. R output 5.2 below returns a detailed summary of the estimated location, scale and shape parameters of the residuals' distribution. A Shapiro-Wilk test for the newly emerged residuals returns a p-value of 0.92, which is in plain favour of a normal distribution.

R output 5.2: Residuals of GAMLSS Fit on KCC 2

```

1 *****
2      Summary of the Quantile Residuals
3      mean      = -0.01811135
4      variance   = 1.042057
5      coef. of skewness = 0.08348086
6      coef. of kurtosis  = 2.645021
7      Filliben correlation coefficient = 0.996831
8 *****

```

5.1.2 Key Category Cluster 6

The same procedure as in Subsection 5.1.2 for key category cluster 2 will be applied here to analyze the marginal distribution of the log-sales in key category cluster 6.

Excluding all covariates, simple maximum likelihood estimation results can be summarized within Table 5.3, Figure 5.6 and Figure 5.7. A Shapiro-Wilk test on the residuals returns a p-value of 0.87 and the fails to reject the null hypothesis of non-normality.

$\hat{\mu}$	$\hat{\sigma}$	$\hat{\nu}$
9.62	0.20	0.41

Table 5.3: Estimated parameters for log-sales of KCC 6 fitted to ex-Gaussian distribution with no covariate effects

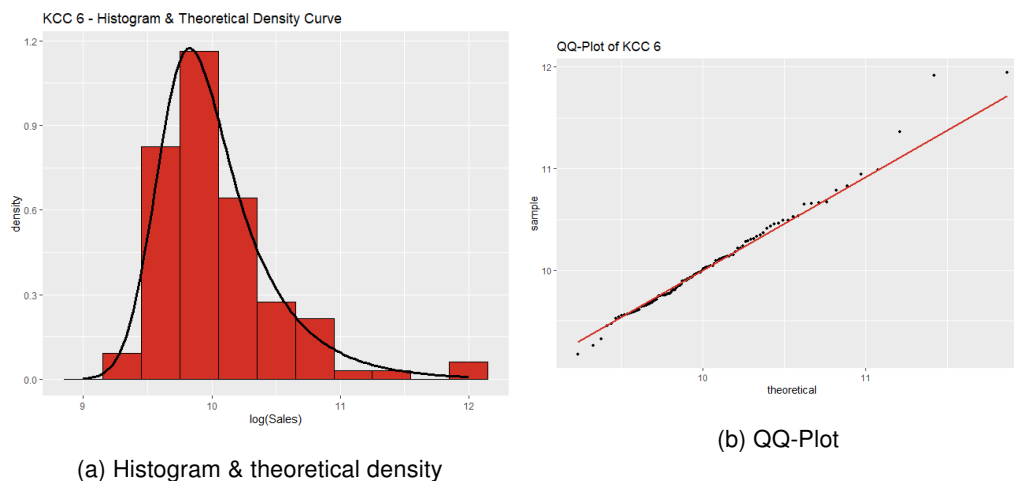


Figure 5.6: ex-Gaussian distribution fitted to log-sales of KCC 6

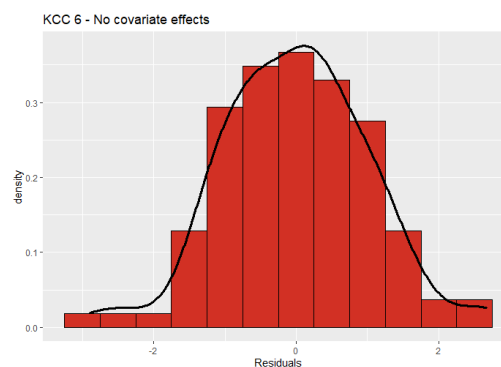


Figure 5.7: Residuals of KCC 6 log-sales fitted to an ex-Gaussian distribution with no covariate effects together with their density curve

Reviewing different model specifications, the same model as in the previous Subsection is chosen (Model 5.1) with an ex-Gaussian distribution family for the response variable. A summary is printed below in R output 5.3. The estimated time-varying location and scale parameters can be seen in Figure 5.8 and the skewness parameter $\hat{\nu}$ with 95% CI in Table 5.4. Fitted values are close to real values, capturing the promotion peaks fairly well. The standard deviation fluctuates throughout time within a range between 0.1 and 0.3.

R output 5.3: GAMLSS Fit on KCC 6

```

1 *****
2 Family:  c("exGAUS", "ex-Gaussian")
3
4 Call:    gamlss(formula = logsales_kcc_6 ~ pb(time_obs) + pb(total_markdown_pct) +
5             promo_type * total_markdown_pct, sigma.formula = ~pb(time_obs),      nu.formula = ~1, family = "exGAUS",
6             data = data_agg_KCC)
7
8 Fitting method: RS()
9 -----

```

```

10 Mu link function: identity
11 Mu Coefficients:
12
13             Estimate Std. Error t value Pr(>|t|)
14 (Intercept)      8.3111193   0.1157520   71.801 < 2e-16 ***
15 pb(time_obs)      0.0024889   0.0004789    5.197 1.15e-06 ***
16 pb(total_markdown_pct) 4.0074977 0.3016532   13.285 < 2e-16 ***
17 promo_typeBlack Friday -0.8054399 0.2951362   -2.729 0.00756 **
18 promo_typeFriends & Family 0.8703618 0.4802656    1.812 0.07309 .
19 promo_typeBlack Friday:total_markdown_pct 1.0176236 0.5352771    1.901 0.06031 .
20 promo_typeFriends & Family:total_markdown_pct -2.4686730 0.8798442   -2.806 0.00608 **
21 ---
22 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
23
24 Sigma link function: log
25 Sigma Coefficients:
26
27             Estimate Std. Error t value Pr(>|t|)
28 (Intercept)     -1.255651    0.149038   -8.425 3.7e-13 ***
29 pb(time_obs)     -0.010311    0.003173   -3.250 0.0016 **
30 ---
31 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
32
33 Nu link function: log
34 Nu Coefficients:
35
36             Estimate Std. Error t value Pr(>|t|)
37 (Intercept)      -3.126      1.164   -2.686 0.00852 **
38 ---
39 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
40
41 NOTE: Additive smoothing terms exist in the formulas:
42 i) Std. Error for smoothers are for the linear effect only.
43 ii) Std. Error for the linear terms maybe are not accurate.
44
45 No. of observations in the fit: 109
46 Degrees of Freedom for the fit: 13.62438
47 Residual Deg. of Freedom: 95.37562
48 at cycle: 19
49
50 Global Deviance: -105.8531
51 AIC: -78.6043
52 SBC: -41.93636
53 *****

```

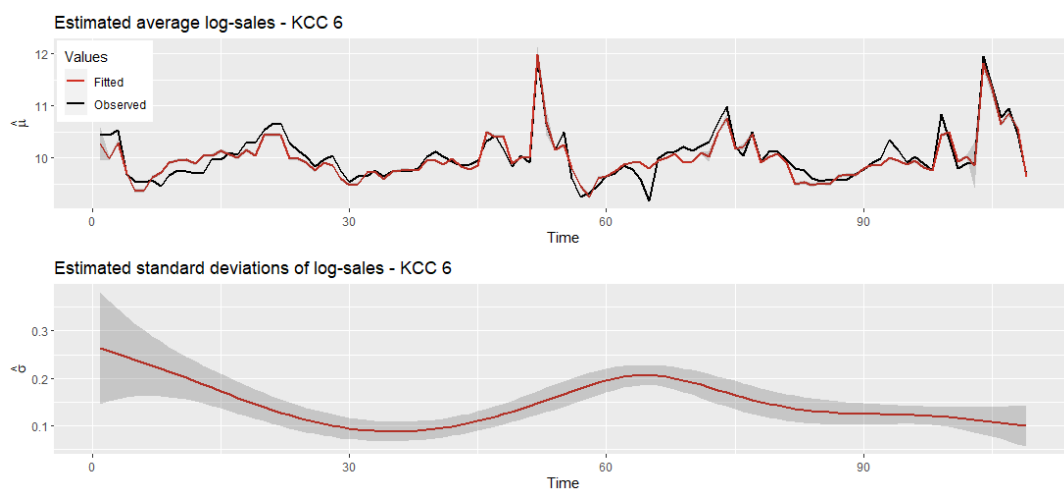


Figure 5.8: Estimated location parameter $\hat{\mu}$ compared to the observed values and scale parameter $\hat{\sigma}$ with confidence bands of GAMLSS fit - KCC 6

Lower	$\hat{\nu}$	Upper
0.044	0.031	0.057

Table 5.4: Estimated skewness parameter $\hat{\nu}$ of GAMLSS fit with 95% confidence interval bounds - KCC 6

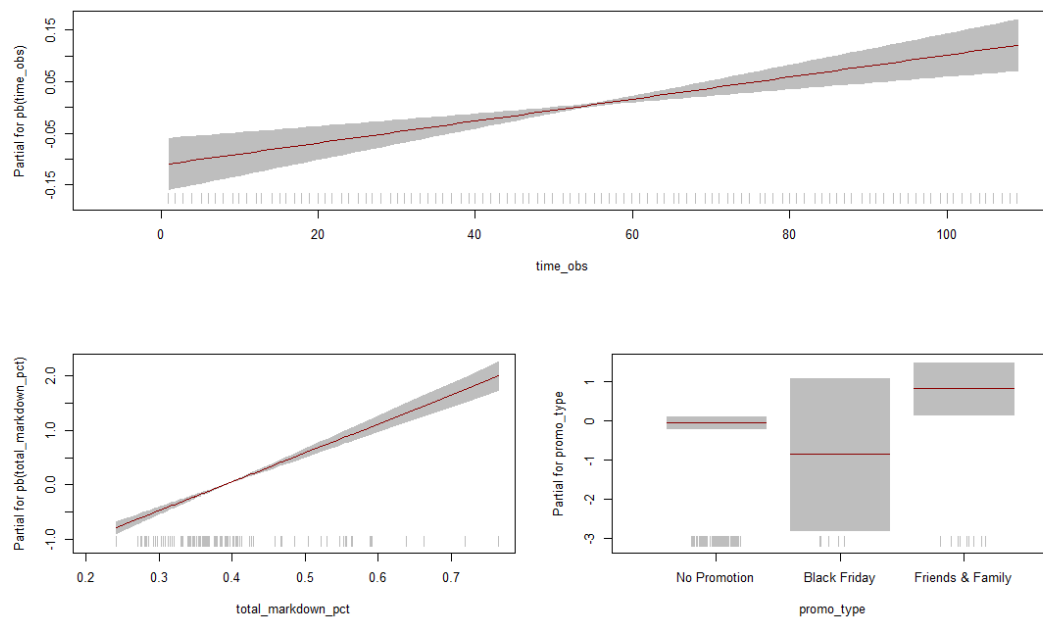


Figure 5.9: Covariate effects on the expected response variable (log-sales) of GAMLSS fit - KCC 6

Figure 5.9 reveals some interesting points regarding covariate effects. The temporal effect, just like the total markdown percentage, collapses to an increasing straight line. As opposed to the GAMLSS fit for KCC 2, Friends & Family seems to have the highest effect of all promos for this KCC. Controversial results are again the case here, as can be seen in R output 5.3. The two promotions seem to negatively interact with the total markdown percentage. Those kinds of behaviour might need further investigation.

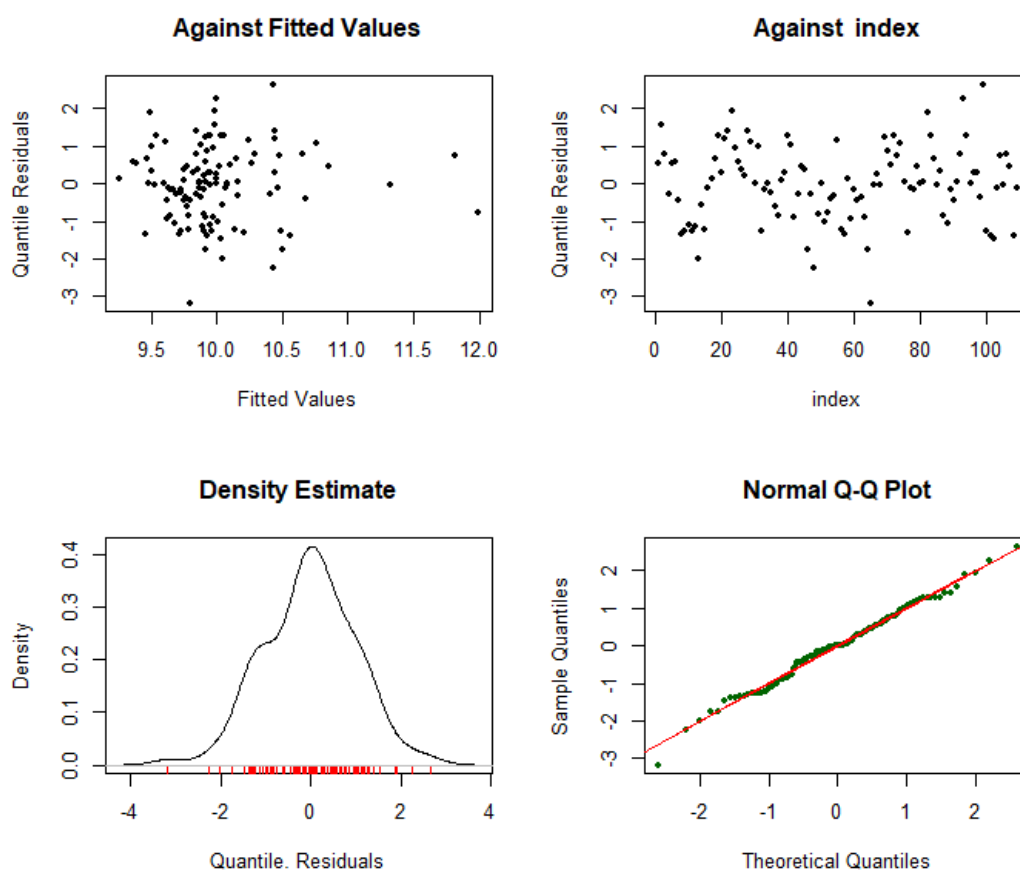


Figure 5.10: Residuals of GAMLSS fit - KCC 6

R output 5.4: Residuals of GAMLSS Fit on KCC 6

```

1 *****
2      Summary of the Quantile Residuals
3      mean      = -0.01692598
4      variance   = 1.011483
5      coef. of skewness = -0.1401063
6      coef. of kurtosis  = 3.144701
7      Filliben correlation coefficient = 0.9948268
8 *****

```

Inspecting the diagnostic plots for the residuals in Figure 5.10 along with the associated summary output, we can again confirm an appropriate fit. A Shapiro-Wilk test returns a p-value of 0.7, which is below the p-value of the fit without covariate effects. Nevertheless, normality is a steady assumption for the quantile residuals.

5.1.3 Key Category Cluster 8

The procedure is continued also for key category cluster 8 with the same conditions, since we have similar issues as in the previous two clusters.

Table 5.5, Figure 5.11 and Figure 5.12 summarize the findings when the log-sales of KCC 8 are fitted to an ex-Gaussian distribution with no regressors. Normality of the residuals can be assumed, as the Shapiro-Wilk test returns a p-value of 0.99 and thus fails to reject the null hypothesis of non-normality.

$\hat{\mu}$	$\hat{\sigma}$	$\hat{\nu}$
7.21	0.27	0.46

Table 5.5: Estimated parameters for log-sales of KCC 8 fitted to ex-Gaussian distribution with no covariate effects

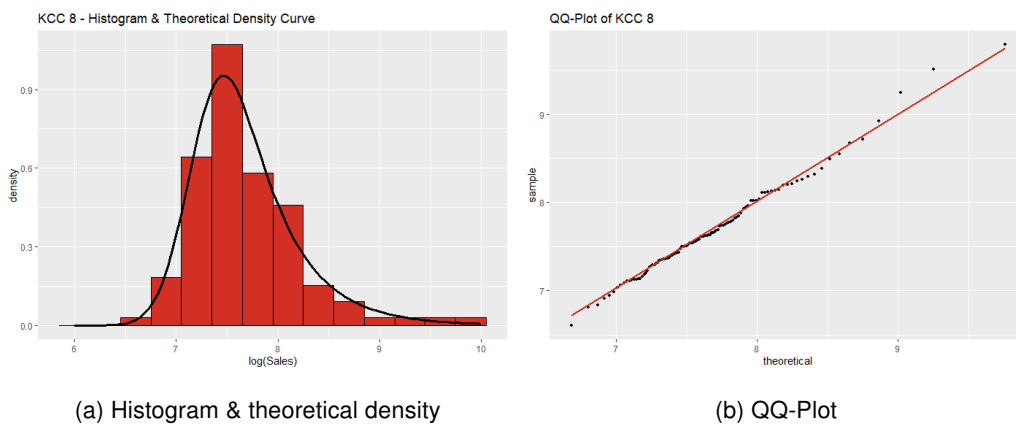


Figure 5.11: ex-Gaussian distribution fitted to log-sales of KCC 8

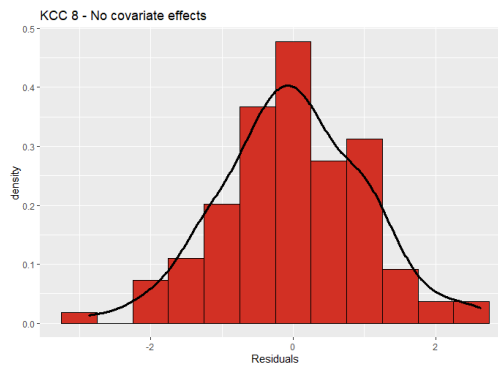


Figure 5.12: Residuals of KCC 8 log-sales fitted to an ex-Gaussian distribution with no covariate effects together with their density curve

Again, Model 5.1 is applied to the log-sales. The summary output and estimated parameters with confidence intervals can be seen in Figure 5.13 and in Table 5.6. We notice that models fit is acceptable matching the elevated sales during promo weeks and that the variability is strictly decreasing with the overall range having a range between 0.1 and 0.3. Skewness remains low in the data.

R output 5.5: GAMLSS Fit on KCC 8

```

1 *****
2 Family:  c("exGAUS", "ex-Gaussian")
3
4 Call:  gamlss(formula = logsales_kcc_8 ~ pb(time_obs) + pb(total_markdown_pct) +
5         promo_type * total_markdown_pct, sigma.formula = ~pb(time_obs),      nu.formula = ~1, family = "exGAUS",
6         data = data_agg_KCC)
7
8 Fitting method: RS()
9
10 -----
11 Mu link function:  identity
12 Mu Coefficients:
13
14             Estimate Std. Error t value Pr(>|t|)
15 (Intercept)    5.5055060   0.1744217   31.564 < 2e-16 ***
16 pb(time_obs)    0.0042645   0.0008424    5.063 1.91e-06 ***
17 pb(total_markdown_pct)  4.5349719   0.4527266   10.017 < 2e-16 ***
18 promo_typeBlack Friday  -0.6541342   0.3738172   -1.750  0.0832 .
19 promo_typeFriends & Family -0.0367560   0.6637042   -0.055  0.9559
20 promo_typeBlack Friday:total_markdown_pct  0.8760110   0.7295349    1.201  0.2327
21 promo_typeFriends & Family:total_markdown_pct -0.7643296   1.2393106   -0.617  0.5388
22 ---
23 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
24
25 -----
26 Sigma link function:  log
27 Sigma Coefficients:
28
29             Estimate Std. Error t value Pr(>|t|)
30 (Intercept)  -1.347871   0.271081  -4.972 2.78e-06 ***
31 pb(time_obs) -0.008544   0.005004  -1.708  0.0908 .
32 ---
33 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
34
35 -----
36 Nu link function:  log
37 Nu Coefficients:
38
39             Estimate Std. Error t value Pr(>|t|)
40 (Intercept)  -1.7105    0.2198  -7.783 7e-12 ***
41 ---
42 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
43
44 -----
45 NOTE: Additive smoothing terms exist in the formulas:
46 i) Std. Error for smoothers are for the linear effect only.
47 ii) Std. Error for the linear terms maybe are not accurate.
48 -----
49 No. of observations in the fit:  109
50 Degrees of Freedom for the fit:  10.0084
51 Residual Deg. of Freedom:  98.9916
52
53 at cycle:  7
54
55 Global Deviance:  -11.3607
56
57 AIC:  8.656098
58
59 SBC:  35.59218
60
61 *****

```

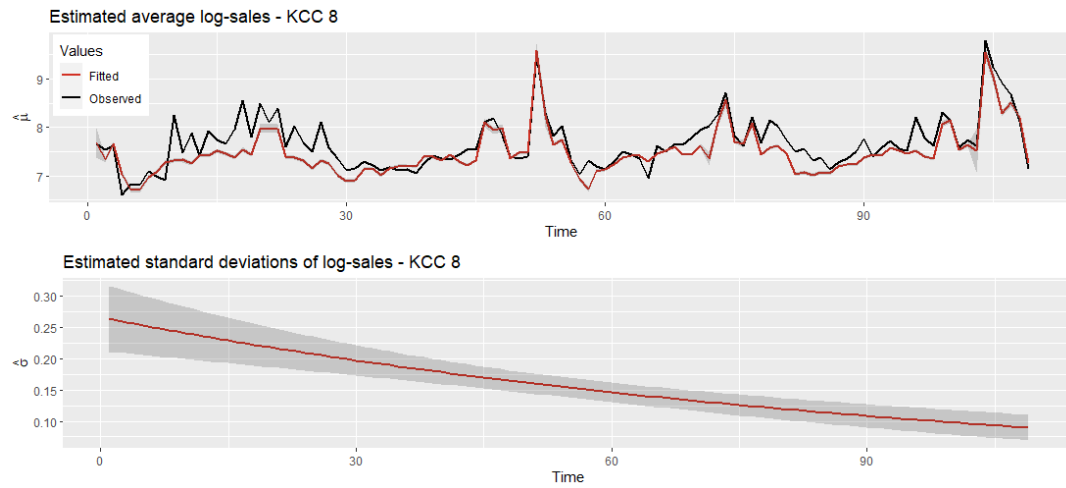


Figure 5.13: Estimated location parameter $\hat{\mu}$ compared to the observed values and scale parameter $\hat{\sigma}$ with confidence bands of GAMLSS fit - KCC 8

Lower	$\hat{\nu}$	Upper
0.181	0.158	0.203

Table 5.6: Estimated skewness parameter $\hat{\nu}$ of GAMLSS fit with 95% confidence interval bounds - KCC 8

Time as well as the total markdown percentage exhibit similar positive effects on the response as in KCC 6, collapsing into a straight line. The promo effects seem to be more balanced, with different interquartile ranges for all cases.

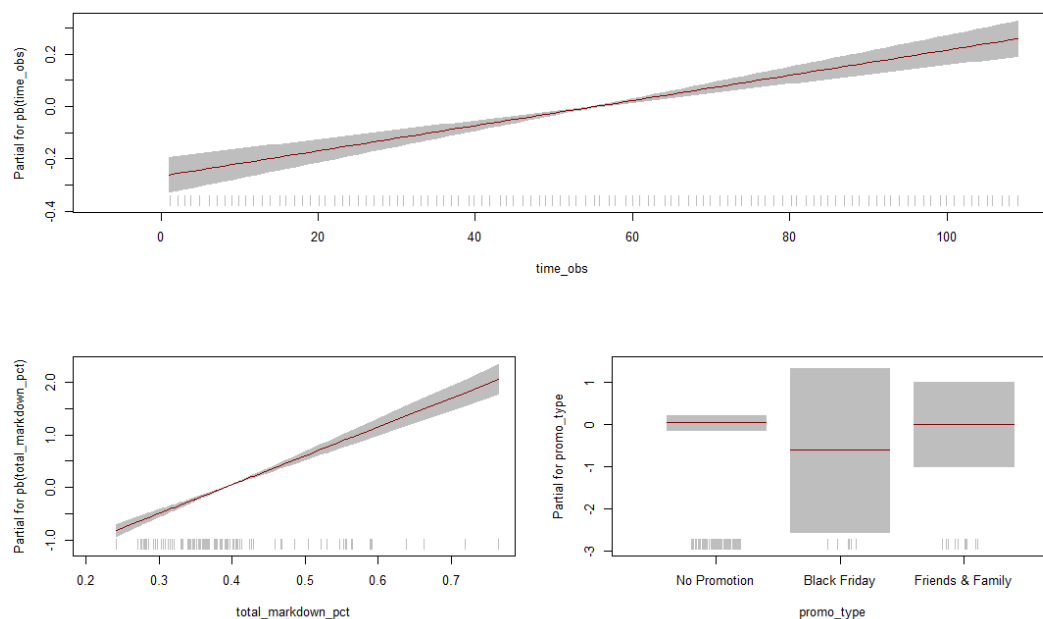


Figure 5.14: Covariate effects on the expected response variable (log-sales) of GAMLSS fit - KCC 8

Looking at Figure 5.15 and the summary output for the distribution of the quantile residuals, the fitting method for this cluster is also justified. The Shapiro-Wilk test is "weaker" in comparison to the fit without covariate effects with a p-value of 0.86, which is still a solid reason to retain the null hypothesis of normality.

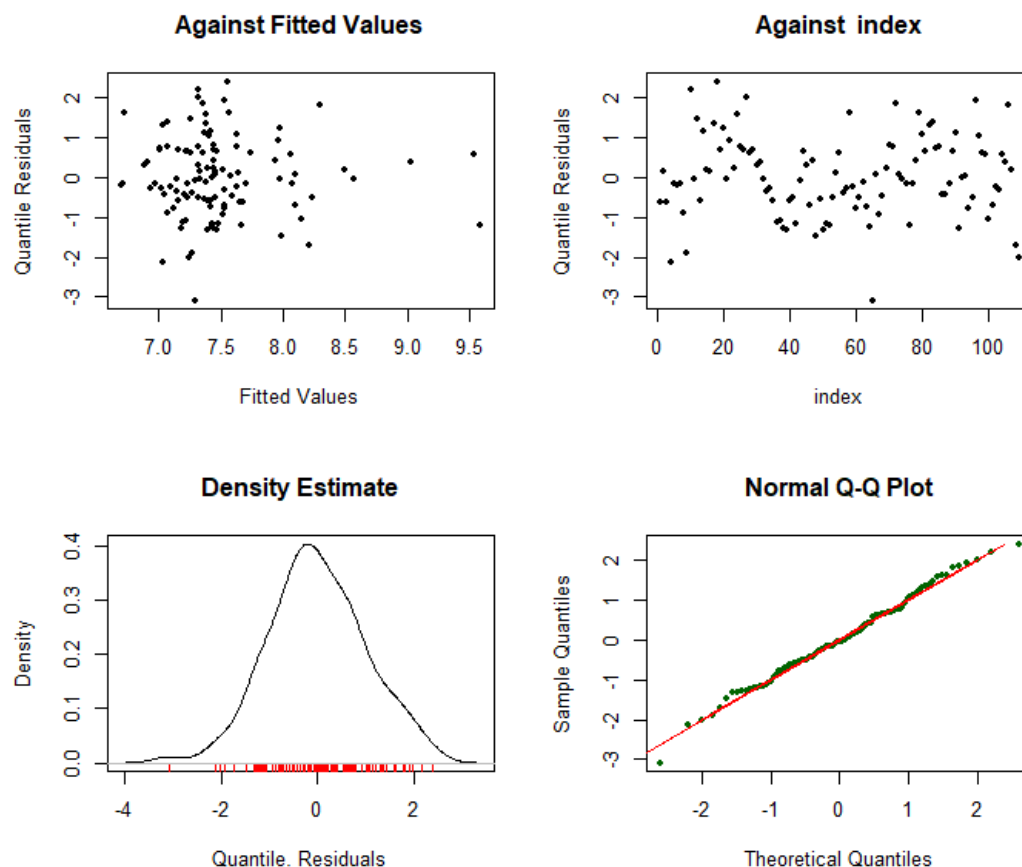


Figure 5.15: Residuals of GAMLSS fit - KCC 8

R output 5.6: Residuals of GAMLSS Fit on KCC 8

```

1 *****
2      Summary of the Quantile Residuals
3      mean      = 0.0004673878
4      variance   = 1.008849
5      coef. of skewness = -0.02817569
6      coef. of kurtosis  = 3.04467
7      Filliben correlation coefficient = 0.9963667
8 *****

```

5.2 Key Category Cluster - Pairwise Copulas

The next step, after fitting proper models to the marginal distributions of the log-sales aggregated on key category cluster level, is to enter the pairwise modelling of the clusters. Specifically, we are interested in capturing the dependence structure over time which is

delineated in the next three Subsections (5.2.1, 5.2.2 and 5.2.3).

Recalling the previous Section 5.1, the residuals from the fitting method are depicted in Figure 5.16 for each time-point. In a second step, the residuals will be used in a pairwise fashion after the marginal modelling to estimate the dependence structure with the help of conditional copulas (see Section 3.4).

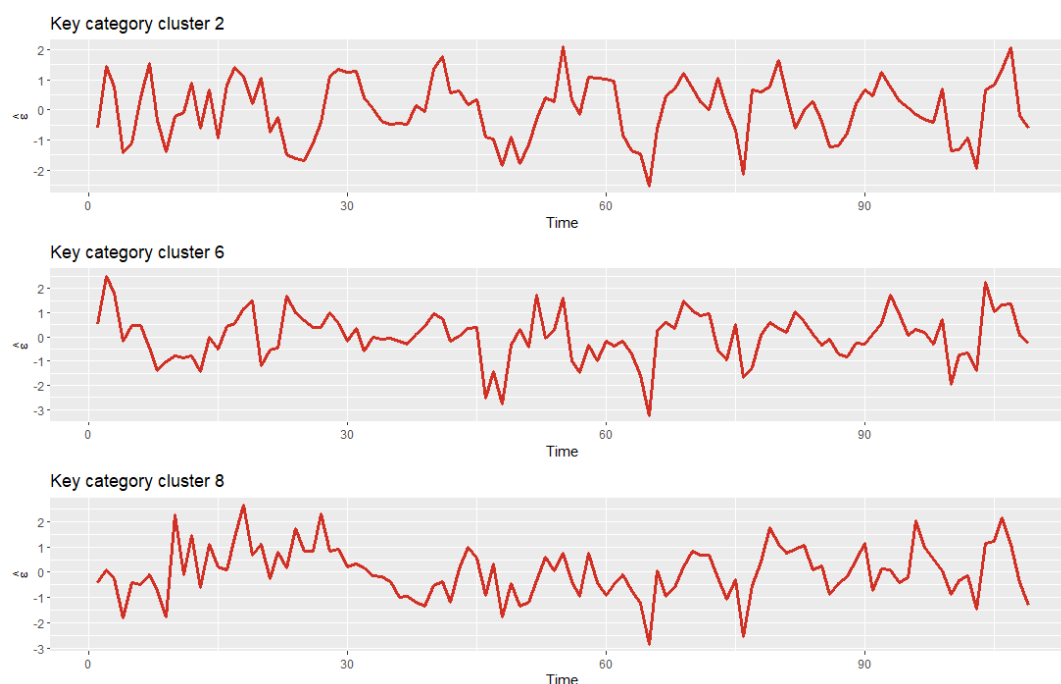


Figure 5.16: Estimated residuals of GAMLSS fits for the three key category clusters

R output 5.7: AIC values of distribution fits on KCC with *fitDist()* function of the *gamlss* package

1	[1] "Fit distribution to KCC 2"											
2	PE	PE2	SEP1	SHASH	SHASHo2	SHASHo	SEP2	SEP3	SEP4	SN2	GT	NO
3	311.5332	311.5332	311.6930	311.7580	311.8708	311.8708	311.8838	312.0426	312.2981	313.0165	313.5115	313.5151
4												
5	[1] "Fit distribution to KCC 6"											
6	LO	PE	PE2	TF	TF2	SHASH	NO	SEP4	SHASHo2	SHASHo	SEP2	SEP1
7	310.7827	312.5686	312.5686	313.0641	313.0641	313.5135	313.5174	313.6367	313.6676	313.6676	313.6834	313.8563
8												
9	[1] "Fit distribution to KCC 8"											
10	NO	LO	PE2	PE	TF2	TF	SN2	SN1	exGAUS	SEP2	SEP1	SEP3
11	312.9735	313.2301	314.5925	314.5925	314.6209	314.6209	314.7309	314.8506	314.8713	315.5988	315.7642	316.1121

In the previous Section 5.1, the model fits resulted in quantile residuals that we were able to approximate parametrically by normal distributions. When the three sets of residuals are passed into the *fitDist()* function of the *gamlss* package, it returns multiple suggestions of parametric distribution that can be used to fit to the data, ordered by ascending Akaike Information Criterion (AIC). An excerpt is given in R output 5.7. The only distribu-

tions that are also at the disposal of the *gjrm* package¹³ are the normal and the logistic distributions and the AIC values are close, indicating that both are good fits. Thus, the normal distribution is chosen for all three residual sets in the following.

5.2.1 Key Category Clusters 2 & 6

To start things off, a look at the scatterplot in Figure 5.17 between the residuals of KCC 2 & KCC 6 provides a first hint of a potential correlation structure. For the most part, the data look quite elliptically scattered. Thus, a normal or a t-copula might be appropriate copulas to be used.

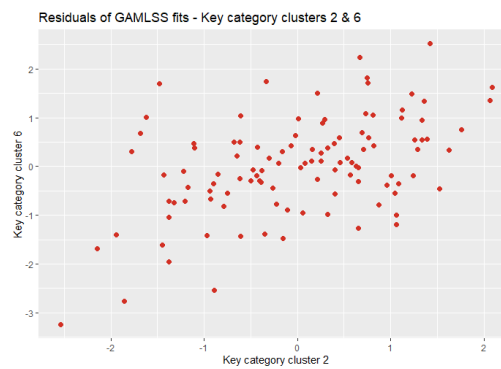


Figure 5.17: Scatterplot of estimated residuals of GAMLSS fits for key category clusters 2 & 6

With the help of the function *BiCopSelect()* of the R package *VineCopula* [Nagler et al., 2019], we can select an appropriate bivariate copula family for the data. A set of possible copula families is considered and maximum likelihood estimations for each are carried out. Selection of a bivariate copula is based on the lowest AIC. The normal and the t-copula are the first in the family set. The selected copula is a t-copula with 3.17¹⁴ d.o.f. and the Pearson's rho as well as Kendall's tau correlation coefficients coincide with the empirical sample coefficients of 0.49 and 0.3 respectively.

Furthermore, to estimate the copula parameter flexibly over time, the Generalized Joint Regression Models (GJRM) framework introduced by Marra and Radice [2016] will be utilized¹⁵. Essentially, the scope of the GAMLSS framework is extended to a bivariate copula additive model, where all parameters of the marginals as well as the copula parameter can be estimated simultaneously using structured additive predictors. The parameters

¹³Elaboration on this in the following subsections.

¹⁴Estimation returns degrees of freedom as positive real values above 2 instead of just integer values.

¹⁵See Section 3.4 as well as the referred paper.

are estimated within a penalized likelihood framework using a trust region algorithm with integrated automatic smoothing parameter selection (More details can be found in the referenced literature). This framework has been implemented in R by Marra and Radice [2020] within the scope of the *gjrm* package.

With the GAMLSS fit residuals of the key category clusters 2 & 6 acting as marginal inputs, normal distributions for both and a t-copula with the above mentioned degrees of freedom as starting value, the formula specification is as follows:

$$\begin{aligned}
 \mu_{KCC2} &= \beta_{\mu, KCC2} & \mu_{KCC6} &= \beta_{\mu, KCC6} \\
 \log(\sigma_{KCC2}) &= \beta_{\sigma, KCC2} & \log(\sigma_{KCC6}) &= \beta_{\sigma, KCC6} \\
 \log(\nu) &= \beta_{\nu} \\
 \tanh^{-1}(\theta) &= \beta_{\theta} + f(t_{time}),
 \end{aligned} \tag{5.2}$$

where ν denotes the degrees of freedom of the t-copula, \tanh^{-1} is the inverse hyperbolic tangent function¹⁶ relating the expected value of the copula parameter $\hat{\theta}$ to the linear predictor $\beta_{\theta} + f(t_{time})$ and f being a smooth function build upon truncated power splines and 30 equidistant knots. Note that as the chosen copula is a Student's t-copula, θ is basically Pearson's correlation coefficient ρ . The rest of the model parameters are all set as constant values as the model seems to be robust to any changes including covariates. Incorporating covariates within smooth functions with high numbers of knots on the contrary lead to less reliable estimations (especially due to increasing number of parameters compared to this sample size).

Model 5.2 along with the mentioned prespecified settings in the *gjrm()* function generates a good overall fit, which is confirmed when checking the histogram and the QQ-Plots of the quantile residuals for the two marginals (see Figure 5.18). A summary can be found in R output 5.8.

R output 5.8: Summary of GJRM fit on key category clusters 2 & 6

```

1
2 COPULA: Student-t (dof = 249)
3 MARGIN 1: Gaussian

```

¹⁶Defined as $\tanh^{-1}(x) = \frac{1}{2} \ln \left(\frac{1+x}{1-x} \right)$ on the domain $\{x \in \mathbb{R} : -1 < x < 1\}$.

```

4 MARGIN 2: Gaussian
5
6 EQUATION 1
7 Link function for mu.1: identity
8 Formula: res_gamlss_kcc_2 ~ 1
9
10 Parametric coefficients:
11      Estimate Std. Error z value Pr(>|z|)
12 (Intercept) -0.04986    0.14980  -0.333   0.739
13
14
15 EQUATION 2
16 Link function for mu.2: identity
17 Formula: res_gamlss_kcc_6 ~ 1
18
19 Parametric coefficients:
20      Estimate Std. Error z value Pr(>|z|)
21 (Intercept)  0.1524     0.1552   0.982   0.326
22
23
24 EQUATION 3
25 Link function for sigma.1: log
26 Formula: ~1
27
28 Parametric coefficients:
29      Estimate Std. Error z value Pr(>|z|)
30 (Intercept) 6.276e-05  6.970e-02   0.001   0.999
31
32
33 EQUATION 4
34 Link function for sigma.2: log
35 Formula: ~1
36
37 Parametric coefficients:
38      Estimate Std. Error z value Pr(>|z|)
39 (Intercept) 0.002922   0.069706   0.042   0.967
40
41
42 EQUATION 5
43 Link function for dof: log(. - 2)
44 Formula: ~1
45
46 Parametric coefficients:
47      Estimate Std. Error z value Pr(>|z|)
48 (Intercept) 211.888     3.112    68.08 <2e-16 ***
49 ---
50 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
51
52
53 EQUATION 6
54 Link function for theta: atanh
55 Formula: ~s(time_obs, k = 30)
56
57 Parametric coefficients:
58      Estimate Std. Error z value Pr(>|z|)
59 (Intercept)  0.6100     0.1192   5.12 3.06e-07 ***
60 ---
61 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
62
63 Smooth components' approximate significance:
64      edf Ref.df Chi.sq p-value
65 s(time_obs) 26.64  28.39 108.4 2.84e-11 ***
66 ---
67 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
68
69 sigma.1 = 1(0.867,1.17)  sigma.2 = 1(0.851,1.17)
70 dof = 249(249,249)
71 theta = 0.37(-0.201,0.819)  tau = 0.286(-0.166,0.672)
72 n = 109  total edf = 32.6

```

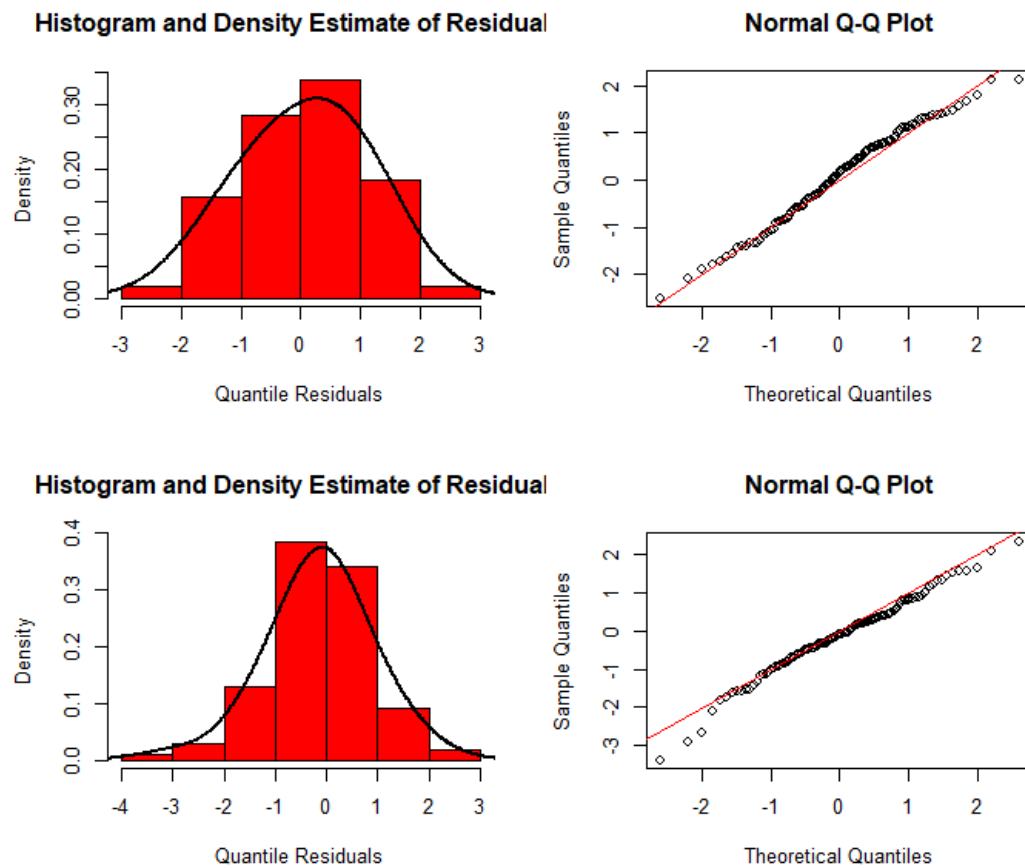


Figure 5.18: Diagnostic plots of quantile residuals based on GJRM models for key category clusters 2 & 6

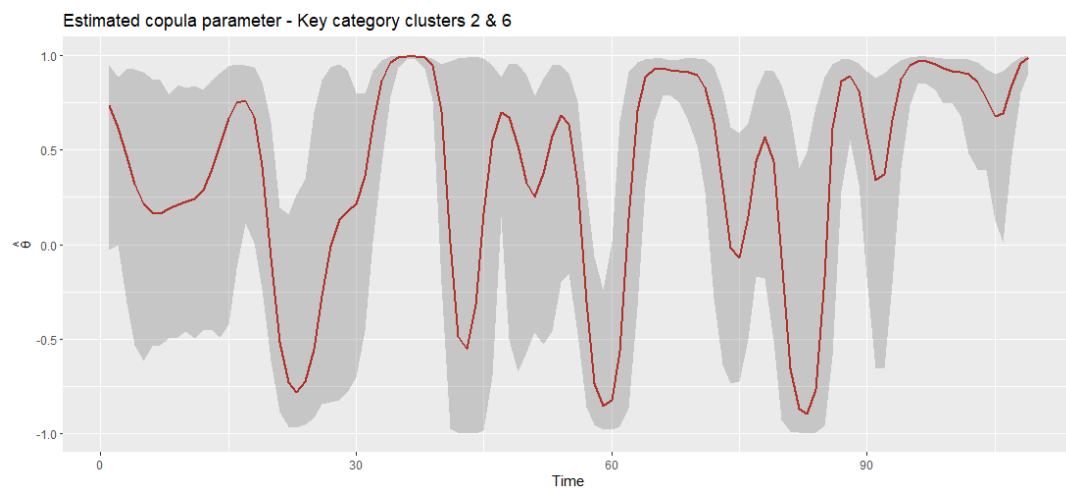


Figure 5.19: Estimated copula parameter over time from a GJRM t-copula model with normal margins for key category clusters 2 & 6 with 95% confidence bands

Figure 5.19 displays the correlation between the two margins highly fluctuates between (almost) perfect negative and positive dependence, suggesting that only copulas which can account for both of those dependence (concordance) types should be considered. Candidate copulas were the Frank copula, the Ali-Mikhail-Haq copula and Fari-Gumbel-

Morgenstern copula, where the last two can only account for weak dependencies [Marra and Radice, 2016]. The Student's t-copulas provides the most appropriate fit among those types of copulas so we stick to it. The width of the confidence intervals also does vary a lot across different parts of the observation period.

The effect of time on the copula parameter turns out to be significant (R output 5.8 and can be viewed in Figure 5.20, where the number 26.64 in brackets on the y-axis denotes the effective degrees of freedom of the smooth curve, which is centered around zero due to identifiability constraints.

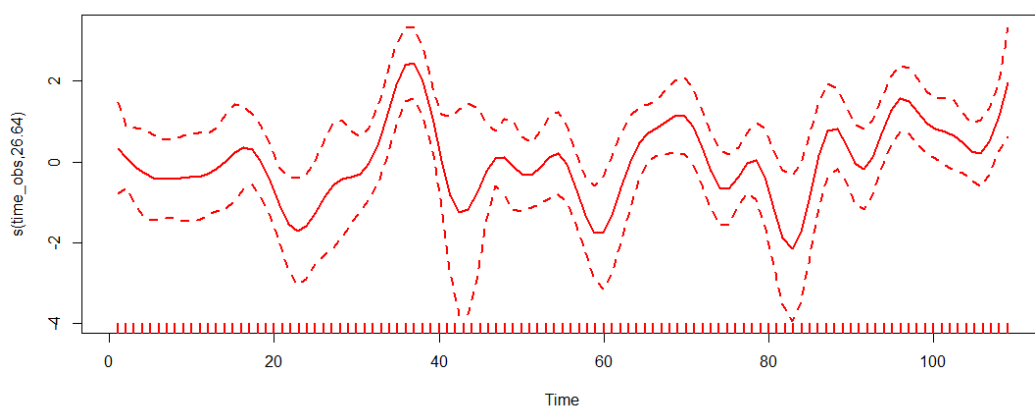


Figure 5.20: Estimated Smooth effect of time on the copula parameter θ with 95% confidence bands for key category clusters 2 & 6

5.2.2 Key Category Clusters 2 & 8

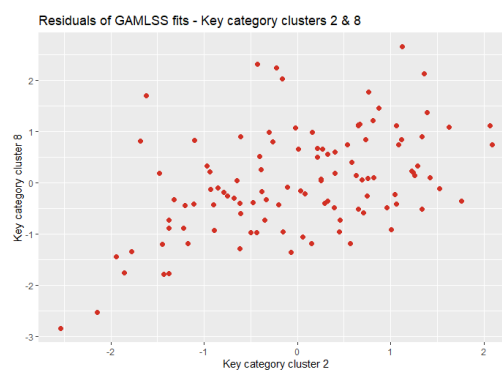


Figure 5.21: Scatterplot of estimated residuals of GAMLSS fits for key category clusters 2 & 8

R output 5.9: Summary of GJRM fit on key category clusters 2 & 8

```
1
2 COPULA: Student-t (dof = 249)
3 MARGIN 1: Gaussian
```

```

4 MARGIN 2: Gaussian
5
6 EQUATION 1
7 Link function for mu.1: identity
8 Formula: res_gamlss_kcc_2 ~ 1
9
10 Parametric coefficients:
11      Estimate Std. Error z value Pr(>|z|)
12 (Intercept)  0.008837   0.098263   0.09   0.928
13
14
15 EQUATION 2
16 Link function for mu.2: identity
17 Formula: res_gamlss_kcc_8 ~ 1
18
19 Parametric coefficients:
20      Estimate Std. Error z value Pr(>|z|)
21 (Intercept)  0.08536   0.09780   0.873   0.383
22
23
24 EQUATION 3
25 Link function for sigma.1: log
26 Formula: ~1
27
28 Parametric coefficients:
29      Estimate Std. Error z value Pr(>|z|)
30 (Intercept) -0.005018   0.066775  -0.075   0.94
31
32
33 EQUATION 4
34 Link function for sigma.2: log
35 Formula: ~1
36
37 Parametric coefficients:
38      Estimate Std. Error z value Pr(>|z|)
39 (Intercept) -0.05304   0.06315  -0.84   0.401
40
41
42 EQUATION 5
43 Link function for dof: log(. - 2)
44 Formula: ~1
45
46 Parametric coefficients:
47      Estimate Std. Error z value Pr(>|z|)
48 (Intercept)  16.952     3.879    4.37 1.24e-05 ***
49 ---
50 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
51
52
53 EQUATION 6
54 Link function for theta: atanh
55 Formula: ~s(time_obs, k = 30)
56
57 Parametric coefficients:
58      Estimate Std. Error z value Pr(>|z|)
59 (Intercept)   0.6381    0.1096   5.825 5.72e-09 ***
60 ---
61 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
62
63 Smooth components' approximate significance:
64      edf Ref.df Chi.sq p-value
65 s(time_obs) 18.5  21.75  41.45 0.00681 **
66 ---
67 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
68
69 sigma.1 = 0.995(0.896,1.13)  sigma.2 = 0.948(0.837,1.06)
70 dof = 249(249,249)
71 theta = 0.466(-0.151,0.847)  tau = 0.34(-0.112,0.684)
72 n = 109  total edf = 24.5

```

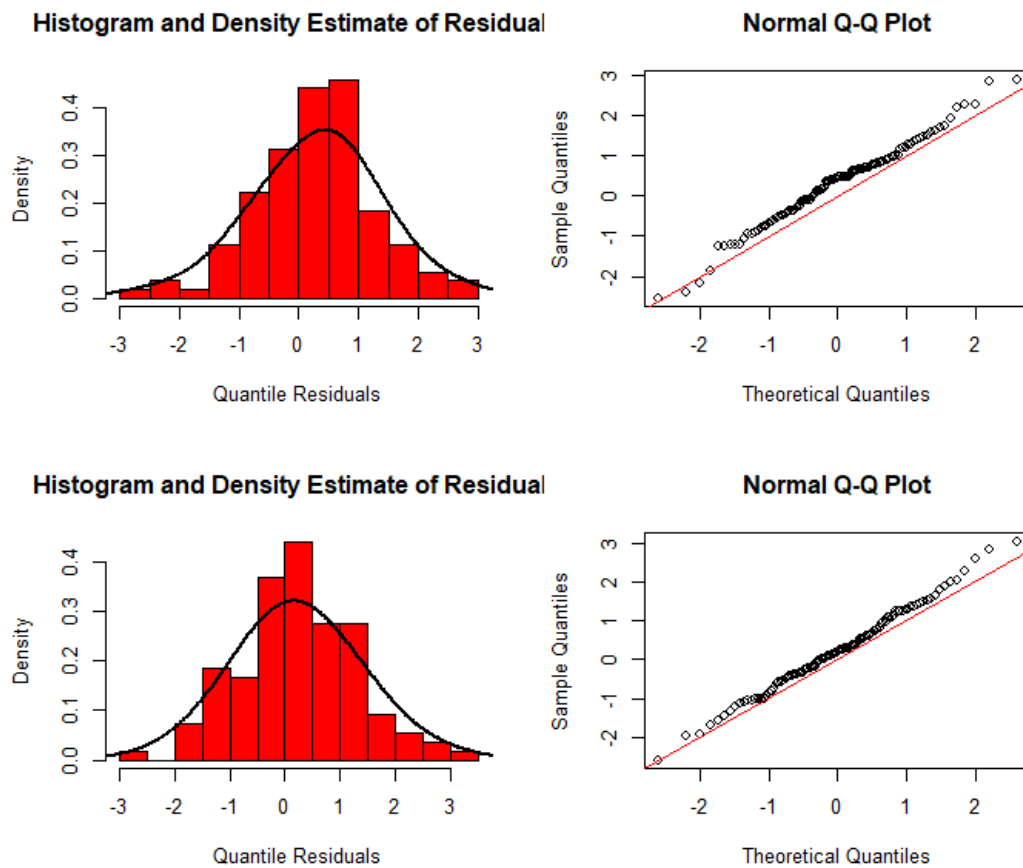


Figure 5.22: Diagnostic plots of quantile residuals based on GJRM models for key category clusters 2 & 8

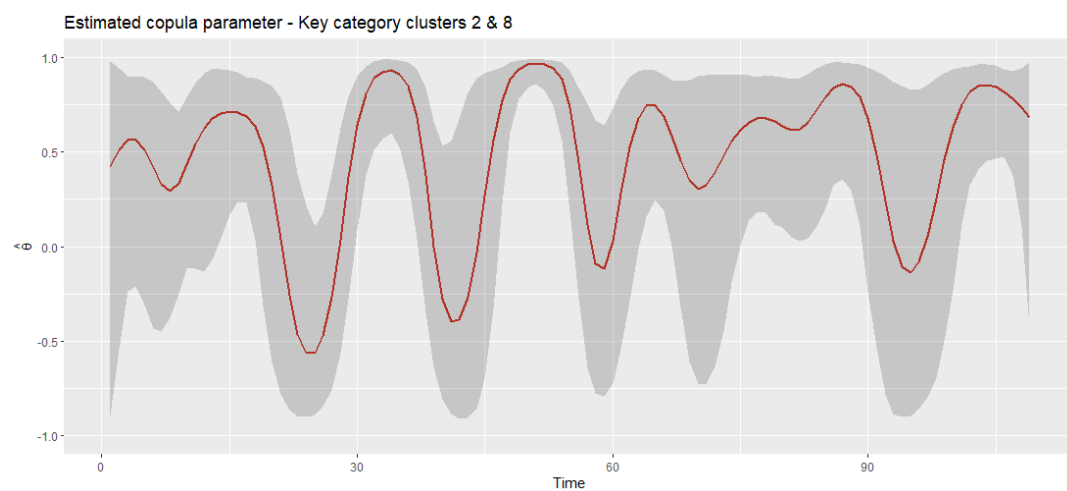


Figure 5.23: Estimated copula parameter over time from a GJRM t-copula model with normal margins for key category clusters 2 & 8 with 95% confidence bands

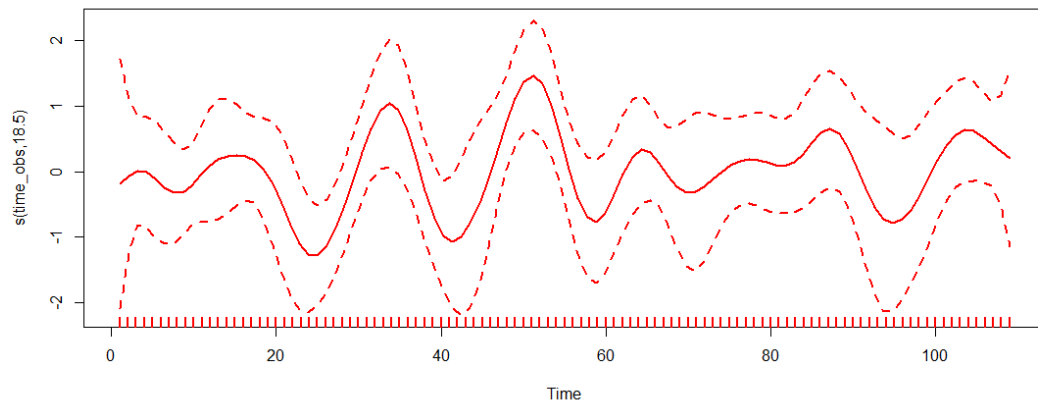


Figure 5.24: Estimated Smooth effect of time on the copula parameter θ with 95% confidence bands for key category clusters 2 & 8

5.2.3 Key Category Clusters 6 & 8

6 Conclusion

List of Abbreviations

AIC Akaike Information Criterion

BS Business Segment

CDF Cumulative Distribution Function

d.o.f. Degrees of Freedom

GAM Generalized Additive Model

GAMLSS Generalized Additive Models for Location, Scale & Shape

GAMM Generalized Additive Mixed Model

GLM Generalized Linear Model

GLMM Generalized Linear Mixed Model

GJRM Generalized Joint Regression Models

KC Key Category

KCC Key Category Cluster

LM Linear Regression Model

LMM Linear Mixed Model

PDF Probability Density Function

RV Random Variable

STAR Structured Additive Regression Model

List of Figures

1.1	Two of the adidas-group logos: Performance (left) & Originals (right) [adidas.com media-center]	2
1.2	adidas celebrates its 70th anniversary and the opening of the ARENA building [adidas 70 years, 2019]	2
3.1	Bivariate Gaussian distribution and Gaussian copula for Pearson's $\rho = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals	16
3.2	Bivariate t-distribution and t-copula with 3 degrees of freedom for Pearson's $\rho = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals	17
3.3	Shape of a generator function	18
3.4	Bivariate Clayton distribution and Clayton copula for Kendall's $\tau = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals	18
3.5	Bivariate Gumbel distribution and Gumbel copula for Kendall's $\tau = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals	19
3.6	Bivariate Frank distribution and Frank copula for Kendall's $\tau = 0.6$ and simulated sample of size $n = 1800$, both with standard normal marginals	20
4.1	Illustration of a hierarchical article structure	25
4.2	Example of a single child node	26
4.3	Course of article unit sales	26
4.4	Scatterplots of promotion intensities against article unit sales; The y-axes are cut at 100	27
4.5	Unit sales in log-scale against total markdown percentage	28
4.6	Unit sales in log-scale against season type	28
4.7	Monthly patterns of article unit sales	29
4.8	Distribution of sold units of articles per week split at 200 units	30
4.9	Empirical CDF of all sold units per week; x-axis cut at 500	30
4.10	Time series and boxplot showing logarithmized sales of the key category clusters	31
4.11	Pairwise scatterplots of sales on KCC level. First row: Logarithmic sales with marginal densities, Second row: Pseudo sales observation with marginal histograms	32

4.12 Correlation plots of the three KCC log-sales with different correlation coefficients. Left: Pearson's rho, Middle: Kendall's tau, Right: Spearman's rho	33
4.13 Boxplots showing log-sales of KCCs against presence of Black Friday . . .	33
4.14 Boxplots showing log-sales of KCCs against presence of Friends & Family .	34
4.15 Scatterplots of KCC log-sales against total markdown percentage	34
4.16 Boxplots of KCC log-sales against the two season types	34
5.1 ex-Gaussian distribution fitted to log-sales of KCC 2	36
5.2 Residuals of KCC 2 log-sales fitted to an ex-Gaussian distribution with no covariate effects together with their density curve	36
5.3 Estimated location parameter $\hat{\mu}$ compared to the observed values and scale parameter $\hat{\sigma}$ with confidence bands of GAMLSS fit - KCC 2	38
5.4 Covariate effects on the expected response variable (log-sales) of GAMLSS fit - KCC 2	40
5.5 Residuals of GAMLSS fit - KCC 2	40
5.6 ex-Gaussian distribution fitted to log-sales of KCC 6	42
5.7 Residuals of KCC 6 log-sales fitted to an ex-Gaussian distribution with no covariate effects together with their density curve	42
5.8 Estimated location parameter $\hat{\mu}$ compared to the observed values and scale parameter $\hat{\sigma}$ with confidence bands of GAMLSS fit - KCC 6	43
5.9 Covariate effects on the expected response variable (log-sales) of GAMLSS fit - KCC 6	44
5.10 Residuals of GAMLSS fit - KCC 6	45
5.11 ex-Gaussian distribution fitted to log-sales of KCC 8	46
5.12 Residuals of KCC 8 log-sales fitted to an ex-Gaussian distribution with no covariate effects together with their density curve	46
5.13 Estimated location parameter $\hat{\mu}$ compared to the observed values and scale parameter $\hat{\sigma}$ with confidence bands of GAMLSS fit - KCC 8	48
5.14 Covariate effects on the expected response variable (log-sales) of GAMLSS fit - KCC 8	48
5.15 Residuals of GAMLSS fit - KCC 8	49
5.16 Estimated residuals of GAMLSS fits for the three key category clusters . . .	50
5.17 Scatterplot of estimated residuals of GAMLSS fits for key category clusters 2 & 6	51
5.18 Diagnostic plots of quantile residuals based on GJRM models for key category clusters 2 & 6	54

5.19 Estimated copula parameter over time from a GJRM t-copula model with normal margins for key category clusters 2 & 6 with 95% confidence bands	54
5.20 Estimated Smooth effect of time on the copula parameter θ with 95% confidence bands for key category clusters 2 & 6	55
5.21 Scatterplot of estimated residuals of GAMLSS fits for key category clusters 2 & 8	55
5.22 Diagnostic plots of quantile residuals based on GJRM models for key category clusters 2 & 8	57
5.23 Estimated copula parameter over time from a GJRM t-copula model with normal margins for key category clusters 2 & 8 with 95% confidence bands	57
5.24 Estimated Smooth effect of time on the copula parameter θ with 95% confidence bands for key category clusters 2 & 8	58

List of Tables

1.1	Transactional raw data description from online purchases of western European countries	3
1.2	Article attribute data	4
3.1	Bivariate relationships in copula families, with T_ν being the Student's t-distribution function with ν degrees of freedom and $D_k(x) = \frac{k}{x^k} \int_0^x \frac{t^k}{e^t-1} dt$ being the Debye function [stanfordphd]	23
4.1	Black Friday weeks	27
4.2	Friends & Family weeks	27
4.3	Number of sold units per week & number of affected articles for various quantiles of sales	29
5.1	Estimated parameters for log-sales of KCC 2 fitted to ex-Gaussian distribution with no covariate effects	36
5.2	Estimated skewness parameter $\hat{\nu}$ of GAMLSS fit with 95% confidence interval bounds - KCC 2	38
5.3	Estimated parameters for log-sales of KCC 6 fitted to ex-Gaussian distribution with no covariate effects	41
5.4	Estimated skewness parameter $\hat{\nu}$ of GAMLSS fit with 95% confidence interval bounds - KCC 6	44
5.5	Estimated parameters for log-sales of KCC 8 fitted to ex-Gaussian distribution with no covariate effects	46
5.6	Estimated skewness parameter $\hat{\nu}$ of GAMLSS fit with 95% confidence interval bounds - KCC 8	48

References

- [adidas 70 years 2019] adidas 70 years: *adidas celebrates its 70th anniversary and the opening of the ARENA building*. 2019. – <https://www.adidas-group.com/en/media/news-archive/press-releases/2019/adidas-celebrates-70th-anniversary>, Last accessed on 2020-04-01
- [adidas-group.com] adidas-group.com: *adidas-group*. – <https://www.adidas-group.com/en/>, Last accessed on 2020-04-01
- [adidas.com media-center] adidas.com media-center: *adidas media-center. Pictures and Videos*. – <https://www.adidas-group.com/en/media/media-center/>, Last accessed on 2020-04-01
- [Dagum 1975] Dagum, Camilo: A model of income distribution and the conditions of existence of moments of finite order. In: *Bulletin of the International Statistical Institute* 46 (1975), S. 199–205
- [Embrechts et al. 2001] Embrechts, Paul ; Lindskog, Filip ; McNeil, Alexander: Modelling dependence with copulas. In: *Rapport technique, Département de mathématiques, Institut Fédéral de Technologie de Zurich, Zurich* 14 (2001)
- [Fahrmeir et al. 2003] Fahrmeir, L. ; Kneib, T. ; Lang, S. ; Marx, B.: *Regression; Models, Methods and Applications*. 2013. 2003
- [Grushka 1972] Grushka, Eli: Characterization of exponentially modified Gaussian peaks in chromatography. In: *Analytical Chemistry* 44 (1972), Nr. 11, S. 1733–1738
- [Hastie and Tibshirani 1986] Hastie, Trevor ; Tibshirani, Robert: Generalized Additive Models. In: *Statist. Sci.* 1 (1986), 08, Nr. 3, S. 297–310. – URL <https://doi.org/10.1214/ss/1177013604>
- [Hastie and Tibshirani 1990] Hastie, Trevor J. ; Tibshirani, Robert J.: Generalized additive models, volume 43 of. In: *Monographs on statistics and applied probability* 15 (1990)
- [Hofert et al. 2019] Hofert, Marius ; Kojadinovic, Ivan ; Mächler, Martin ; Yan, Jun: *Elements of copula modeling with R*. Springer, 2019

- [Klein and Kneib 2016] Klein, Nadja ; Kneib, Thomas: Simultaneous inference in structured additive conditional copula regression models: a unifying Bayesian approach. In: *Statistics and Computing* 26 (2016), Nr. 4, S. 841–860
- [Marra and Radice 2016] Marra, G. ; Radice, R.: A Bivariate Copula Additive Model for Location, Scale and Shape. Cornell University Library (2017). In: *arXiv preprint arxiv:1605.07521* (2016)
- [Marra and Radice 2020] Marra, Giampiero ; Radice, Rosalba: GJRM-package: Generalised Joint Regression Modelling. (2020)
- [McNeil et al. 2015] McNeil, Alexander J. ; Frey, Rüdiger ; Embrechts, Paul: *Quantitative risk management: concepts, techniques and tools-revised edition*. Chap. Copulas and Dependence, Princeton university press, 2015
- [Nagler et al. 2019] Nagler, T. ; Schepsmeier, U. ; Stoeber, J. ; Brechmann, E. C. ; Graeler, B. ; Erhardt, T. ; Almeida, C. ; Min, A. ; Czado, C. ; Hofmann, M. et al.: VineCopula: Statistical Inference of Vine Copulas. In: *R package version 2* (2019), Nr. 0
- [Patton 2006] Patton, Andrew J.: Modelling asymmetric exchange rate dependence. In: *International economic review* 47 (2006), Nr. 2, S. 527–556
- [R Core Team 2018] R Core Team: *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing (Veranst.), 2018. – URL <https://www.R-project.org/>
- [Rigby and Stasinopoulos 2001] Rigby, R. A. ; Stasinopoulos, D. M.: The GAMLSS project: a flexible approach to statistical modelling. In: *New trends in statistical modelling: Proceedings of the 16th international workshop on statistical modelling* Bd. 337 University of Southern Denmark (Veranst.), 2001, S. 345
- [Rigby and Stasinopoulos 2005] Rigby, Robert A. ; Stasinopoulos, D. M.: Generalized additive models for location, scale and shape. In: *Journal of the Royal Statistical Society: Series C (Applied Statistics)* 54 (2005), Nr. 3, S. 507–554
- [Ruppert and Matteson 2015] Ruppert, David ; Matteson, David S.: *Copulas*. S. 183–215. In: *Statistics and Data Analysis for Financial Engineering: with R examples*. New York, NY : Springer New York, 2015. – URL https://doi.org/10.1007/978-1-4939-2614-5_8. – ISBN 978-1-4939-2614-5

- [Schmidt 2007] Schmidt, Thorsten: Coping with copulas. In: *Copulas-From theory to application in finance* (2007), S. 3–34
- [Shapiro and Wilk 1965] Shapiro, Samuel S. ; Wilk, Martin B.: An analysis of variance test for normality (complete samples). In: *Biometrika* 52 (1965), Nr. 3/4, S. 591–611
- [Sklar 1959] Sklar, M.: Fonctions de repartition an dimensions et leurs marges. In: *Publ. inst. statist. univ. Paris* 8 (1959), S. 229–231
- [stanfordphd] stanfordphd: *Copula*. – <https://stanfordphd.com/Copula.html>, Last accessed on 2020-04-27
- [Stasinopoulos et al. 2007] Stasinopoulos, D. M. ; Rigby, Robert A. et al.: Generalized additive models for location scale and shape (GAMLSS) in R. In: *Journal of Statistical Software* 23 (2007), Nr. 7, S. 1–46
- [Trivedi and Zimmer 2017] Trivedi, Pravin ; Zimmer, David: A note on identification of bivariate copulas for discrete count data. In: *Econometrics* 5 (2017), Nr. 1, S. 10
- [Vatter and Chavez-Demoulin 2015] Vatter, Thibault ; Chavez-Demoulin, Valérie: Generalized additive models for conditional dependence structures. In: *Journal of Multivariate Analysis* 141 (2015), S. 147–167
- [Vatter and Nagler 2018] Vatter, Thibault ; Nagler, Thomas: Generalized additive models for pair-copula constructions. In: *Journal of Computational and Graphical Statistics* 27 (2018), Nr. 4, S. 715–727
- [Vatter and Nagler 2019] Vatter, Thibault ; Nagler, Thomas: gamCopula-package: Generalized Additive Models for Bivariate Conditional... (2019)
- [Wood 2017] Wood, Simon N.: *Generalized additive models: an introduction with R*. CRC press, 2017

Statutory Declaration

I hereby declare that I wrote this thesis paper independently, without assistance from external parties, and without use of other resources than those indicated. All information taken from other publications or sources in text or in meaning are duly acknowledged in the text. The written and electronic forms of the thesis paper are the same. I give my consent to have this thesis checked by plagiarism software.

Nuremberg, August 7, 2020

Petros Christanas