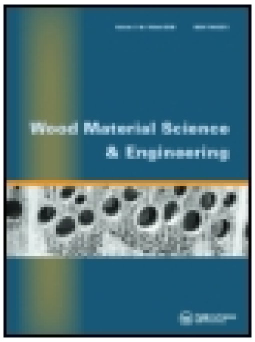

Wood Material Science & Engineering

ISSN: 1748-0272 (Print) 1748-0280 (Online) Journal homepage: http://www.tandfonline.com/loi/swoo20

Adhesive systems used in the European particleboard, MDF and OSB industries

George I. Mantanis, Eleftheria Th. Athanassiadou, Marius C. Barbu & Kris Wijnendaele

To cite this article: George I. Mantanis, Eleftheria Th. Athanassiadou, Marius C. Barbu & Kris Wijnendaele (2017): Adhesive systems used in the European particleboard, MDF and OSB industries, Wood Material Science & Engineering

To link to this article: http://dx.doi.org/10.1080/17480272.2017.1396622

Published online: 09 Nov 2017.

WOOD MATERIAL SCIENCE & ENGINEERING, 2017
https://doi.org/10.1080/17480272.2017.1396622

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

Adhesive systems used in the European particleboard, MDF and OSB industries*

George I. Mantanis[a], Eleftheria Th. Athanassiadou[b], Marius C. Barbu[c] and Kris Wijnendaele[d]

[a]Research Lab of Wood Science & Technology, Dept. of Wood & Furniture Design and Technology, Technological Education Institute (TEI) of Thessaly, Karditsa, Greece; [b]Chimar Hellas S.A., Thessaloniki, Greece; [c]Salzburg University of Applied Sciences, Dept. of Forest Products Technology and Timber Construction, Faculty for Wood Engineering, A-5431 Kuchl, Austria, and Transilvania University of Brasov, Brasov, Romania; [d]European Panel Federation (EPF), Brussels, Belgium

ABSTRACT
In this work, the adhesive systems used today in the European industries of particleboard, medium density fibreboard (MDF) and oriented strand board (OSB) are discussed. The structure of particleboard, MDF and OSB markets in Europe in relation to the types of adhesives and product specifications are presented as well. It is noticeable that new markets for wood-based panels like particleboard and fibreboard, known as non-furniture markets, are growing in Europe at a fast rate. It was concluded that most of the technological changes concerning the adhesive systems applied and additives have been realised from the need for niche panel products, the obligation to reach even lower formaldehyde emissions, and the necessity to decrease production costs due to the stringent competition in the market of wood-based panels.

ARTICLE HISTORY
Received 11 September 2017
Revised 25 September 2017
Accepted 20 October 2017

KEYWORDS
Wood-based panels; formaldehyde-based adhesives; urea-formaldehyde; melamine-urea-formaldehyde; polymeric methylene di-isocyanate (PMDI); formaldehyde emission

Introduction

In the recent years, the particleboard, medium density fibreboard (MDF) and oriented strand board (OSB) industries in Europe have been encountered with many challenges such as faster curing times, production of niche products and lower formaldehyde emissions (Markessini 1993, Dunky 1995, Wolf 1997, Alexandropoulos *et al.* 1998, Dunky 1998, Guerin 1998, Mantanis and Markessini 1998, Dunky *et al.* 2000, Pizzi 2006, Irle and Barbu 2010, Kutnar and Burnard 2014, Barbu 2015), while a series of technological changes relating to new adhesive systems has been taking place (Dunky 2003, Athanassiadou and Ohlmeyer 2009, Tsirogiannis 2011, Stroobants and Grunwald 2014, Vnučec *et al.* 2017).

As a matter of fact, aminoplastic adhesives are still the most important adhesives for the different types of wood-based panels, particularly in particleboard and MDF (Kutnar and Burnard 2014, Athanassiadou *et al.* 2015, Sandberg 2016). Aminoplastic adhesives, as synthetic adhesives made from amino-compounds, include two basic types: urea-formaldehyde (UF) and melamine-urea-formaldehyde (MUF), with different proportions of melamine ($C_3H_6N_6$). They are both thermosetting polymers and of condensation type (Pizzi and Mittal 2003). While UF adhesives are used mostly for interior-use panels, the incorporation of melamine, an organic base and a trimer of cyanamide, results in adhesives with a lower susceptibility against hydrolysis and, hence, wood panels with better water and weather resistance (Dunky 1995, Alexandropoulos *et al.* 1998, Dunky 2003, Athanassiadou *et al.* 2010, 2015). Nearly all kinds of requirements can be met with aminoplastic adhesives. It should be noted though that, in wood adhesives, the application parameters other than the characteristics of the adhesive itself, can account for a substantial part of the performance (Dunky and Niemz 2002, Dunky 2003).

Furthermore, new special wood-based panels such as moisture-resistant, fire-retardant, biologically resistant, shuttering and other, have shown a growth in the European particleboard and MDF market in the recent years (Irle and Barbu 2010, Barbu 2015, Sandberg 2016).

Aminoplastic adhesives, with very low content of free formaldehyde, fulfil today the stringent regulations, concerning the subsequent formaldehyde emission, that have been enforced in Europe during the last three decades (Alexandopoulos *et al.* 1998, Dunky 2003, Tsirogiannis 2011, Athanassiadou *et al.* 2015). Besides, wood-based panels with extremely low formaldehyde emission, similar to that of natural wood, can be produced particularly by means of special MUF adhesives (Alexandropoulos *et al.* 1998, Dunky 2003, Tsirogiannis 2011, Sandberg 2016). MUF adhesives containing small amounts of phenol (3–8%) or hydroxymethylphenols (MUPF), as well as phenol-formaldehyde (PF) adhesives are less used in the particleboard and MDF production, and added only supplementarily for niche products. The general

CONTACT George I. Mantanis mantanis@teilar.gr Research Lab of Wood Science & Technology, Dept. of Wood & Furniture Design and Technology, Technological Education Institute (TEI) of Thessaly, GR-43100 Karditsa, Greece

*This work is dedicated to Emeritus Professor *Dr Edmone Roffael* (University of Göttingen) for his significant research contributions in the field of wood-based panels and adhesives.

Table 1. General properties of formaldehyde-based adhesives (Grunwald 2014).

Property	Type of adhesive UF	MUF	PF	MUPF
Hardening temperature (°C)	100	100	135	100
Colour of hardened adhesive	Clear white	Clear white	Brown	Yellow
Dry shear strength (MPa)	13	13	12	12
Wet shear strength (MPa) after 48 h storage in water	8	9	10	9
Water and climate resistance	Conditionally permanent vs. Humidity	Permanent vs. humidity. Not against weather	Permanent vs. humidity and weather	Permanent vs. humidity. Not against weather
Rheological behaviour	Minor flow	Minor flow	Good to very good flow	Minor to average flow
Use of a hardener	Yes	Yes	Yes (sometimes)	Yes

physicochemical and mechanical properties of the formaldehyde-based adhesives are shown in Table 1 (Grunwald 2014). In general, the quantities of MUPF, PF and PMDI adhesives consumed today by the European particleboard and MDF industries are negligible, approximately 2–3% (Grunwald 2017).

On the contrary, polymeric methylene di-isocyanate (PMDI) today is the primary adhesive applied in the European OSB industry (Stroobants and Grunwald 2014), in varying addition levels, depending upon the required properties of the final products (Grunwald 2014).

Adhesives based on natural resources (named as 'bio-adhesives') have shown not significant importance for the European wood-based panels industry. Actually, only minute volumes of niche products based on tannins are offered in the market. Lately, there has been a high research interest in bio-adhesives mainly in soy-based adhesives (Vnučec *et al*. 2017), as well as in lignin- and tannin-based adhesives (Nakos *et al.* 2016, Hemmilä *et al.* 2017, Papadopoulou 2017). The interest of the industry is strong in North America and China, but much lower in Europe. The main reasons for the interest in such adhesives are the legislation, and the growing attention in more environmentally friendly products, not dependent on petrochemicals. As a matter of fact, for soy-based adhesives, there are many concentrated forms of soy proteins, i.e. concentrates and isolates, which are suitable raw materials for adhesives, except that their prices are high. Some soy-based compounds are presently used in the wood-based panels industry as additives, hardeners or cross-linking agents (Papadopoulou 2017). According to Vnučec *et al*. (2017), a soy-based adhesive named soy protein-Kymene® in the USA is widely used for interior plywood and wood flooring, with limited acceptance in particleboard. Another system, known as Soyad™ adhesive, is used in North America for hardwood plywood, particleboard, MDF and wood flooring. Noticeably, very recently, two major European groups announced the use of a bio-based resin technology, named DuraBind™, for the production of 'no-added-formaldehyde' (NAF) wood panels, having the highest level of renewable content. A few years ago, two German plants (particleboard, MDF) used quebracho (*Schinopsis sp.*) and wattle (*Acacia sp.*) tannin-based adhesives in their production for special panel products (Roffael *et al.* 2000). Today in the European market, there is only a very small usage of tannins, in two MDF mills, for the production of niche MDF products.

Nonetheless, the main adhesive systems used in the European wood-based panels industry today are UF, MUF, PF and PMDI adhesives, whose main characteristics are briefly discussed in the sections that follow.

UF adhesives

UF is the main adhesive for wood-based panels with many strong advantages: very low cost, non-flammable, light colour and fast curing rates (Dunky 2003, Pizzi and Mittal 2003). Today worldwide, UF adhesives are by far the major types of aminoplastic adhesives used mainly for panels of indoor use. The major drawback of these adhesives is their poor water resistance (Pizzi 1994, Dunky 1998, 2003), where some bondline failures can be observed under accelerated aging. UF adhesives occasionally exhibit some problems with long-term hydrolytic instability (Dunky 1998, Pizzi and Mittal 2003, Grunwald 2014).

MUF adhesives

MUF adhesives, with different proportions of melamine, show high resistance against moisture and climate, and are used in particleboard, MDF and high-density fibreboard (HDF), and sometimes in OSB production. Pure melamine-formaldehyde (MF) adhesives are only used for decorative laminates and paper coatings, which are outside of the scope of this work.

PF adhesives

PF is the oldest type of synthetic adhesives. They are used less in particleboard and MDF production, and mostly in OSB (see N. America market) and plywood, as well as in laminated wood products (e.g. LVL, GLT). After proper curing, PF adhesives possess permanent resistance under humid climatic conditions (Grunwald 2014). They yield very good adhesion to wood, and have excellent stability. The common additive for PF adhesives is urea $[CO(NH_2)_2]$ to provide improved flow properties, to reduce the cost, and to scavenge the free formaldehyde (Sandberg 2016); also, to reduce the water content of the resins, which can have a positive impact on the use in core layer gluing of OSB and particleboard (Grunwald 2017). Sometimes, common hardener for the PF adhesive systems is potassium carbonate (K_2CO_3), even though, sodium carbonate (Na_2CO_3) is used infrequently (Roffael 2017).

PMDI adhesives

PMDI adhesives are commonly used in bonding wood panels because of the high bond strength they provide. Usually, they are a mixture of monomeric diphenylmethanediisocyanate and methylene-bridged oligo-aromatic isocyanates with several NCO groups on each molecule (Dunky 2003, Sandberg 2016). The higher cost of the PMDI adhesives is offset by the faster reaction time, compared to PF, the very high bond strength and the superior resistance to water and climatic conditions (Dunky 2003). These adhesives are marketed as formaldehyde-free systems in Europe. However, PMDI adhesives need special precautionary protection measures when used in the industry, and press-sticking problems need special care, when used in the face layer. Cured PMDI adhesives though, pose no recognised health concerns (Grunwald 2014).

The following chapters focus on the adhesive systems used today in the particleboard, MDF and OSB industry in Europe, providing detailed technical information and summarising the state-of-the-art in the area of wood-based panels. In addition, special focus is given on the structure of the corresponding European wood-based panel markets, with data provided about the capacity and production as well as the special (niche) panel products.

Methodology

This work examined research and review articles published as well as conference and seminar presentations given between January 1994 and August 2017, in this subject. The relevant literature collected was interrelated with the particular subject of adhesives and additives of wood-based panels. Much of the technical information came straight from several European subject experts, as shown in references, through personal communication done via questionnaires. Some of the technical information, presented in this work, is part of the knowledge possessed by the authors through year-long work and experience in the field of wood-based panels.

The presented statistical data regarding the capacity and production of particleboard, MDF and OSB, as well as other interrelated data, are derived from dependable sources, such as the annual reports 2015–2016 and 2016–2017 of the European Panel Federation (EPF), the database of Food and Agriculture Organization (FAO) of the United Nations, the database of the United Nations Economic Commission for Europe (UNECE), as well as from other reliable periodicals in the field of wood-based panels such as *Wood-Based Panels International*.

European wood-based panels industry

The particleboard industry

The European particleboard industry experienced a positive growth during 2016, according to the annual report 2016–2017 of EPF (2017). EPF is the European federation of the particleboard, MDF and OSB industrial manufacturers, and has 25 member countries. EPF represents also the manufacturers of plywood, hardwood and softwood panels.

The overall level of particleboard production (2016), in the EPF member countries, amounted to 30.25 million m^3. This level of particleboard production remained far below from the peak of 37.8 million m^3 produced in 2007. Figure 1 outlines the capacity and production of particleboard in the EPF member countries through the years 2011–2016 (2016, 2017).

Since 2013, the production of particleboard throughout Europe has presented slight increasing growth rates. In 2016, there was an increase of particleboard production of about 0.8% over 2015, in the EPF member countries, which altogether have 98 operating particleboard plants (as in 2016). The particleboard production per each EPF member country in the period 2011–2016 is shown in Table 2 (2017). In addition, it was estimated that the key figures of the particleboard industry in other European countries like Russia, Turkey, Ukraine and Serbia, in the years 2011–2016, were those shown in Table 3 (EPF 2016, 2017). Table 3 also outlines the estimates of the particleboard production in major-producing countries worldwide, for comparative purposes (EPF 2017).

Technical standards have been adopted by the European Committee for Standardisation (CEN) for the different

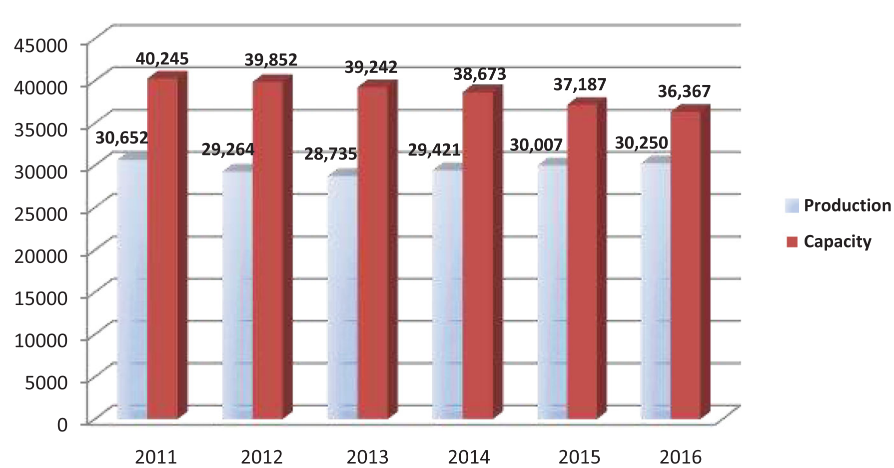

Figure 1. Particleboard capacity and production in the EPF member countries in 2011–2016 (EPF 2017).

Table 2. Particleboard production (in 1000 m^3) in the EPF member countries in 2011–2016 (EPF 2017).

Country	2011	2012	2013	2014	2015	2016	Change (%) 2015–2016
Austria (5)*	2094	2181	2202	2160	2180	2300	+5.5
Belgium (2)	1297	1300	1154	1180	1180	1050	−11.0
Bulgaria (3)	475	480	500	520	520	520	0
Croatia (1)	105	110	120	120	121	121	0
Czech Republic (3)	1150	1200	1062	1095	1115	1140	+2.3
Denmark (1)	335	349	358	373	379	392	+3.4
Estonia (1)	193	169	190	190	151	160	+6.0
Finland (1)	185	93	98	90	90	101	+12.0
France (11)	3997	3870	3797	3779	3630	3627	−0.1
Germany (17)	5750	5608	5626	5665	5532	5500	−0.6
Greece (1)	270	240	140	93	83	119	+43.0
Hungary (1)	280	285	300	320	320	320	0
Ireland (0)***	–	–	–	–	–	–	–
Italy (11)	2976	2588	2354	2316	2396	2569	+7.2
Latvia (1)	300	320	325	312	327	345	+5.4
Lithuania (2)	495	500	665	674	682	682	0
Luxemburg (0)	–	–	–	–	–	–	–
Norway (2)	316	286	235	267	274	275	+0.3
Poland (5)	2860	2831	2576	2790	2793	2807	+0.5
Portugal (3)	686	577	563	625	744	774	+4.0
Romania (7)	1100	1200	1250	1650	1765	1915	+8.5
Slovakia (2)	710	715	720	689	804	840	+4.5
Slovenia** (1)	130	120	125	130	139	0	−100.0
Spain (10)	1601	1346	1313	1458	1737	1806	+4.0
Sweden (2)	510	572	542	494	539	543	+0.7
Switzerland (1)	522	545	555	383	391	395	+1.0
The Netherlands (0)	–	–	–	–	–	–	–
UK (5)	2316	1779	1965	2050	2115	1949	−7.9
Total EPF:	30,652	29,264	28,735	29,421	30,007	30,250	+0.8

* In the parentheses, the number of particleboard plants (2016) in each country (EPF 2017).
** In Slovenia, the only one particleboard plant has closed down at the end of 2015 (EPF 2017).
*** Ireland, Luxemburg and The Netherlands have no particleboard plants (as in 2016).

Table 3. Estimates of particleboard production in major-producing countries (EPF 2016, 2017).

Country	2011	2012	2013	2014	2015	2016	Change (%) 2015 to 2016
A. European non-EPF member countries (in 1000 m^3)							
Russia	6634	6753	6657	6543	6518	6865	+5.3
Turkey	n/a	n/a	n/a	n/a	4360	4150	−4.8
Ukraine*	2689	2508	2439	2250	2160	2334	+8.1
Serbia	202	247	221	262	227	215	−5.3
B. Major-producing countries worldwide (in 1000 m^3)							
Australia	920	840	837	855	903	915	+1.3
Brazil	3070	3261	3381	3195	2719	2816	+3.6
Canada	1650	1704	1694	1717	1723	1761	+2.2
China	12,698	12,891	12,247	16,729	20,300	22,330	+10.0
Chile	755	755	755	755	755	755	0
Iran	795	886	981	1010	804	840	+4.5
Japan	960	920	1040	1070	1070	1089	+1.8
S. Korea	795	801	802	830	820	815	−0.6
USA	4010	3664	4128	4134	4209	4087	−3.0

* Bekhta (2017).

particleboard types produced today in Europe (EN 312). Specific requirements, depending upon the thickness range, have been issued for each particleboard type. The types of particleboard produced in Europe are outlined in Table 4.

In respect to the final applications of particleboard, the furniture market remains the largest user of particleboard in Europe (EPF 2017) with 66% in 2016. The building sector accounted for a share of 22% including doors and flooring applications. The remaining 12% of particleboard consumption, distributed to other applications such as packaging, panelling and frames.

It is difficult to accurately determine the exact proportions of adhesives consumed in Europe for particleboard production. According to recent sources (Kutnar and Burnard 2014, Grunwald 2017), it was estimated that the adhesive use in the European particleboard industry was split between UF (90–92%), MUF (6–7%) and PMDI (1–2%) adhesives.

Table 4. Types of particleboard produced in Europe (EN 312).

Type	Particleboard application	Standard
P1	General purpose boards for use in dry conditions	EN 312: 2010
P2	Boards for interior fitments (including furniture) for use in dry conditions	EN 312: 2010
P3	Non-load-bearing boards for use in humid conditions	EN 312: 2010
P4	Load-bearing boards for use in dry conditions	EN 312: 2010
P5	Load-bearing boards for use in humid conditions	EN 312: 2010
P6	Heavy duty load-bearing boards for use in dry conditions	EN 312: 2010
P7	Heavy duty load-bearing boards for use in humid conditions	EN 312: 2010

Table 5. Estimates of MDF capacity and production in Europe (as in 2016).

Country	Number of mills[a]	Capacity[b]	Production[c]	(in 1000 m^3)
Austria	1	450	550	
Belarus	6	1060	n/a	
Belgium	1	300	320	
Czech Republic	1	92	35	
France	4	1040	980	
Germany	12	4020	3500	
Greece	1	130	60	
Hungary	1	210	175	
Ireland	1	420	440	
Italy	4	1260	950	
Luxemburg	1	270	225	
Poland	8	2900	3150	
Portugal	3	475	285	
Romania[d]	1	350	305	
Russia[e]	17	2800	1510	
Slovenia	1	180	130	
Spain	7	1445	660	
Switzerland	1	240	205	
Turkey[e]	17	5100	4750	
Ukraine	3	535	n/a	
UK	2	950	680	

[a] WBPI (2017a) and EPF (2017).
[b] EPF (2017).
[c] Production data from FAO (2017), EPF (2017) and UNECE (2017).
[d] As in the end of 2016; two (2) MDF mills are currently operating in Romania (September 2017).
[e] Data for Russia and Turkey from EPF (2017).

The MDF industry

MDF was first introduced in Europe in 1973, in the former East Germany, with the first sales occurring in 1976 at the United Kingdom (Alexandropoulos *et al.* 1998). At the end of 2016, there were 49 MDF manufacturing plants in the EPF member countries (EPF 2017), while another 43 MDF industrial mills were operating in Russia, Turkey, Ukraine and Belarus, as a whole (WBPI 2017a).

Fibreboard production in Europe includes mainly MDF, which represents about 70% of all the fibreboard market in Europe. This MDF volume includes HDF for flooring, thin HDF, and also, low-density fibreboard. The rest of fibreboard production consists of wet-process hardboard, and rigid and flex softboard, in volume proportions 4% and 26%, respectively (EPF 2017).

Table 5 outlines the estimates of MDF capacity and production in Europe in year 2016 (EPF 2017, UNECE 2017, WBPI 2017a). Newer data showed that the European MDF capacity in the EPF member countries reached the level of 14.7 million m^3 in 2016 (2017). Turkey possesses the highest MDF capacity (5.1 million m^3), while Russia has a capacity of 2.8 million m^3 for MDF.

The production of MDF in the EPF member countries grew by 2.0% in year 2016, exceeding 12.0 million m^3 (EPF 2017). This figure does not include the MDF production of Turkey and Russia, which summed up 4.75 and 1.51 million m^3, respectively (EPF 2017). The production of 12.0 million m^3 in the EPF member countries remained lower than the peak of 13.3 million m^3 of MDF produced in 2007. The types of MDF manufactured in Europe today are presented in Table 6 (EN 622-5).

In 2016, all European MDF industries produced standard grade, while many MDF mills fabricated various grades of special products (Table 7). Seventy-five percent of the mills also produce moisture-resistant MDF (MDF.H), and 65% produce melamine-faced MDF. Other niche products include fire resistant, veneered, and shuttering MDF and other such as biological-resistant MDF (EPF 2017).

Table 6. Types of MDF produced in Europe (EN 622-5).

Type	Board application	Standard
MDF	General purpose boards for use in dry conditions	EN 622-5
MDF.H	General purpose boards for use in humid conditions	EN 622-5
MDF.LA	Load-bearing boards for use in dry conditions	EN 622-5
MDF.HLS	Load-bearing boards for use in humid conditions	EN 622-5
L-MDF	Light-MDF boards for use in dry conditions	EN 622-5
L-MDF.H	Light-MDF boards for use in humid conditions	EN 622-5
UL1-MDF	Ultra-light-MDF boards for use in dry conditions	EN 622-5
UL2-MDF	Ultra-light-MDF boards for use in dry conditions	EN 622-5
MDF-RWH	Boards for use in rigid underlays in roofs and walls	EN 622-5

Table 7. MDF grades produced in mills operating in the EPF member countries (EPF 2016).

MDF grades	No. of MDF mills	Percent of the mills (%)
Raw	43	100
Melamine-faced	28	65
Veneered	7	16
Moisture-resistant	32	75
Biologically resistant	3	7
Fire-resistant	14	32
Shuttering	2	5
Other grades (L-MDF, UL-MDF, printed, thin)	27	63

It is known that MDF applications outside the furniture industry (interior-use MDF) are more developed in the European market than elsewhere (Irle and Barbu 2010, EPF 2016). According to EPF (2017), furniture applications (45%) and laminate flooring applications (32%) remained the two major buyers of the European-produced MDF panels in 2016 (Table 8). 'Do-it-yourself' applications were counted to ca. 16%, despite the increased popularity of renovation. The remaining 7% of MDF production, forwarded to moulding and other applications such as outdoor panelling, small cabinets, frames, games and toys.

According to EPF (2017), the produced European MDF and HDF in relation to the nominal panel thickness was divided into three classes: (a) thick panels, with a thickness >9 mm (49% of the total production), (b) panels with a thickness between 5–9 mm (42%) and (c) thin MDF (thickness <5 mm), which represented a share of just 9% of the total European production.

The OSB industry

The OSB industry in Europe has been growing increasingly in the recent years. At the end of 2016, 24-OSB plants have been running in Europe. The OSB capacity and production per each European country is shown in Table 9 (EPF 2017, FAO 2017, UNECE 2017, WBPI 2017b).

Table 8. Applications of European MDF products (EPF 2017).

Application	Percent of the total (%)
Furniture uses	45
Laminate flooring	32
'Do-it-yourself' applications	16
Panelling, cabinets, frames, games, etc.	7

Table 9. Estimates of OSB capacity and production in Europe (as in 2016).

Country	Number of plants[a]	Capacity[a]	Production[b] (in 1000 m^3)
Belarus	1	300	n/a
Belgium	1	400	240
Bulgaria	1	240	205
Czech Republic	1	500	n/a
France	1	400	355
Germany	3	1270	1350
Hungary	1	300	235
Ireland	1	500	350
Italy	1	130	70
Latvia	1	500	n/a
Luxemburg	1	200	205
Poland	2	740	950
Romania	2	1000	920
Russia	4	930	900
Turkey	1	170	75
Ukraine[c]	1	200	125
UK	1	320	345

[a]WBPI (2017b) and EPF (2017).
[b] Production data from FAO (2017), EPF (2017) and UNECE (2017).
[c] Bekhta (2017).

Recent calculations revealed that the OSB production, in the EPF member countries, increased by 6.9% in year 2016 (2017), and thus, exceeded 5.4 million m^3. As shown in Table 9, Germany, Poland and Romania hold the largest OSB production outputs; noticeably, the overall OSB capacity in the EPF member countries (2016) surpassed the mark of 6.5 million m^3 (2017). As rapidly grown market, European OSB production is expected to increase further within 2017.

According to EN 300 (2006), OSB produced in the European market is divided into four different quality types, namely: OSB/1, OSB/2, OSB/3 and OSB/4, as described in Table 10. The loading-bearing OSB panel, suitable for structural uses in humid conditions (called as OSB/3), is the major OSB type, which accounted for approximately 85% of the whole European output. The type OSB/2, i.e. panels suitable for structural and non-structural use in dry conditions, accounted for 10% in 2016, according to EPF data (2017). Five percent of the European OSB production was devoted to the OSB/4 category.

Adhesive systems used in particleboard and MDF production

Most of the adhesives currently used in the particleboard industry are formaldehyde-based adhesives (UF, MUF), which have a molar ratio of formaldehyde to urea (F:U) between 1.00 and 1.10 (Markessini 2017). In MDF, this F:U ratio can be lower (0.85–1.00) in some cases. It is to be noted that 20 years ago, the majority of the adhesives used had molar ratios as high as 1.25 (Dunky 1995, Alexandropoulos *et al.* 1998). The major reason for this significant reduction over the years was the attempt of resin manufacturers to decrease largely the formaldehyde emission. The driving force behind that has been the consumer opinion, along with the legal regulations (Dunky *et al.* 2000, Kutnar and Burnard 2014, Hill *et al.* 2015). It should be noted that the formaldehyde emission from finished wood panels depends upon exogenic factors (temperature, relative humidity), and endogenic factors such as wood species, type of adhesive, resin addition level, production conditions and type of press (Roffael 2006).

Table 10. Types of OSB produced in Europe (EN 300).

Type	OSB application	Standard
OSB/1	General purpose, non-load-bearing panels, and panels for interior fitments for use in dry conditions	EN 300: 2006
OSB/2	Load-bearing panels for use in dry conditions	EN 300: 2006
OSB/3	Load-bearing panels for use in humid conditions	EN 300: 2006
OSB/4	Heavy duty load-bearing panels for use in humid conditions	EN 300: 2006

Furthermore, the reduction of the F:U ratio was initially achieved by introducing in the resin cooking process one or two extra steps in the urea addition (Alexandropoulos *et al.* 1998, Dunky 2003). The urea reacted with the residual formaldehyde, and the free formaldehyde emitted from the board was drastically reduced. However, this outcome had many negative side-effects. The plants had to tolerate longer pressing times, tighter control of wood moisture content, and higher resin consumption, in addition to the fact that the mechanical properties and water resistance of the panels were lowered. Thus, further developments to address these problems included the addition of a small quantity of melamine (usually 1–4%). Although this increased the production cost, it proved to be quite successful. Such MUF adhesives generally better tolerate process variations than straight UF. For formaldehyde-based adhesives, the mentioned approach appears, up to day, to be the preferred way to produce particleboard and MDF with low formaldehyde emission, without the use of any scavengers (Dunky 2003, Tsirogiannis 2011, Athanassiadou *et al.* 2015). Another approach to overcome the negative side-effects of the low-emission UF adhesives is the addition of small amounts of PMDI in the UF binder, in the core layer of particleboards.

In meanwhile, the industry has invested much in the research of low free formaldehyde straight UF adhesives (Athanassiadou *et al.* 2015). New technologies of such UF adhesives have, in the recent years, come out in the European market by a number of manufacturers. Such adhesive systems, when used, result in boards with low formaldehyde emission, with the addition of special formaldehyde scavengers (Dunky 2003, Irle and Barbu 2010, Tsirogiannis 2011, Athanassiadou *et al.* 2015). After all, it appears that resin formulation changes to the direction of reducing the F:U ratio of the UF adhesives are at the maximum feasible level.

Hardeners

The hardeners (or catalysts) used in the manufacture of particleboard and MDF are mainly ammonium sulfate [$(NH_4)_2SO_4$] and ammonium nitrate (NH_4NO_3). Ammonium salts are used because they are cheap, convenient to handle, and give a high ratio of pot-life to setting time (Pizzi 1994, Dunky 1998). The use of ammonium chloride (NH_4Cl) has been banned for environmental reasons already, i.e. approximately 20 years ago. The hardeners react with the free formaldehyde in the resin, and liberate either sulfuric acid or nitric acid, which speeds up the polymerisation reaction by lowering the pH (Pizzi 1994). More than two decades ago, UF adhesives had F:U ratios between 1.10 and 1.25, and wood panels produced exhibited high levels of free formaldehyde, i.e. class E2 or E3 (EN ISO 12460-5). Though, since the trend today is to use UF with significantly lower free formaldehyde, this level is insufficient to produce a significant pH drop, in case that ammonium salts are employed as catalysts. Such problems can be overcome by using new hardeners, which incorporate special accelerating agents that will not rely on the available formaldehyde in order to generate acidity (Alexandropoulos *et al.* 1998). Therefore, their effectiveness will not be influenced by the free formaldehyde in the adhesive used. The development of such special catalysts has being carried out by some European resin manufacturers. Noticeably, some particleboard and MDF plants in Europe employ such special catalysts, like aluminium sulfate [$Al_2(SO_4)_3$], ammonium persulfate [$(NH_4)_2S_2O_8$], citric acid ($C_6H_8O_7$), mixtures thereof, or other combined hardener systems.

Formaldehyde scavengers

Formaldehyde scavengers, often called formaldehyde catchers, are chemical compounds added to the glue mix in order to decrease the formaldehyde emission from the finished wood panels. They are widely used today in the European particleboard and MDF industry. Mostly, aqueous solutions of urea (40% or 45% solids content) are applied. Additionally, agents like sodium metabisulfite ($Na_2S_2O_5$), ammonium bisulfite ($(NH_4)HSO_3$), or ammonium phosphates, are also applicable in the European panel industry (Costa *et al.* 2013). Formaldehyde scavengers are also added directly on the wood chips ahead of gluing. In some particleboard plants, urea is added as a solid material ahead of blending to keep moisture content of chips as low as possible (Roffael 2017).

In fact, there are truly many practical advantages in industrially applying a scavenger system. One advantage to note is the flexibility it provides to the manufacturing plant to vary its quantity, and subsequently, control the reduction of formaldehyde emission, according to the conditions and production requirements. However, the major advantage of a scavenger system is the fact that it provides a much more efficient system than that of a straight UF. The formaldehyde scavengers can be in most cases tailor-made to meet the needs of the particular plant. They are used up to a maximum 10–15% on the liquid resin, achieving thus reduction in emission up to 50% (Alexandropoulos *et al.* 1998). Experience in Europe has shown that instead of using a very low F:U ratio adhesive, a plant can achieve better results by using a system of an equivalent F:U ratio, which is a combination of a higher F:U ratio UF, and a formaldehyde scavenger (Athanassiadou and Ohlmeyer 2009, Tsirogiannis 2011).

Paraffin waxes

In the particleboard and MDF production, typically small quantities of paraffin waxes are incorporated in the adhesive mix to impart hydrophobic properties (i.e. lower thickness swelling) to the finished wood panels (Dunky 1998, 2003). Paraffin waxes are white or colourless soft solids derived from petroleum or coal. They consist of a mixture of hydrocarbon molecules containing between 20 and 40 carbon atoms. The diverse influence of paraffin waxes, usually added as wax emulsions, on the board properties is well known (Dix *et al.* 2003); this varies depending upon their chemical type, chain length, type of emulsifier and total amount added (Roffael *et al.* 2005).

In the European particleboard and MDF production, paraffin waxes are used today in the industry, in amounts below 0.5% (based on dry wood). In some cases, the wax content can be higher than 1%. However, in other cases, the wax content is even higher than 2% in order to decrease the thickness swelling, especially the edge swelling of the boards, e.g. flooring HDF and moisture-resistant panels (Roffael 2017).

Use of adhesives in particleboard production

Noticeably, in the European particleboard industry today, the main requirement of the UF adhesive system is speed, since the modern continuous presses run with high belt speed, meaning at low press factors, which can be in some European particleboard plants as low as 3 sec per mm (Grunwald 2017). This unit (s/mm) is commonly used in the industry, and is referred to the press time of a board per 1 mm thickness of the final panel. In addition, UF adhesives applied require different cooking procedures, or the addition of special additives (Tsirogiannis 2011, Athanassiadou *et al.* 2015). This is considered to be a major technical achievement in the field of formaldehyde-based adhesives.

Standard grade particleboard

It is estimated that, approximately >85% of all particleboard produced in Europe is of standard grade. The majority of this falls within a thickness of 16–19 mm. Straight UF adhesives of low F:U ratio (1.00–1.10) are used for this grade. The average gluing addition factor is in the range of 7–8%. The press times in modern press lines, typically vary between 3 and 5 s/mm. All particleboard products manufactured today in the EPF member countries belong strictly to E1 class according to EN 312, regarding the formaldehyde emission. They are used mostly for interior applications. Due to the CARB II emission standards (CPA 2013), which have been enforced in North America lately (2013), exported wood panels from Europe must comply with the new stricter law, regarding formaldehyde emission. Thus, UF adhesives of lower F:U ratio (0.98–1.02) containing a small amount of melamine (<2%), are mainly applied in the industry (Athanassiadou *et al.* 2015, Markessini 2017).

PMDI is also used in the European particleboard production. It is estimated (Grunwald 2017) that ca. 30 particleboard plants in Europe occasionally run the production with PMDI for niche products. A few particleboard plants employ UF systems, but they add PMDI as accelerator (0.3–0.5% on dry wood) in the core layer. Typical gluing factor for standard particleboard grades is roughly 1.5–2.5% using PMDI systems (Grunwald 2014, Stroobants and Grunwald 2014).

It is noted that very few particleboard plants occasionally utilise the steam injection technology, especially in the case of very thick boards (50–100 mm) to increase the production speed (Roffael 2017). However, in Europe, this technology today is of minor importance.

It is well known that PMDI can be used as an accelerator and a special crosslinker for UF adhesives (Dunky 2003). Usually 0.3–0.5% PMDI based on dry particles is used, whereas the UF gluing factor is not reduced. The press time in this case is reduced by 10–15%. Moreover, addition of PMDI to UF binders with a very low F:U ratio is used in some European particleboard plants to achieve extremely low formaldehyde emission (Dunky 2003, Stroobants and Grunwald 2014, Stroobants *et al.* 2016).

Moisture-resistant particleboard

An important grade in the European market is that of moisture-resistant particleboard. Typically, such particleboards bear a green colour, for distinction purposes. Strict requirements for moisture-resistant boards have been enforced, in accordance with the demanding end-user applications. Some years ago, the French/English originating 'V313' test and the German originating 'V100' test, were actually in force, similar, but not identical with the actual particleboard P5 type of 'Option 1' or 'Option 2'. The aforementioned tests today are the two valid European tests for moisture-resistant panels, and described further on in the text.

- 'Option 1' (cyclic test in humid conditions; EN 321); still, often called 'V313'. This accelerated ageing test requires the measurement of the internal bond of panel (IB), and the final panel thickness increase, after a cyclic test (3 cycles, each cycle consists of: (i) 70 h immersion in a 20°C water bath; (ii) 24 h placement in a freezing cabinet; and (iii) 70 h placement in a drying cabinet at 70°C).
- 'Option 2' (determination of moisture resistance – Boil test; EN 1087-1). This strict test requires measurement of the residual IB, after a specific boil test (i.e. 2 h immersion in a boiling-water bath).

'Option 1' and 'Option 2' tests are mostly used in Europe, for qualifying particleboard products in types P3 and P5 (see Table 4); even rarely in type P7 as well. In specific, for 'Option 1', moisture-resistant boards are qualified as that of type P3, P5 or P7, following compliance with the different requirements (EN 312), concerning the residual IB strength and the final board thickness increase after the cyclic test (EN 321). In addition, according to standard EN 312 (2010), the adhesive systems suitable for the production of particleboard of 'Option 1' or 'Option 2', are not restricted anymore. This practically means, that not only MUPF adhesives, as used in the past, but also MUF adhesives can be applied in the manufacture of moisture-resistant particleboard. Additionally, in very rare cases, when PF or PUF (phenol-urea-formaldehyde) adhesives are used, the alkali content of the final boards must not exceed 2.0%, based on the oven-dry mass (EN 312).

Moisture-resistant particleboard of 'Option 1' is, at present, the major special grade with volumes estimated to be around 4–5% of the total market (EPF 2017). Such boards are designed for use in humid conditions, i.e. bathroom and kitchen. Also, moulded particleboard panels, suitable for tables and windows, belong to this moisture-resistant grade. In general, this market has been developed in the recent years, mostly in Belgium, France, Italy, Spain and United Kingdom. Particleboard grade of 'Option 1' (former 'V313') is primarily produced with MUF adhesives, having a melamine content of approximately 15–20%. Such adhesive systems have molar ratios of around 1.07–1.10, thus yielding boards of E1 formaldehyde class (EN 312 with the usual perforator test method according to EN ISO 12460-5). The glue factor is in the range of 12–13%, based on dry wood. The press times, in this case, are significantly longer (i.e. 6–10 s/mm).

In addition, particleboard of 'Option 1' is also manufactured in Europe by a small number of particleboard plants, using PMDI binders (Grunwald 2017). Typical average PMDI addition level varies, in this production, between 2.5 and 3.5%.

The other moisture-resistant particleboard grade ('Option 2'), which is also used in extreme humid and load-bearing conditions is qualified according to EN 1087-1 (1995) test method. Technically, the boil-test requirements are stricter than those of the cyclic test. Option-2 grade represents one more special grade in Europe, although its market volumes are small (1–2% of the particleboard production). This market has been initially developed in Germany for applications in harsh wet environment and outdoor uses (Dunky 2003). Particleboard of 'Option 2' according to EN 312 is presently manufactured with MUF adhesives, which contain melamine at a percentage of around 18–23%, having a molar ratio $F/(NH_2)_2$ of 1.05–1.10. MUPF adhesives are only used nowadays if special certificates, from the past, request this adhesive type. The gluing addition level in such a production is ca. 13–14%. On the average, for particleboard production of 'Option 2', the press times in the European particleboard industry are around 8–10 s/mm.

In Germany, for this particular particleboard grade ('Option 2'), PF adhesives were used in the near past. However, they are now rather seldom applied, due to the required much longer press times as compared with the MUF adhesive systems. PF-bonded boards usually have almost negligible formaldehyde emission, although, this is dependent on the alkali content (Roffael 1982, Pizzi and Mittal 2003). As a matter of fact, in Europe today, no particleboard plant uses PF adhesives, on a regular basis, for particleboard production of 'Option 2' (Roffael 2017).

Fire-resistant particleboard

Fire-resistant particleboard is another special grade in Europe. Such boards are used in public buildings, where fire must be diminished to comply with fire safety regulations (Östman and Mikkola 2006). Although the production volume of this grade is relatively small (1–2%), a trend for further development of this market appears lately. The adhesives used for this grade are exclusively MUF adhesives, with a melamine content of 13–20%. Such adhesives have an F:U ratio of approximately 1.25–1.30, even that, resulting in panels of E1 formaldehyde class. The glue factor for this special product is 14–16%.

Fire retardants for particleboard are used in solid form, i.e. usually in granulates having a particle size between 200 and 600 µm. Halogen-free compounds such as zinc oxide (ZnO), zinc borate ($2ZnO{\cdot}3B_2O_3$), aluminium hydroxide ($Al(OH)_3$), aluminium trihydrate (AlH_6O_3), magnesium hydroxide ($Mg(OH)_2$), ammonium polyphosphate ($(NH_4PO_3)_n$, ammonium dihydrogen phosphate ($NH_4H_2PO_4$), diammonium phosphate ($(NH_4)_2HPO_4$), boric acid (H_3BO_3), sodium tetraborate ($Na_2B_4O_7{\cdot}10H_2O$), ammonium sulfate ($(NH_4)_2SO_4$), ammonium borate ($(NH_4)_3BO_3$), ammonium carbonate ($(NH_4)_2CO_3$), urea (CH_4N_2O), melamine ($C_3H_6N_6$), dimelamine phosphate ($C_3H_9N_6PO_4$), guanidine phosphate ($CH_8N_3PO_4$) or mixtures thereof are typically applied in the industry (Wiehn 1995, Mantanis 2002, Pizzi and Mittal 2003). These fire-retarding agents are mixed with the wood chips in the blending stage, at a percentage rate of 12–16%, on the dry/dry basis (Mantanis 2002, Markessini 2017). Much lower press speed, i.e. 20–30% slower, need to be applied in such a production.

PMDI-bonded particleboard

Particleboard of E1 class using isocyanate adhesives is also produced in Europe. This production process was introduced some decades ago and has a few disadvantages, e.g. sticking to the press belt, low tack of the mat and very high cost. Today, there are a couple of plants in Europe producing regularly this type of board. PMDI adhesives can also be used in combination with UF adhesives (Grunwald 2017). In such cases, UF adhesives are being used particularly in the surface layer, in order to avoid press-sticking problems, whereas, the UF adhesive, in the core layer, is accelerated for curing by small amounts of PMDI.

Boards produced with PMDI in core and surface layers 'suffer' from the high cost of PMDI, especially in recent times, when the PMDI price is more than doubled compared to the status-quo less than two years ago. Although smaller quantities of PMDI are used, such boards are more expensive than standard UF-bonded boards, and need longer press times. This market is very limited, certainly less than 1%. The main feature of such pure PMDI-bonded boards is the absence of formaldehyde; thus, named as 'no-added formaldehyde' (NAF) boards. For that reason, direct comparison with class E1, or CARB II particleboards, is difficult.

In addition, in the production of 'Option 1' or 'Option 2' particleboard, PMDI in the core layer, in combination with PF or MUF adhesives in the surface layer, are also used by a few plants, or full PMDI-bonded particleboards are manufactured (Stroobants *et al.* 2016, Grunwald 2017).

Light particleboard

In the very recent years, a new grade named 'light- and ultra-light' particleboard, belonging to the type P2 (boards for interior fitments, including furniture, for use in dry conditions), has appeared in the European particleboard market. Such niche lightweight panels, under the commercial names Kaurit® light, CoLight, Balanceboard, BoBoard and SuperPan, have a density of less than 500 kg/m^3, containing special polymers and binding agents (Barbu 2015).

Use of adhesives in MDF production

The adhesives used in the European MDF industry are mostly UF, often as melamine-fortified UF (1–4% of melamine), so-called mUF adhesives. NAF or zero-added formaldehyde MDF, bonded exclusively with PMDI, comprises a very small market in Europe (<1%).

It is estimated that approximately 50% of all MDF produced is of standard grade (EPF 2017), with the majority being in the 16–19 mm thickness class. UF and mUF (1–4% melamine) adhesives of low F:U ratio (0.95–1.00) are used for the standard grade, with resin addition levels of 8–10%. The press times in modern continuous MDF lines vary between 9 and 11 s/mm.

Moisture-resistant MDF

Moisture-resistant MDF is the dominant special grade in Europe, with volumes estimated at 41% of the total production (EPF 2017). Markedly, this percentage includes also flooring HDF, which has moisture-resistant properties. This grade in Europe has increased dramatically over the last fifteen years. Moisture-resistant MDF is a product designed for use in humid conditions. It is successfully used for kitchen furniture, bathrooms, windows etc., and is produced with MUF or PMDI adhesives. Thus, moisture-resistant MDF, known as 'MDF.H Option 1' or 'Option 2' (Table 6), is produced, for the most part, with MUF which contains melamine at a percentage of 12–15%. Typical press times are around 9–11 s/mm. In fact, the continued growth of moisture-resistant MDF makes it a suitable substitute for conventional products in joinery applications and elsewhere.

PMDI is employed by few European MDF manufacturers for the production of moisture-resistant MDF 'Option 1' in gluing addition levels of 3–4%. For these special grades, PMDI can be more competitive to MUF adhesives, on a cost and performance basis (Grunwald 2017).

Flooring (HDF)

HDF (density >780 kg/m^3) known as HDF, represents almost 30% of the fibreboard production volume in Europe. HDF itself represents approximately 80% of the total laminate flooring market in Europe (EPF 2017). Laminate flooring HDF has achieved spectacular growth over the past few years. This special MDF grade, with high density, has been successfully used as a substrate for a wide variety of overlay materials such as veneers, high pressure laminates and melamine impregnated papers (Barbu 2015).

Dry-process fibreboard of this grade (flooring HDF; thickness range 5–12 mm), is preferably produced with melamine-fortified UF adhesives having extremely low molar ratio (0.88–0.92), and 6–8% content of melamine, as in the liquid resin. For this grade, thickness swelling of the raw board and edge swelling of the final flooring element are the main strict requirements. Press times in the European industry diverge between 10 and 12 s/mm.

In central Europe, a few MDF manufacturing plants produce flooring HDF of 'Option 2' (called once 'V100 flooring') by using emulsifiable types of special PMDI adhesives at high adhesive addition, approximately 5–6% (Grunwald 2017).

MDF from acetylated fibres

This MDF grade is new in the European market. It refers to the manufacture of an innovative MDF panel, commercially named as Tricoya®, which comprises of wood fibres produced by the acetylation process (Rowell 2014, Mantanis 2017). A proprietary PMDI adhesive system is utilised, in adhesive addition levels of 6–8%. Thus, acetylated fibres are glued to yield exterior-grade MDF products, which are suitable for highly demanding outdoor uses, like cladding and siding, fascia and soffit panels, window components, door skins and other exterior furniture and structures (Clifton 2017).

Fire-resistant MDF

Another special grade is that of fire- or flame-resistant MDF (FR-MDF). Such a product is used in public buildings, where fire spread must be controlled to satisfy the fire safety regulations (Östman and Mikkola 2006). Although this grade is relatively small (in volume <3%), there has been recently a trend for further growth, due to enforced regulations in construction, in some European countries. High addition levels (15–20% on dry/dry basis) of fire-retarding compounds such as phosphates, borates, sulfates are applied to the fibres, in the refiner blowline, before the resination (Mantanis 2002). Typically, these FR additives are formulated in aqueous solutions (40–60% content of solids).

Monoammonium and diammonium phosphate, as well boric acid and borax, comprise the most frequent fire-retarding additives in MDF industry (Wiehn 1995, Mantanis 2002). However, upcoming changes in the European regulations may lead soon to the prohibition of boric acid from such wood applications. In general, the fire retardants used are non-corrosive agents and halogen-free, since bromine- and chlorine-containing compounds have been prohibited in Europe from such industrial applications according to REACH (EC 2006). Fire-resistant MDF is produced in Europe by exclusively using MUF adhesives (15–18% melamine content) having molar ratios of 1.20–1.25 (Markessini 2017). The glue factor in such a production is higher than 14% (on the dry/dry basis).

Today in Europe, the single burning item (SBI) test is applied as the harmonised European standard method for FR-treated particleboard and MDF (EN 13823 2002). Actually, all construction products sold in Europe are classified using the said test method for determining the reaction to fire behaviour of building products (excluding floorings), when exposed to the thermal attack by a SBI, e.g. a sand-box burner supplied with propane (EN 13501-1). As a consequence, most of the old barriers, i.e. no common FR test equipment, difficulty to compare fire-test results of wood products, lack of harmonisation in the standards, have been removed (Tsantaridis 2017).

CARB II MDF

CARB II boards (thickness range 16–19 mm) are produced with UF adhesives, with F:U ratios of 0.92–0.96. This represents a small portion (approximately 10%) of the total production volume in Europe, while E1-class boards being the major category. The gluing factor in the production of CARB II MDF is approximately 9–12%, while the press time is at around 6–8 s/mm in modern mills.

MUF adhesives are also used in about 10% of the total production volume. The F:U ratio of MUF used varies between 0.92 and 0.96 having a melamine content of 12–15%. The glue loading varies at around 12–14%, and the press time is approximately 9–11 s/mm.

PMDI is used also to produce such special grades, in about 5% of the total production volumes. Though more expensive, this MDF grade is marketed as 'formaldehyde-free' or NAF. The glue loading can be approximately 4–5%, and the press times are at around 10–12 s/mm.

Other grades

Thin HDF (i.e. thickness 3–6 mm, and ultra-thin <3 mm), called thin HDF, is produced with UF of a molar ratio of 0.86–0.90. On the other hand, low-density fibreboard (density 180–400 kg/m^3), labelled as low-density MDF ('L-MDF') or ultra-low-density MDF ('UL-MDF'), represents a small portion of the total MDF production in Europe (<5%), and is used mostly for insulation applications (Barbu 2015).

Adhesive systems used in OSB production

As mentioned, PMDI is the primary adhesive system used in OSB production in Europe (Grunwald 2014, Stroobants and Grunwald 2014), contrary to the status-quo of OSB production in North America, where still PF adhesives are used in bigger share. PMDI is actually a mixture of monomeric diphenylmethane di-isocyanate and methylene-bridged oligo-aromatic isocyanates (Lay and Cranley 2003). Usually no hardeners are added during the industrial production of OSB (Dunky 2003). Mostly, it is necessary to use special emulsifiers (EMDI) for better distribution of the adhesive. With special additives (e.g. polyols), a distinct acceleration of the hardening reaction and hence, shorter press times can be achieved. This happens especially in the particleboard and OSB production. To note, chemical compounds such as triethanol amine, triethylamine, N,N,-dimethyl-cyclohexylamine can be applicable in OSB production in order to enhance the curing of PMDI binder (Lay and Cranley 2003).

In the European production lines, almost all of the OSB plants use PMDI at different addition levels, especially in the core layer. Type OSB/2 production requires usually 1.5–2.5% adhesive addition (on the dry wood basis), while the upgraded OSB types require even higher addition levels, i.e. OSB/3 (2.5–3.5%) and OSB/4 (4–5%). Special flooring products made from OSB require PMDI addition factors >5% (Grunwald 2017).

In OSB, PMDI adhesives dominate the European market (i.e. 75% of the total), while the aminoplastic adhesives such as UF

(10%) and MUF (15%) occupy much smaller proportions in general (Kutnar and Burnard 2014).

Formaldehyde emission from wood-based panels: status-quo in Europe

Several decades ago, formaldehyde emission was a problem for the industry of wood-based panels, principally for particleboard and MDF. New regulations that were enforced in the European level, especially in the member countries of EPF, have changed the situation completely (EPF 2017).

One of the first drastic actions taken to reduce emission of formaldehyde was to standardise the emission levels. Acceptable levels of formaldehyde emission have being continuously reduced in Europe over the last three decades. In nowadays, the corresponding highest permitted limit for particleboard, MDF and OSB stands at 8 mg/100 g board (E1 class), measured according to EN ISO 12460-5, with preferred half-year gliding average at 6.5 mg. All the industrial manufacturers in the EPF member states are obliged to manufacture wood panels strictly of E1 class. Such products are very safe and of high quality, both for the customers and the end-users (Kutnar and Burnard 2014, Athanassiadou *et al.* 2015, Hill *et al.* 2015).

At present, there is no problem whatsoever with the formaldehyde emissions in the European markets. Moreover, stricter regulations concerning formaldehyde have been in force according to California Air Resources Board (CARB), named as CARB I, in order to reduce formaldehyde emissions from composite wood products that are manufactured, imported, distributed, sold and fabricated in the State of California, USA. These regulations affected the European industry to some extent, since the industry as exporters to N. America markets had to comply with these rules. In fact, this regulation set ceiling limits for the emission of formaldehyde (CARB I) from wood panels have gone into effect by 1 January 2009. This specifies the use of a large chamber test method (ASTM E1333), as the reference scheme for demonstrating compliance. Furthermore, newer stricter measures for formaldehyde emissions, known as CARB II, have recently been in force in the USA, starting 1 January 2013.

According to the specialists, in conformity with ASTM E E1333-14 (2014), CARB II limits are as follows (CPA 2013): (i) 0.09 ppm formaldehyde emission for particleboard (i.e. this corresponds to a value of 2–4 mg/100 g compared with the Perforator method); (ii) 0.11 ppm formaldehyde emission for MDF; (iii) 0.13 ppm formaldehyde emission for thin MDF/HDF (maximum thickness of 8 mm). Such regulations have brought formaldehyde emissions 10 to 20 times lower, than the allowable levels existed 30 years ago, thus solving the problem for the time being.

However, based on the re-classification of formaldehyde as carcinogenic substance (EU 2014), i.e. carcinogenic (category 1B) and mutagenic (category 2), new debates have started a few years ago, and might end up in even lower limits, regarding the subsequent formaldehyde emissions of wood-based panels.

Conclusions

The main conclusions drawn from this review work are summarised as follows:

- Review of the adhesive systems applied today in the European industry of wood-based panels (particleboard – MDF – OSB) has shown that many developments have been taken place in the recent years. Most of the technological changes concerning the adhesives and additives used have been realised either from the need for new value-added special products, the necessity to achieve extremely low formaldehyde emission levels, or to lower the production costs due to the harsh competition in the market.
- The European industry of wood-based panels is growing steadily in the Eastern part of Europe, within an existing installed overcapacity in the Central part, and newly developed adhesive systems have influenced the European market as a whole, in a positive way.
- Several niche grades of particleboard, HDF and MDF like insulation, moisture-resistant, fire-resistant and other, have been developed in Europe by the use of new advanced adhesive systems.
- European OSB industry is growing very fast. In the recent years, many investments have been taken place, while the industry is concentrated over the use of PMDI systems, which dominate the European OSB industry.
- Last but not least, the European industry of particleboard and MDF, by employing new advanced formaldehyde-based adhesives (UF, MUF), thanks also to the coordinating efforts of EPF, has handled well the chronic issue of formaldehyde emissions in the European countries by applying very strict regulations (i.e. class E1, CARB II). Nevertheless, new and even lower limits are presently in discussion, triggered by the re-classification of formaldehyde as a carcinogenic substance.

Acknowledgements

The authors highly acknowledge the subject experts, namely, Mr Charles Markessini, Mr Panagiotis Nakos, Mr. Paschalis Tsirogiannis, Mrs Electra Papadopoulou of Chimar Hellas SA (Greece), Dr Dirk Grunwald (Huntsman Polyurethanes), Prof. Em. Edmone Roffael (Univ. of Göttingen, Germany), Prof. Mark Irle (Ecole Supérieure du Bois - Nantes, France), Assoc. Prof. Andreja Kutnar (Univ. of Primorska, Slovenia), Dr Lazaros Tsantaridis (RISE, Sweden), Prof. Dick Sandberg (Luleå University of Technology, Sweden), Prof. Pavlo Bekhta (Ukrainian National Forestry University, Ukraine) and Mr Peter Clifton (Medite Tricoya, UK) for the valuable technical feedback provided in this work.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Alexandropoulos, D., Nakos, P. and Mantanis, G. (1998) European approach to particleboard and MDF adhesives. In 1998 *Resin and Blending Seminar Proceedings*, Composite Panel Association (CPA), 10–11 December 1998, Charlotte, N. Carolina, USA, pp. 133–141.

ASTM E1333-14. (2014) *Standard test method for determining formaldehyde concentrations in air and emission rates from wood products using a large chamber*, Annual Book of ASTM International, West Conshohocken, PA, USA.

Athanassiadou, E. and Ohlmeyer, M. (2009) Emissions of formaldehyde and VOC from wood-based panels. In M. Fan, M. Ohlmeyer, M. Irle, W. Haelvoet, E. Athanassiadou, and I. Rochester (eds.) *Performance in Use and New Products of Wood Based Composites* (London: Brunel University Press (supported by COST Office)), pp. 219–240.

Athanassiadou, E., Markessini, C. and Tsiantzi, S. (2010) Producing panels with formaldehyde emission at wood level. In *Proceedings of the 7th European Wood-Based Panel Symposium*, 13–15 October 2010, European Panel Federation and Wilhelm Klauditz Institute, Hannover, Germany, pp. 110–117.

Athanassiadou, E., Markessini, C. and Tsiantzi, S. (2015) Industrial amino adhesives satisfying stringent formaldehyde limits. In 2015 *Melamine Conference*, 15–16 November 2015, Dubai, available at: http://www.chimarhellas.com/wp-content/uploads/2016/03/CHIMAR-HELLAS-DUBAI.pdf

Barbu, M. C. (2015) An overview of the forestry and wood industry development worldwide. In *Proceeding of the 26th International Conference on Wood Science and Technology*, 16 Oct. 2015, Zagreb, Croatia, pp. 29–38.

Bekhta, P. (2017) Ukrainian National Forestry University, Ukraine (personal communication).

Clifton, P. (2017) Coillte Panel Products, Medite Tricoya, UK (personal communication).

Composite Panel Association – CPA. (2013) California passes tough limits on formaldehyde emissions from composite wood panels. *Second Wave Magazine*, 20, 1–2.

Costa, N. A., Pereira, J., Ferra, J., Cruz, P., Martins, J., Magalhães, F. D., Mendes, A. and Carvalho, L. H. (2013) Scavengers for achieving zero formaldehyde emission of wood-based panels. *Wood Science and Technology*, 47, 1261–1272.

Dix, B., Roffael, E. and Schneider, T. (2003) Parafinne unterschiedlicher Kettenlänge als Hydro-phobierungsmittel in Mitteldichten Faserplatten (MDF). *Holz als Roh- und Werkstoff*, 61(6), 469–470.

Dunky, M. (1995) Formaldehyde based glue resins: European state of the art in the 1990s. In *Proceedings of the Wood Adhesives* 1995, 29–30 June 1995, Portland, Oregon, USA, pp. 77–80.

Dunky, M. (1998) Urea–formaldehyde (UF) adhesive resins for wood. *International Journal of Adhesion and Adhesives*, 18, 95–107.

Dunky, M., Pizzi, A. and Leemput, M.V. (2000) *Wood Adhesion and Glued Products, Vol. 1: Wood Adhesives*. State of the Art-Report, COST Action E13 Wood Adhesion and Glued Products, pp. 1–158, available at: http://users.teilar.gr/~mantanis/E13-Wood-Adhesion.pdf

Dunky, M. and Niemz, P. (2002) *Wood Based Panels and Adhesive Resins: Technology and Influential Parameters* (in German; Holzwerkstoffe und Leime: Technologie und Einflußfaktoren) (Heidelberg: Springer), pp. 1–986.

Dunky, M. (2003) Adhesives in the wood industry. Chapter 47 In A. Pizzi, K. L. Mittal (eds.) *Handbook of Adhesive Technology* (New York: Marcel Dekker), pp. 872–941.

EN 300. (2006) Oriented Strand Boards (OSB) – Definitions, Classification and Specifications. European Committee for Standardisation, Brussels.

EN 312. (2010) Particleboards – Specifications. European Committee for Standardisation, Brussels.

EN 321. (2002) Wood-based panels – Determination of moisture resistance under cyclic test conditions. European Committee for Standardisation, Brussels.

EN 622-5. (2006) Fibreboards – Specifications. European Committee for Standardisation, Brussels.

EN 1087-1. (1995) Particleboards – Determination of moisture resistance – Boil tests. European Committee for Standardisation, Brussels.

EN ISO 12460-5. (2015) Wood-based panels – Determination of formaldehyde release – Part 5. Extraction method (called the perforator method). European Committee for Standardisation, Brussels.

EN 13501-1. (2009) Fire classification of construction products and building elements - Part 1: Classification using test data from reaction to fire tests. European Committee for Standardisation, Brussels.

EN 13823. (2002) Single burning item (SBI) – Fire technical testing of building products. European Committee for Standardisation, Brussels.

European Commission – EC. (2006) REACH – Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals, available at: https://ec.europa.eu/growth/sectors/chemicals/reach_en

European Panel Federation. (2016) *EPF Annual Report 2015*–2016. European Federation of Manufacturers of particleboard, MDF and OSB, Brussels, pp. 1–270.

European Panel Federation. (2017) *EPF Annual Report 2016*–2017. European Federation of Manufacturers of particleboard, MDF and OSB, Brussels, pp. 1–280.

European Union – EU. (2014) *Reclassification of formaldehyde*. Commission Regulation (EU) No. 605/2014, 5 June 2014, Brussels, Belgium, pp. 1–14.

FAO - Food and Agriculture Organization of the United Nations. (2017) FAO database. Statistics data retrieved on 04/09/2017 from the website, available at: http://www.fao.org/faostat/en/#data

Grunwald, D. (2014) Adhesives for wood-based boards. Presented in *1st Euro-Asian International Short-Course on Wood-based Composites*, 15 April 2014, Karadeniz Technical University, Trabzon, Turkey. Accessed in: https://www.researchgate.net/profile/Dirk_Grunwald2

Grunwald, D. (2017) Huntsman Polyurethanes, Belgium (personal communication).

Guerin, J. (1998). The development of specialty products and markets within the European MF industry. In *Proceedings of 2nd European Panel Products Symposium*, 10–12 September 1998, Hannover, pp. 168–179.

Hemmilä, V., Adamopoulos, S., Karlsson, O. and Kumar, A. (2017) Development of sustainable bio-adhesives for engineered wood panels – A review. *RSC Advances*, 7, 38604–38630.

Hill, C. A. S., Norton, A. and Kutnar, A. (2015) Environmental impacts of wood composites and legislative obligations. In M. Ansell (ed.) *Wood Composites* (Cambridge: Woodhead Publishing, Elsevier), pp. 311–333.

Irle, M. and Barbu, M. C. (2010) Wood-based panels technology. In H. Thoemen, M. Irle, M. Šernek (eds.) *Wood-Based Panels: An Introduction for Specialists* (Brunel University Press), available at: http://www.cost.eu/media/publications/10-35-Wood-Based-Panels-An-Introduction-for-Specialists

Kutnar, A. and Burnard, M. D. (2014) The past, present and future of EU wood adhesive research and market. In *Proc. of the International Conference on Wood Adhesives* 2014, 9–11 October 2014, Toronto, Canada, available at: http://www.forestprod.org/ckfinder/userfiles/files/akutnar_08102013.pdf

Lay, D. G. and Cranley, P. (2003) Polyurethane adhesives. In A. Pizzi and K. L. Mittal (eds.) *Handbook of Adhesive Technology* (New York: Marcel Decker), pp. 695–718.

Mantanis, G. and Markessini, E. (1998) Formaldehyde emission from wood-based panels: Current status. *Wood & Furniture*, 169, 63–69 (in Greek).

Mantanis, G. (2002) Aqueous fire retardant. *International Patent WO 02/102926 A1*, World Intellectual Property Organisation, Geneva, pp. 1–13.

Mantanis, G. (2017) Chemical modification of wood by acetylation or furfurylation – A review of the present scaled-up technologies. *BioResources*, 12(2), 483–488.

Markessini, A. C. (1993) Formaldehyde emission: A novel approach – Standards and limitations in Europe. In *Proc. of the 27th W.S.U. Int. Part./Comp. Mat. Symp*. Pullman, Washington, USA, pp. 207–219.

Markessini, C. (2017) Chimar Hellas SA, Greece (personal communication).

Nakos, P., Achelonoudis, C., Papadopoulou, E., Athanassiadou, E. and Karagiannidis, E. (2016) Environmentally-friendly adhesives for wood products used in construction applications. In *Proc. of WCTE 2016 - World Conference on Timber Engineering*, 22–25 Aug. 2016, Vienna, pp. 32–38.

Östman, B. and Mikkola, E. (2006) European classes for the reaction to fire performance of wood products. *Holz als Roh- und Werkstoff*, 64(4), 327–337.

Pizzi, A. (1994) *Advanced Wood Adhesives Technology* (New York: Marcel Dekker).

Pizzi, A. and Mittal K. L. (2003) *Handbook of Adhesive Technology* (New York: Marcel Dekker).

Pizzi, A. (2006) Recent developments in eco-efficient bio-based adhesives for wood bonding: Opportu-nities and issues. *Journal of Adhesion Science and Technology*, 20(8), 829–846.

Papadopoulou, E. (2017) Chimar Hellas SA, Greece (personal communication).

Roffael, E. (1982) *Die Formaldehydabgabe von Spanplatten und anderen Werkstoffen* (in German), DRW-Verlag, Berlin, Germany, pp. 123.

Roffael, E., Dix, B. and Okum, J. (2000) Use of spruce tannin as a binder in particleboards and medium density fibreboards (MDF). *Holz als Roh- und Werkstoff*, 58(5), 301–305.

Roffael, E., Schneider, T., Dix, B. and Buchholz, T. (2005) On paraffin sizing of medium density fiberboards (MDF). Part 1. Influence of the chemical composition of paraffin and type of emulsifier on the hydrophobic properties of MDF. *Holz als Roh- und Werkstoff*, 63(3), 192–203.

Roffael, E. (2006) Volatile organic compounds and formaldehyde in nature, wood and wood-based panels. *Holz als Roh- und Werkstoff*, 64(2), 144–149.

Roffael, E. (2017) University of Göttingen, Germany (personal communication).

Rowell, R. M. (2014) Acetylation of wood - A review. *International Journal of Lignocellulosic Products* 1(1), 1–27.

Sandberg, D. (2016) Additives in wood products – Today and future developments. In *Environmental footprints and eco-design of products and processes*. Springer Science, available at: https://www.diva-portal.org/smash/get/diva2:993130/FULLTEXT01.pdf

Stroobants, J. and Grunwald, D. (2014) Wood based panels with enhanced properties: What is possible with MDI today? Oral presentation, In *9th European Wood based Panels Symposium*, 10 October 2014, Hannover, Germany, available at: https://www.researchgate.net/publication/280250674

Stroobants, J., Singulé, B. and Grunwald, D. (2016) Non added formaldehyde adhesives based on MDI. *Internal report*, Huntsman Polyurethanes, Everberg, Belgium.

Tsantaridis, L. (2017) RISE - Research Institutes of Sweden (personal communication).

Tsirogiannis, P. (2011) Producing panels with formaldehyde emission at wood level. In *Proc. of the 1st World Formaldehyde* 2011, 8 December 2011, Grand Millennium Hotel, Kuala Lumpur, Malaysia, available at http://www.chimarhellas.com/wp-content/uploads/2011/12/presentation-WF2011.pdf

United Nations Economic Commission for Europe – UNECE. (2017) *Forestry and Timber*. Statistics data retrieved on 10/09/2017 from the website, available at: http://www.unece.org/forests/welcome.html

Wiehn, H. (1995) Method of manufacturing fire-resistant foam and wood particle boards or shaped bodies. *US Patent 5,418,282*. United States Patent and Trademark Office, USA, pp. 1–5.

Wolf, F. (1997) Wood-based panels produced with amino resins with formaldehyde release ‘like natural wood’. In *Proc. of 1st European Panel Prod. Symposium*, pp. 243–249.

Wood Based Panels International. (2017a) *Global MDF producing industry*. June/July 2017, pp. 16–21.

Wood Based Panels International. (2017b) *OSB is good for the future*. April/May 2017, pp. 38–42.

Vnučec, D., Kutnar, A. and Gorŝek, A. (2017) Soy-based adhesives for wood-bonding: a review. *Journal of Adhesion Science and Technology*, 31(8), 910–931.