

# ANALYSING AND CONCLUDING THE COST/PERFORMANCE MATRIX FOR BIOPOLYMER BLENDS WITH DIFFERENT RENEWABLE CONTENTS

Lund University, Department of Chemistry, Centre for Analysis and  
Synthesis

Authors: Linda Ehrenberg & Filip Nilsson  
Supervisors: Puneet Trehan, Baozhong Zhang  
Examiner: Patric Jannasch  
2018-06-18

---

## Abstract

Due to increasing awareness and consumer demands it has become important for companies to develop an economical and environmentally sustainable alternative to traditional petroleum-based plastics. The transition from fossil material to bio based is important for the future of people and planet, still, how the transformation should be implemented is yet unknown. In this report, the possibilities of developing a polymer blend between PP and the biopolymers PLA, PBS and PHA are investigated for commercial application in IKEA plastic products. The value chain, from feedstock to polymer is covered to give the reader a holistic understanding of the challenges and opportunities for biopolymer blends in plastic applications. Cost is introduced as a crucial parameter to increase the relevancy of the material from a commercial point of view, in addition to technical aspects. The mechanical and thermal properties of the bio/fossil blends is examined in a joint venture between IKEA and Fraunhofer ICT. The report also covers a deeper explanation of PHA materials and a cost/capacity evaluation for this polymer. After the material properties of the blend material is examined, an extensive discussion about the application and recyclability follows. Blends between PP and PHA modified with additives were made and tested in relation to IKEA specifications as cost was considered. The blends show promising properties but should be further optimized to be implemented in IKEA products.

## Scope

- Exploring the possibilities to create a polymer blend between PP, PLA, PHA and PBS.
- Evaluation of the mechanical and thermal properties of the blend material.
- Developing a blend with a minimum bio content of 20%.
- Create a blend with an estimated price below, or close to 2 000 €/ton.
- Consider the processability of the blends with the aim to injection mould the IKEA products “Mammut” and “Trofast”.
- Creating a Cost/Performance matrix where the cost and performance of the blends are weighed against each other.
- Investigation of different compatibilizers and fillers to improve properties and/or price.

## Out of scope

- First generation feedstock impact on food industry – Food v/s Feed aspect of sustainability impact assessment
- Biodegradability, since most IKEA applications are long service life applications like furniture, storage boxes etc.
- Evaluation of polyesters like PET, PEF, PTT, PBT etc. since these polyesters need a rather different approach for downstream applications like fibres and yarns.
- Evaluation of polyurethanes for the same reason as for the polyesters.
- Evaluation of drop-in solutions e.g. cracking of bio-diesel leading to different base chemicals like ethylene and propylene which can further be polymerized to plastics which are same in chemical structure like fossil based BUT with renewable C14 carbon instead.

## Table of content

Scope.....	2
Out of scope.....	2
Preface .....	5
Introduction.....	6
Background .....	8
Size of industry .....	8
Feedstock .....	10
Conversion technology.....	11
Polymerization and compounding.....	11
Applications.....	16
New material solutions .....	17
Drop-In.....	17
Novel.....	17
Blends.....	18
Project: “Blends” .....	20
PLA.....	23
PBS .....	23
PHA.....	24
Blends 1.0.....	25
Blends 1.5.....	26
Blends 2.0.....	27
Method.....	28
Price estimations.....	28
Compounding, extrusion, and injection moulding of test bars.....	30
Testing parameters .....	32
Cost/Performance matrix layout.....	32
Results.....	34
Discussion .....	40
Project discussion .....	40
Recyclability .....	42
General discussion .....	43
Conclusions.....	45
References .....	47
Appendices.....	50

Appendix A.....	50
Results and price.....	50
Appendix B.....	51
Extrusion parameters .....	51
Appendix C .....	52
Testing parameters.....	52
Appendix D .....	53
Price calculations .....	53
Appendix E.....	54
Injection moulding parameters .....	54

## Preface

This report was written in the spring of 2018 and serves as a master thesis for M.Sc. degree in chemical engineering. Together with IKEA of Sweden and Lund University we worked with a development project, and for this we spent most of our time in the “New Business and Innovation department” (NB&I) at IKEA (Älmhult). IKEA recognizes the fact that sustainability and circularity are important for the future of people and planet, therefore they are making big efforts to replace fossil materials with bio-based alternatives. This thesis was created to help IKEA understand the different aspects of replacing fossil-based material with a more sustainable alternative, and at the same time give us an insight in the company organization and prepare us for future challenges.

Firstly, we would like to thank IKEA and the whole “Polymer team” working in IKEA, you made our time together fun and made us feel like colleagues! Hopefully we spread some joy at the office. A special thanks to Puneet Trehan, for supervising us at IKEA and mentoring us throughout this time. We sure learned a lot and could not have done this without you. Also, thank you Maria, Jan and Johan for working with us in the project.

Lastly, thanks to Lund University and Baozhong Zhang for supervising us.

## Introduction

As we move towards the next decade we continue to consume the fossil reserve. This exploitation is affecting the climate, with a global rise of temperature and melting of the polar ice as examples of the commonly debated problems. Together with the knowledge of a growing population, it becomes obvious that sustainability and renewability becomes key, if we are to improve everyday life for the many people. To move in a direction where sustainability is achieved will require effort from multiple actors due to the complex nature of replacing fossil-based materials with renewables. An issue with the oil and gas industry is the price volatility. This could be explained with facts such as “energy security” concerns of countries, and unstable regions who dictates the market. In turn, this partly explains the oligopolistic character of the petrochemical industry. The resistance of changing today's fossil feedstocks and inability to act towards further use of biomass prevents the progress of developing Bio Based Materials and Chemicals (BBMC). The polymer industry has seen little progress in the commercialization of new polymers in recent times. This could be explained by the lack of driving force from larger industries which are highly invested in the existing polymers and technologies. Extraction of shale gas could prove to further slowdown the development of BBMC [1]. Shale gas is also troublesome from a sustainable point of view, where processes as flaring of methane is highly contributing to the carbon footprint. This extraction is a short-term fix and not the solution to the problem.

Consumers and producers are becoming increasingly aware of the importance of environmental and economic sustainability. The external pressure from governments and non-government organizations (NGO's) also affects the debate. Some statements from large companies which are more progressive and are addressing the problems related to climate change are seen below.

- BRASKEM - *“Goal 2020: To be among the leading producers of chemicals and thermoplastic resins from renewable raw materials. And remain the world's largest producer of thermoplastic resins from renewable sources.”* [2]
- Bayer - *“We are increasingly working on the use of renewable raw materials - and also carbon dioxide - as feedstocks for polymers.”* [3], and *“Sustainability is a core element of our strategy and we are committed to strengthen the positive impact of our business to society.”* [4]
- Mitsubishi chemical - *“We are cultivating sustainable resources, centred on polymers made from biomass resources, contributing to the environment and carbon sustainability.”* [5]
- Coca-Cola - *“Our goal is to reduce the carbon footprint of the Coca-Cola drink in your hand by 25% by 2020. We are working to responsibly manage our manufacturing emissions and improve our energy efficiency per litre of product*

*produced. We are also driving collaboration throughout our supply chain in an effort to reduce emissions associated with getting our products in the hands of consumers- from growing our ingredients, producing our packaging, and distributing and refrigerating our products.” [6]*

- *Danone -”We strive to be a game-changer to foster positive solutions for the planet. We commit to sustainable sourcing for all our ingredients and to enhance the circular economy of packaging. We will protect soil health through regenerative agricultural practices co-developed with partners and we will even amplify our ambitious water stewardship journey. We play our part in the fight against climate change by implementing carbon positive solutions and aiming to achieve carbon neutrality by 2050.” [7]*
- *Nestlé -”Packaging is crucial for protecting foods and beverages, preventing food waste, and providing important information for individuals and families. We work to optimise our packaging to minimise resource use; use more materials from sustainably managed renewable resources; support initiatives to recycle or recover energy from used packaging; and use recycled materials wherever there is a clear environmental benefit and it is appropriate. Nestlé’s ambition is that 100% of our packaging is recyclable or reusable by 2025.” [8]*
- *IKEA -”We need to transform our business. To be able to fulfil future customer needs, promote equality and secure sustainable access to resources, while driving down emissions and maintaining our low prices, we need to do things differently. It’s no longer possible to use 20th century approaches to meet 21st century demands. Simply working towards being less bad will not get us where we need to be - we need transformational change - which means challenging old ways and embracing the new, being bold, innovative and committed to taking action. It means taking many steps, both large and small, that, together, will have transformational impact.” [9]*

Even with this increasing interest of many brands and companies to use renewable feedstocks for future products, some major challenges remain unsolved. There is a need for affordable renewable feedstocks to produce polymers. The feedstocks stand for 50%-60% of the cost for the final polymer. As the volumes of BBMC is expected to rise so will the feedstock volumes. This might lead to a conflict of interests in whether to produce biomaterials or bio-fuels, an example of such a conflict is bio-based ethanol and bio-based polyethylene (PE). Today the BBMC is struggling in terms of cost, and they are an insignificant share of the market where petrochemicals hold the major share. As scaling of BBMC industries will bring economies of scale, there is an opportunity for them to further compete with petrochemicals.

Compared to the petrochemical industry where the catalysts often are inorganic compounds and the yields are high, for BBMC, microorganisms (biocatalysts) is primarily used to convert biomass into chemicals. These yields are seldom as high. In



recent years there has been a lot of development on the microorganisms and BBMC value chain. Continued development, which happens at a fast pace will lower the prices of BBMC further. The production of BBMC is interesting because it needs lower volumes to reach economies of scale, e.g. a typical polypropylene (PP) plant would have a capacity of 600 000 t/a and for polyethylene terephthalate (PET) it could be as high as 1 000 000 t/a. The most well-developed plant for biopolymers produces polylactic acid (PLA) and has a capacity of 150 000 t/a [10].

Historically, IKEA has been striving towards being an environmentally conscious company, with focus always on the customers. In recent years, this conviction on sustainability has grown even stronger and IKEA has taken a strong position when it comes to their concept of "People and Planet". IKEA is making an effort in reducing the carbon footprint where original plans of being carbon neutral is being replaced by goals of significantly reducing the CO<sub>2</sub> footprint even further. IKEA also focus on circularity, moving away from virgin materials to recycled materials and moving away from fossil-based materials to renewable materials as one aspect of circularity. These are all reasons why IKEA is planning stepwise changes from now until 2030 where plastics is an important area [10].

This thesis focus on developing blend formulations between PP and biopolymers with at least 20% bio content and similar properties as PP. The blends should also be commercially relevant whereas a cost aspect is evaluated. We specifically focus on blending PP with PHA, where compatibilizers and fillers are introduced to improve properties and price. This thesis was done at IKEA, in collaboration with Lund University and Fraunhofer ICT where the experiments were conducted. Our work is a part of a bigger IKEA project called "Blends", where many biopolymers have been evaluated and lots of different blends have been tested, both with PP and other biopolymers.

## Background

### Size of industry

The focal point of this report will be on certain biopolymers. However, to understand these in a broader context, the production of BBMC other than polymers will have to be included. As of today, there are several incentives for moving towards further development and usage of BBMC, although this is no simple task and it comes with technological and economical challenges. Using biopolymers is nothing new, (e.g. biopolymers which have been used historically is natural rubber, cotton and wood) however, the industrial upscale to commercial production is a different story. The total amount of biopolymers produced by the year of 2016 was 2 030 000 tonnes, and by 2026 it is estimated to reach 3 900 000 tonnes [11]. Regardless of today's production volume, and the estimated growth in the coming years, biopolymers only accounts for a very small fraction of the overall production of plastics. In 2012 biopolymers accounted for 0.5% of the overall production of plastics which were estimated to be between 200-250 million tonnes [12]. Some reasons why biopolymers are having

difficulty in penetrating the market is material properties, cost, feedstock availability and the fact that they are competing with the well-developed value chain of petrochemicals.

There are many different polymers used in current plastic applications, where the characteristics of these are highly individual, still it is estimated that 90% of the current polymer materials can be replaced by bio-based polymers [12]. Bio-PET (polyethylene terephthalate) is currently the most produced bio-based plastic followed by starch-based plastics and polylactic acid (PLA), see Figure 1. Over the coming years, Bio-PET is estimated to keep its position with the largest capacity, even though the market share of bio-PET is estimated to decrease from 31% (2016) to 24% (2026). It is important to mention that the classification of what is considered a biopolymer is not obvious, e.g. bio-PET consists of two different monomers, mono ethylene glycol (MEG) and terephthalic acid (PTA), MEG can be derived from bio-based ethylene however PTA is usually not bio-based. Therefore what is considered bio-PET actually only contains approximately 30% bio content. Development of bio-based PTA is still in an early stage and it is estimated that the first commercial production will be in place approximately 2025.

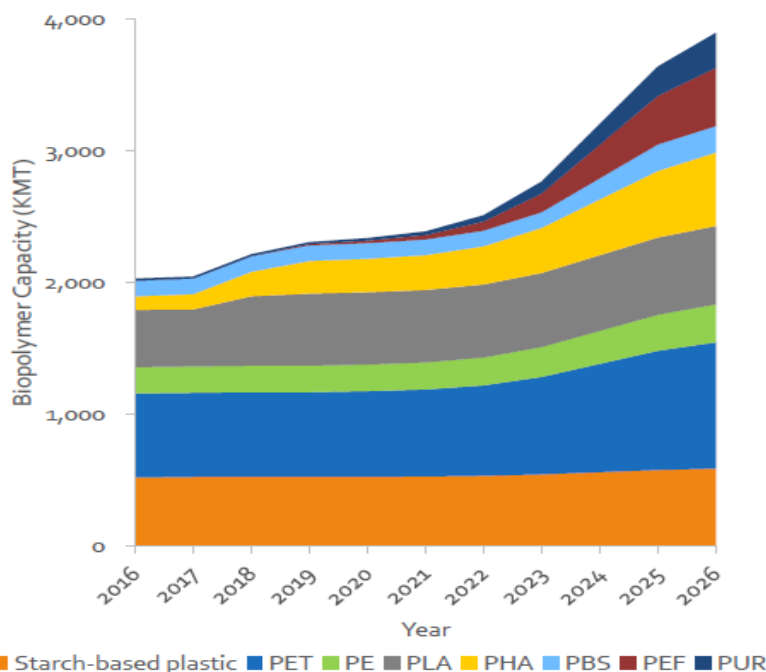


Figure 1. Predicted production of bio-based plastics until 2026 [11].

Besides the overall increase of biopolymers, it is estimated that biopolymers such as PLA, PHA and PBS, belonging to the “next generation” of biopolymers will hold the majority of the market instead of the “first generation” biopolymers such as the bio-PET and bio-PE. In numbers, it is estimated that next generation polymers will grow from 33% by 2016 to 53% by 2026. Even though using first generation biopolymers in existing product chains is advantageous, they are expected to lose market share because they compete with petrochemicals in cost [11]. It is important to develop the properties to meet customer demand. In the end, this industry will succeed when the

different players – ones who control the feedstock, ones who develop future technologies and convert the monomers or base chemicals to polymer and brands come together to create future value chains. This is what IKEA is focussed on!

An overview of the different steps in the biopolymer industry can be seen in Figure 2 and each step is explained in the following text.

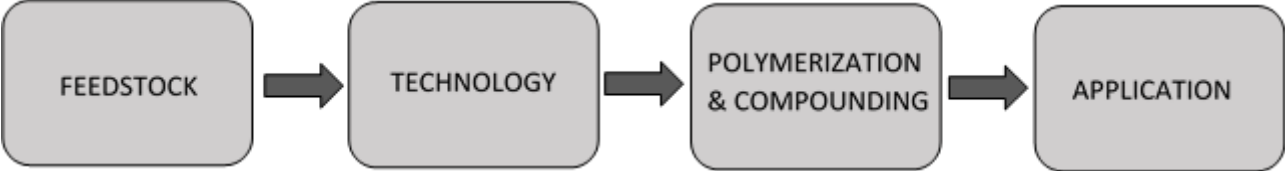


Figure 2. An overview of the different steps of the supply chain for biopolymers.

**Feedstock**

Majority of the BBMC is currently produced from first generation biomass, which includes food crops like sugar cane, corn, sugar beet, cassava, soybeans, rice, oatmeal, wheat etc. An important factor to whether BBMC will succeed in competing with fossil products in the long run lies within the utilization of second generation biomass (non-food). By 2013, 265 million tonnes of first generation sugar was consumed to produce BBMC and alternative fuels, see Figure 3 [13]. Same year, the amount of available second-generation biomass was estimated to be 2.4 billion metric tonnes. Adding the fact that it is not competing with food makes the possibility of using second generation biomass highly interesting. In 2012 the amount of cellulosic biomass (second-generation) utilized for BBMC and biofuels were 12 million metric tonnes. This is predicted to grow with 27% annually until 2030, reaching 867 million tonnes.

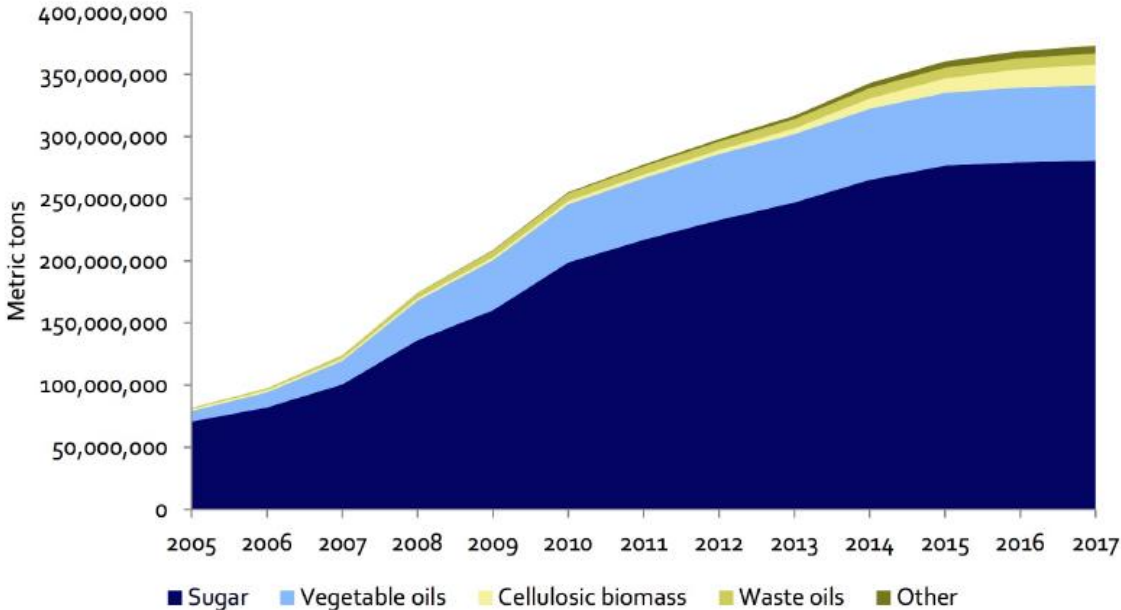


Figure 3. Tonnes of different feedstocks consumed to produce bio-based fuels and chemicals [13].

The increase is mainly driven by corporate investments and regulations by governments since the industry is struggling to make this business profitable. Development is needed and usage of first generation crops is already stressed. In 2010, 16% of all sugar cane crops were used for BMC and biofuel production and this number is increasing. If other alternatives fail to deliver material for the bio industry, the demand for first generation crops will be too high not to interfere with providing enough food for people and violating deforestation limitations [14]. Regardless of the biomass being first or second generation there are difficulties which they share, such as seasonal availability, collection, pre-treatment and fluctuating prices due to more or less successful harvests.

### Conversion technology

Utilizing the first-generation biomass for chemicals has been done historically for a long time (e.g. the process of converting sugar to ethanol is well known). Besides the production of ethanol, chemicals such as butadiene, isoprene, acrylic acid and succinic acid are produced from the sugars of first-generation biomass [15]. To convert second-generation biomass into similar chemicals is a more difficult feat. Existing techniques include thermal processing and using acid solutions which will partly degrade the biomass, decrease the yield and increase the cost of material production [15]. When the chemicals are produced there are usually several steps of treatments for the separation of product and residuals. These will not be described in detail, but have in mind that an effective separation can be a struggle for certain processes.

### Polymerization and compounding

The number of existing biopolymers is huge, however the ones which have reached large scale production is easily counted, these polymers are:

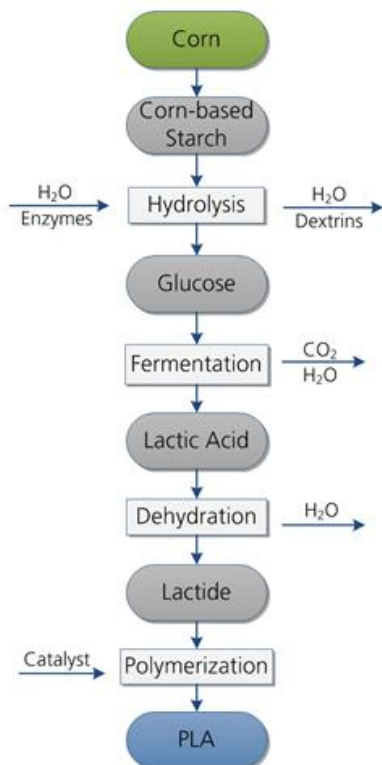
- Starch-based plastics
- Polyethylene terephthalate – partly bio-based (bio-PET)
- Polyethylene – fully bio-based (PE)
- Polylactic acid (PLA)
- Polyhydroxyalkanoates (PHA)
- Polybutylene succinate – 50 or 100% bio-based (PBS)

The chemistry behind the polymerization of monomers varies for the listed polymers, where common processes include esterification, condensation polymerization, catalytic polymerization and extrusion. For reasons which will be described later in this report, IKEA has chosen to focus on using PLA, PHA and PBS, hence additional information about these biopolymers will follow. In Table 1 some of the important actors within this field is mentioned, where some are producing biopolymers on a commercial scale and others are evaluating interesting technology [10].

Table 1. Table showing the main players for the production and technology of PLA, PHA and PBS.

PLA	PHA	PBS
-NatureWorks/Resinex -Purac	-Bio-On -CJ CHEILJEDANG -Danimer scientific -Meredian -Biomer -Tianan	-Showa Denko Europe -BioAmber -Myriant -Reverdia -Mitsubishi/Helian Polymers

PLA is a homopolymer of lactic acid which is produced from the fermentation of sugars, the polymer is usually created by a ring opening polymerization of lactide. Lactide is formed through self-esterification between two lactic acid monomers. Lactic acid exists as two stereoisomers (see Figure 5), thus lactide exists in three different configurations. If the stereoisomers are isolated and polymerized there is a possibility to create polymers with different crystallinity and therefore different properties. This is something Purac is looking into [16]. NatureWorks is the main producer of PLA with a capacity of 150 000 t/a with an estimated production of 800 000 t/a by 2020, the value chain for corn-based PLA is seen in Figure 4 below [16]. The second largest producer is Purac with a 75 000 t/a facility in Thailand [12].



\*Conversion Rates:  
Glucose – Lactic Acid 85%

Figure 4. Overview of the production flowsheet for PLA based on corn [17].

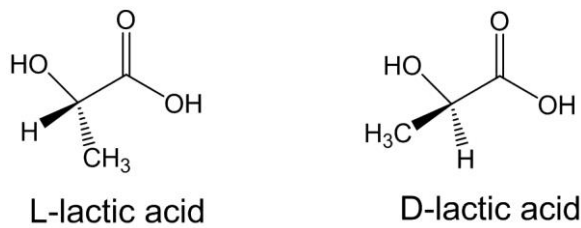


Figure 5. The two stereoisomers of lactic acid, L (left) and D (right) [18].

PBS became commercially available in the beginning of the 90s as Showa Denko produced it by the name of Bionelle, they have developed several grades of the polymer which include blending it with starch compounds and PLA [19]. The polymer consists of succinic acid and 1,4 butanediol (see Figure 6), both can be produced from renewable feedstocks. Although, today the commercial praxis includes using 1,4 butanediol derived from petrochemicals making the polymer only partly bio-based (50%). The supply chain from corn to PBS is seen in Figure 7. Production is costly which has inhibited PBS to penetrate the market. BioAmber, Myriant and Reverdia is developing processes where genetically modified microorganisms are converting feedstocks into succinic acid, they all have interest in using this to produce PBS. Production capacities for the mentioned companies range from 3 000 to 15 000 t/a [20].

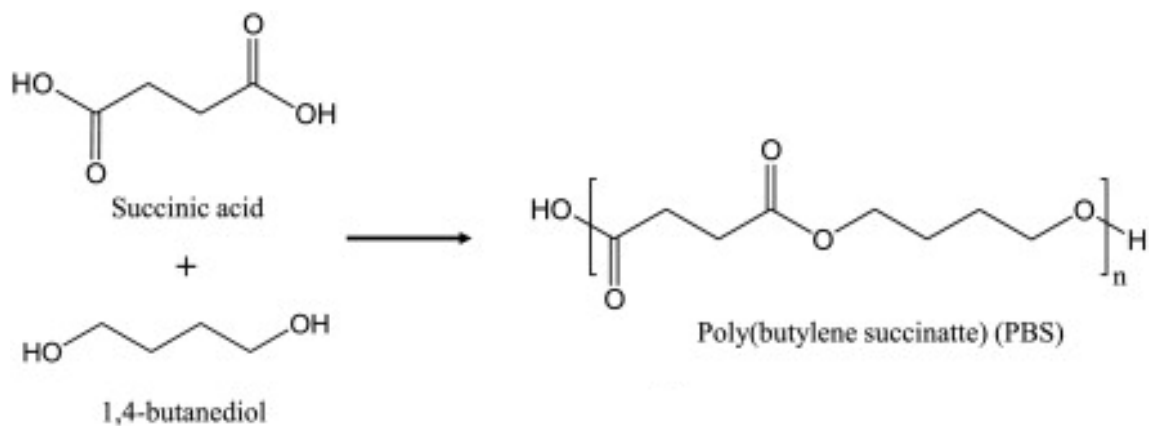
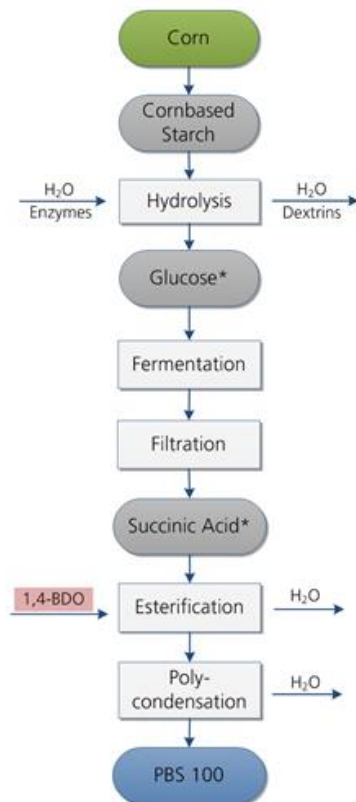


Figure 6. Molecular structure of the PBS monomer, where succinic acid and 1,4 butanediol is the starting chemicals [21].

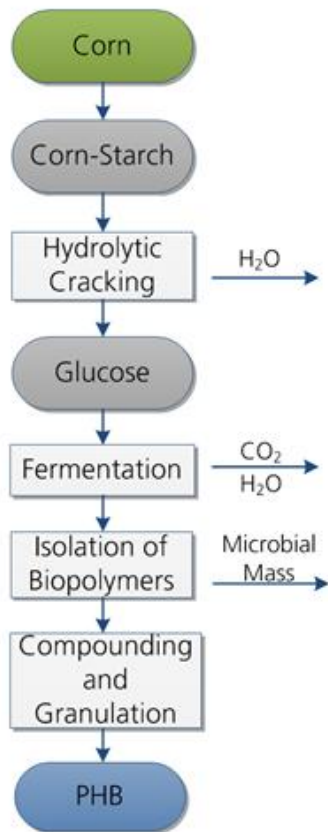


\*Conversion Rates:  
 Starch – Glucose 90%  
 Glucose – Succinic Acid 80%

 **IfBB**  
 Institute for Bioplastics  
 and Biocomposites  
[www.downloads.ifbb-hannover.de](http://www.downloads.ifbb-hannover.de)  
 Last updated on 27-09-2013

Figure 7. Overview of the production flowsheet for PBS based on corn and fossil 1,4 butanediol [17].

Polyhydroxyalkanoates (PHA) refers to a family of over 100 different polymers where polyhydroxybutyrate (PHB) is one of them, these are polyesters created by certain microorganisms as a response to stress. The feedstock could be different depending on availability, where beet, cane, glycerol, corn and waste streams is plausible. A value chain for PHB where corn is used as a feedstock can be seen in Figure 8. PHA, PHB and Poly3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV) is targeted as platform polymers for large scale production, the molecular structures of these monomers are shown in Figure 9. PHA has not reached the same commercial level as PLA, companies are expanding capacity, but the lack of downstream applications of PHA is a limiting factor of growth, as well as cost. Bio-on is currently one of the major producers of PHA, using fermentation of different feedstocks. The company has demonstrated products such as plastic toys and cosmetics and has a production capacity of roughly 100 000 t/a. Tianan currently produce PHBV material on a commercial scale. Finally, Danimer Scientific is using canola oil to produce PHA. PepsiCo has stated that they will develop Danimer’s process to use it for their products [11].



**\*Conversion Rates:**  
Glucose – PHB 35%

 **IfBB**  
Institute for Bioplastics  
and Biocomposites  
[www.downloads.ifbb-hannover.de](http://www.downloads.ifbb-hannover.de)  
Last updated on 09-04-2013

Figure 8. Overview of the production flowsheet for PHB based on corn. [17].

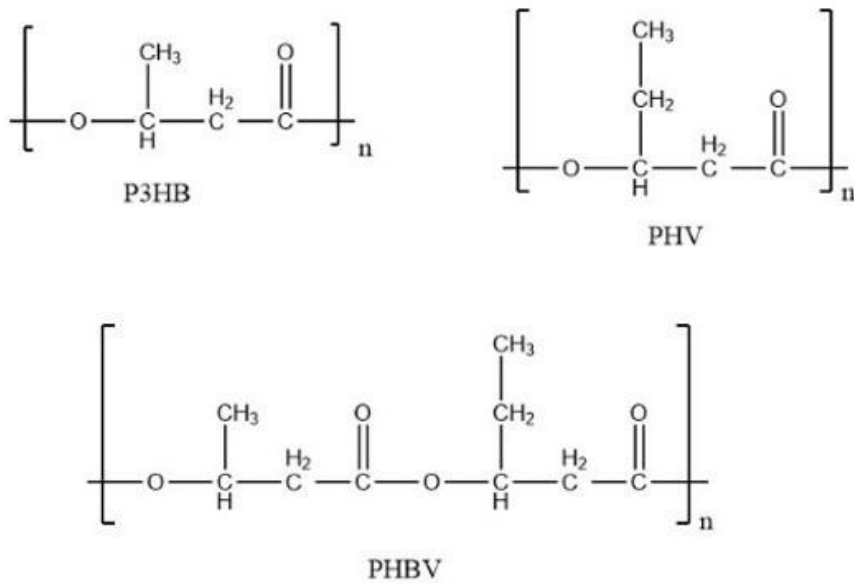


Figure 9. PHB, PHV and PHBV monomers [22].



Because PHBV is a copolymer which may contain different fractions of the two monomers (PHB and PHV) it could be difficult to use several suppliers to create similar blends. In contrast to PBS which have the molecular structure of its two monomers in a 50/50 ratio, the valerate (PHV) content in a PHBV material is dependent on microorganism, feedstock, processing, etc. Also, to improve the properties of the blends, one possibility could be to use different types of PHA. New PHA grades are under development, e.g. PHBH could be an alternative. Unfortunately, these alternatives are under development and cannot compete with the already commercialized PHBV, therefore they are not interesting for this project. The PHV content (or longer chains such as PHBH etc.) could be increased to an extent where it disturbs crystallization to increase the flexibility of the blend.

After polymerization of monomers, polymers are usually compounded into pellets for distribution and further use in downstream processes such as injection moulding and extrusion. During this stage any additives (e.g. UV stabilizers, antioxidants) can be added and/or different types of polymers can be mixed in specific proportions. A twin-screw extruder is normally used for this [23].

### Applications

IKEA represent the end of the product chain as they use the final polymer compound. Today the company approximately use 700 000 tonnes/a of plastics. PP, PE, and PET/polyesters accounts for roughly 80% of the plastic consumption.

- The PET/polyesters are used for fibres and yarns in textile and comfort products.
- PP is used for machine made carpets and plastics products including food storage boxes and children products.
- PE represent a smaller share, it is used in several products where a lot is recycled and bio based.

The proportions of the plastics consumption for different products in IKEA is illustrated in Figure 10, as well as the processes connected to them. This project initially targets injection moulded products, but a polymer blend could be applicable in plastics, textiles and comfort.

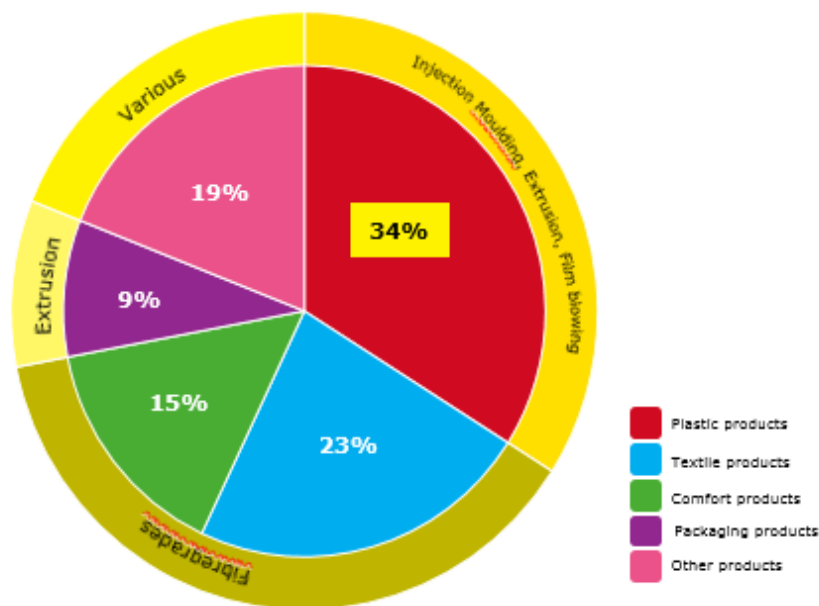


Figure 10. Proportions of plastic consumption within IKEA today [24].

## New material solutions

### Drop-In

With the conversion of biomass into BBMC there are different approaches on how to effectively penetrate the market. Amongst these is the “drop in” solution, which refers to a process where the bio-based chemical can be used in the already existing product chain. Ethylene is a good example of such a solution, as there is no molecular difference between bio-based ethylene and petro-based ethylene, once produced, the products have identical properties. Because of this there is no need to replace current technology which is well developed. As major parts of the product chain already exist the cost/risk analysis is more accurate. However, for these drop-ins some producers are struggling with being able to prove that their product is bio-based to the extent they claim. Existing production lines are often continuous and a shutdown to change feed would cost a lot of time and money. Therefore a bio-based material is often introduced as a second feed, gradually replacing the standard feed, making some material a product mix of bio-based and fossil-based. As quantities of bio-chemicals are far less in volume than fossil, the switch back to the normal feed must be done before or shortly after reaching pure bio product. If the volumes of bio-based reactants will increase in the future, the amount of pure bio products can be increased, or complete bio production facilities can be financially motivated. Measuring the content of C14 in relation to C12 can determine the bio-based content of the polymer product [10].

### Novel

Novel materials offer interesting possibilities, however with new structures compared to the existing materials current facilities might need development. Likely, the production chain of novel materials must be developed separately. This will in most

cases raise the capital expenses to high levels resulting in expensive materials. In advantage, new materials could enable completely new properties and property combinations, like self-assembly, self-healing and structural colours [25]. An example of a novel bio-based polymer is polyethylene furanoate (PEF). PEF is being developed as an alternative to PET. Avantium in Amsterdam have patented an economic, catalytic process to produce PEF which is currently on pilot scale. In comparison to the traditional PET, it can offer significantly improved barrier properties making it a very interesting packaging alternative in the food and beverage industry [26]. Companies like Coca-Cola and Danone are already involved in partnerships with Avantium to further expand the production and implementation of PEF [11].

Novel process routes to produce biopolymers can be found in the production of PHAs. Start-ups are looking into the utilization of carbon dioxide (CO<sub>2</sub>) and hydrogen (H<sub>2</sub>) for bacterial conversion of these into polymers. Oakbio is one company currently working on lab scale with this, but they claim their technology is sufficient for scaling up and operating a pilot plant. They aim to produce low cost resins of PHA at a commercial scale [27]. Another possibility, that Newlight Technologies develop, is converting methane and hydrogen into PHA. Common issues for companies using such technologies is accessing the feedstock gases in an efficient way. These companies would benefit from joint ventures with industries producing steel and cement as these produces large amount of usable flue gases. It should be noted that even though companies using novel techniques are scaling up and getting closer to commercial production many have failed to do so, because of insufficient production volumes. To what extent novel processes will be used is highly depending on the development of applications for the product material.

## Blends

Polymer blends can be either miscible or immiscible, this property is directly linked to the molecular interaction between the monomers, e.g. dipole-interactions and hydrogen bonding. The effect of miscibility can also be explained by thermodynamic reasoning. In general miscibility and homogeneity is a result of a negative free energy of mixing. This is rarely seen in practice and only possible when there is strong interaction between the different polymers. When the interaction is not as strong, (but still present) partial solubility can be observed. For these systems complete miscibility may be achieved by changing temperature and composition [28]. It should be noted that it is not only the miscible blends which offer interesting properties for application. Several immiscible blends could be useful, and these are sometimes termed compatible. The blend between PLA and PP can be used as an example to further explain this. PLA, which is polar, does not create a miscible blend with the non-polar PP, which in turn results in insufficient mechanical properties for most applications [29]. Polymers which generally show immiscible behaviour could be modified by using compatibilizers and additives (e.g. glycerol) to behave differently. The structure of compatibilizers can look different depending on the desired blend properties, but the idea is to create an interface between the two immiscible polymers. For the PLA/PP blend, a graft polymer could be used with both polar and nonpolar properties to link together the individual polymers [30]. According to Thabo Gcwabaza et al. [31]

blends of PP and PBS will create a material with weak interfacial strength, hence with poor mechanical performance. The effect of a compatibilizer on a blend of PP/PBS (70:30) is seen in Figure 11. The spheres/ellipses seen in the top left image of Figure 11 is the PBS within a PP matrix. As the amount of compatibilizer is increased, the blend homogenizes and thus the properties are modified.

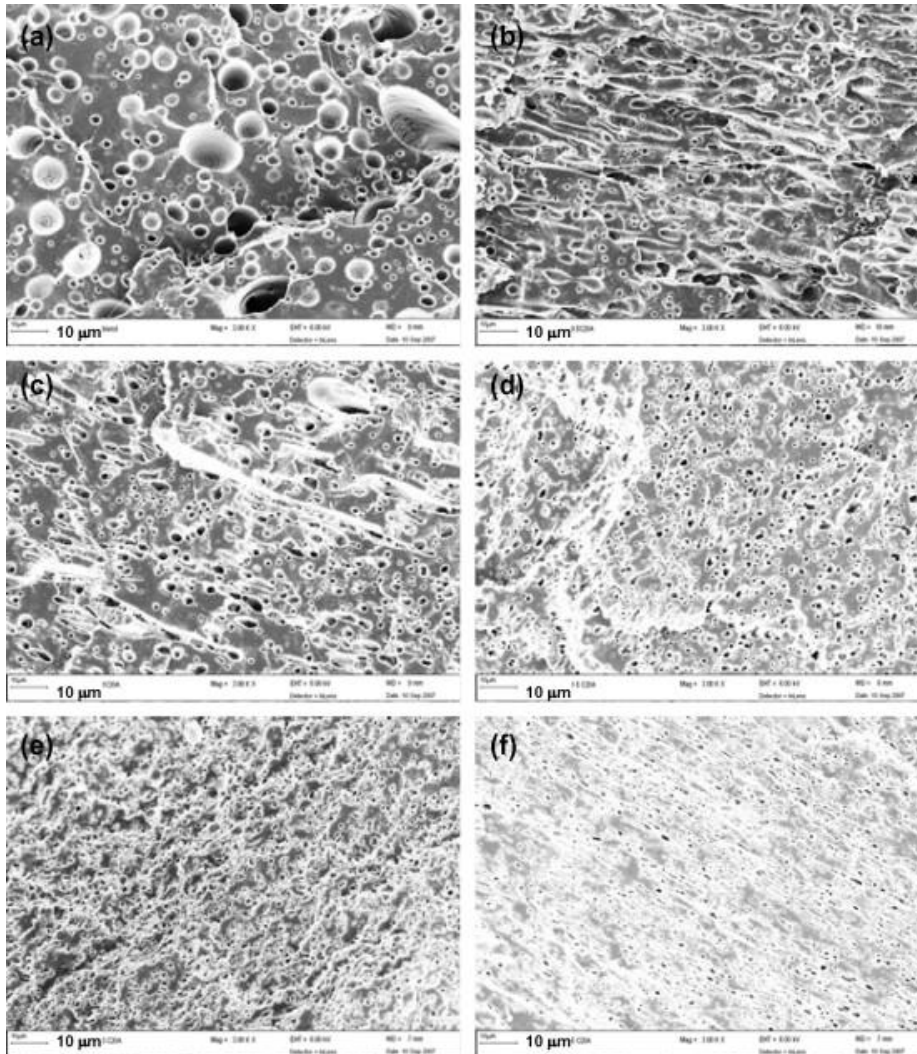


Figure 11. Blends of PP/PBS with different amount of compatibilizer, (a) Unmodified blend, (b) 0,5 wt%, (c) 1 wt%, (d) 1,5 wt%, (e) 3 wt%, (f) 5 wt% [32].

PP and PHA are also immiscible in a blend [33]. However, there has been mixing to successfully improve the mechanical properties of injection moulded samples compared to that of pure PHA. Further studies on compatibilizers in the PP/PHA blend by R.K. Sadi, R.S. Kurusu, G.J.M. Fecine, N.R. Demarquette [34] proved that between several compounds of poly (ethylene-co-methyl acrylate-co-glycidyl methacrylate) [P(E-MA-GMA)] showed the best results in terms of improved elongation and impact strength. They also observed dispersed spherical particles within a matrix by using SEM imaging.

## Project: “Blends”

IKEA, being a global company, can influence and make decisions which are needed to support and transform trends for sustainability within the polymer industry that are needed for the future of people and planet. After examining several biopolymers to directly replace existing polymers from fossil sources (drop-in and novel), IKEA is now continuing their effort towards developing strategies to deal with the challenges the industry faces. Besides trying to use the mentioned drop-ins and novel materials, IKEA is now looking into polymer blends between different biopolymers and blends between biopolymers and polymers from fossil sources.

This report aims to give an understanding of the biopolymers used for blending, the challenges/opportunities, and the possibility of using them in blends for downstream applications. A cost/performance matrix will be presented to serve as information for future decisions within IKEA. The blends should be able to compete with polypropylene in terms of cost, performance, capacity and recyclability before commercialization can happen. The drive for changing to renewable sources of energy and materials is central in IKEA’s everyday work [9]. This transformational shift needs to be done by IKEA with their strategic partners in the supply chain. To do this for polymers IKEA is working together with Fraunhofer ICT. The overall goal with the collaboration is to find solutions in materials and technologies to replace the fossil feedstocks used today [35]. A direction towards renewable sources would mean diversifying the feedstock portfolio and enable production of products with a less harmful impact on the environment. On the material side of IKEA this means for example, as we focus on in this thesis, replacing fossil based polymers with biopolymer blends [9].

Many different biopolymers exist which are available in different quantities, overall, they come with some drawbacks. Since they are developed in recent years prices are high, big scale production is a challenge, properties are insufficient for several applications and processing parameters are not fully understood. These factors make it difficult for IKEA to directly replace current fossil polymers with biopolymers. To circumvent these problems, blending biopolymers with fossil-based polymers could be a solution. Not to completely replace fossil-based polymers, but as a start to reduce the total amount and to continue improving the bio-based alternatives. As stated earlier IKEA consume approximately 700 000 t/a of plastics (with plans of expansion up to 2 000 000 t/a by 2030). Replacing between 20-50 % of this with biopolymers would be a good start. IKEA has a clear plan to increase the bio content in a stepwise approach: By 2020 the output of all IKEA materials should contain a minimum of 20% bio content, 2020 – 2025 the goal is to increase this to a minimum of 50% and finally between 2025-2030 the aim is having a minimum of 80% bio content. This is illustrated in the following chart (Figure 12).

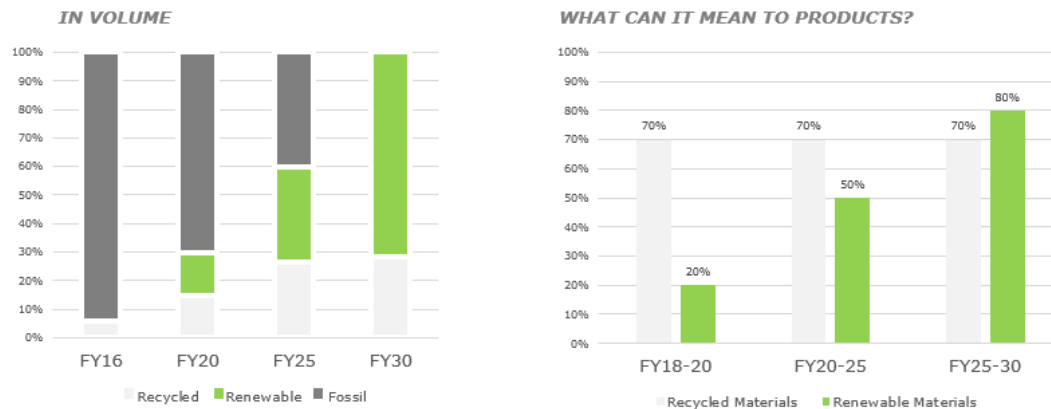


Figure 12. Plan to increase the bio content in IKEA products by stepwise approach [24].

Blending bio-based polymers with petrochemical polymers will hopefully compensate for the insufficient properties of pure biopolymers, and since the price of fossil polymers is lower, the problem with higher cost could perhaps be dealt with. This balance of requests is what this thesis focusses on in the development of a cost/performance matrix for different polymer blends. For the replacement of fossil-based polymers to bio-based within IKEA, following strategies is seen as the most interesting:

- For the replacement of PET/polyesters, PLA is being investigated and bio-PET is commercially available (with 30% bio content) replacing parts of the fossil-based PET.
- In the case of PE, bio-PE is commercially available and used as a drop-in in IKEA products already. Recycling of PE is also possible, shrink film used for packaging is collected from stores and distribution centres and converted into new products.
- PP is partly being recycled but for some application this is not an alternative. Recycled PP does not meet the transparency level required for certain applications. For PP IKEA is trying to find alternative solutions, as there is currently no drop-in solution.

As of today, IKEA produces a set of kid's storage boxes (Figure 13) made of PP through injection moulding. Food and children's applications have very high demands when it comes to grade, purity and emission levels, which recycled PP cannot fulfil. Therefore, there is a need for new solutions, and the Blends project might be a solution. The "MAMMUT" series (Figure 14) is a product for kids that is injection moulded with PP and could be a future application for using blends. The aim is to injection mould some products with the different blends and conduct further testing of the blends in the moulded shape.



Figure 13. "Trofast" boxes [36].



Figure 14. "Mammut" series [36].

Together with Fraunhofer, IKEA has evaluated which alternative biopolymers exist on the market today. As a first criterion, they need to be on at least demo scale, or better, already on industrial scale. Evaluation of available biopolymers required an extensive survey of the market and potential suppliers. In addition to the need of sufficient scale, IKEA, in cooperation with external partners, evaluated the future potential of price. Finally, these polymers are supposed to replace PP in injection moulded products. They should live up to the IKEA specifications for injection moulding as well as material properties, more specifically, the PPCO2, PPCO4 and PPCO 7 specification [35].

Biopolymers such as PEF, polytrimethylene terephthalate (PTT) and polybutylene terephthalate (PBT) were excluded since they are considered to have higher probability for use in fibre applications. Same conclusion applies for polyamides (PA) and polyoxymethylene (POM). Because of their properties to withstand high dynamic loads, they are considered a better fit for other furniture applications. This left IKEA with three promising biopolymers: PLA, PBS (100% bio-based) and PHA. Material data of the biopolymers and the PP specifications can be seen in Table 2 below. These are approximate values for different grades of the different biopolymers to give an overview of the polymers properties, strengths, drawbacks and how they differ from PP. When summarizing the data, few things are worth pinpointing [35]:

Table 2. Approximate values of properties for PLA, PBS and PHA biopolymers and IKEA PP specifications. Insufficient values highlighted in **bold** and sufficient values in underlined [34].

	PLA	PBS	PHA (PHB/PHBV)	PP Specification
Tensile modulus [MPa]	3500	<b>300-700</b>	<u>1150-2600</u>	>1050-1400
Stress at yield [MPa]	<u>70-75</u>	18-40	<u>24-40</u>	>24-27
Elongation at yield [%]	<b>2-3</b>	20	5-12	>4-5
Notched impact strength [kJ/m <sup>2</sup> ]	<b>2-3</b>	<u>8-35</u>	<b>2-5</b>	>5-11,5
Process temperature [°C]	160-200	120-200	150-175	200-300
T <sub>m</sub> [°C]	130-180	95-115	179	160-175
HDT [°C]	<b>55</b>	<b>55-80</b>	<u>109-145</u>	>90-100
Price level (for small quantities of the biopolymers) [€/ton]	2 500-5 000	6 000-1 0000	6 000-1 0000	<2 500
Density [g/cm <sup>3</sup> ] [20]	1,24	1,25	1,25	0,9

### PLA

*Advantages:* Price level is in an acceptable range, especially compared to the other candidates PBS and PHA. The modulus for PLA is also very good.

*Disadvantages:* The most pronounced drawback is the low heat stability, with an HDT value of 55°C. Also, the elongation at yield and impact strength is not good enough to reach the IKEA specifications.

### PBS

*Advantages:* Impact strength is very good, especially compared to the other candidates.

*Disadvantages:* Low tensile modulus is a drawback, and preferably increased heat deflection temperature (HDT) properties is desired. Price levels of PBS are high which is a limitation to motivate a high content in a blend even though properties are good.



## PHA

*Advantages:* PHA are an overall a good candidate to replace fossil-based polymers, with grades showing good modulus, and HDT values.

*Disadvantages:* Drawback lies in notched impact strength and in it being an expensive material.

The Blends project includes three types of blending approaches:

- Biopolymer blends with additives
- “Bio-Bio” polymer blends with additives
- “Petro-Bio” polymer blends with additives

This thesis will focus on petro-bio blends, and more specifically the blends of PP/PLA, PP/PBS and PP/PHA. Focus is mainly on the needed properties, cost, bio-content and capacities. The polymer blends will be evaluated according to the criteria's shown in Figure 15 (recyclability and capacity is out of scope for this thesis, still they are included in the discussion). Fraunhofer ICT will compound the blends and conduct performance tests on injection moulded test bars. This thesis will focus on understanding the work of Fraunhofer ICT and together making a decision to create a material according to what is illustrated in Figure 15. The material properties will be evaluated in relation to the PP specifications and held against the estimated cost of the blend. Cost cannot be too high compared to the fossil standard, since the final price of a product should be economically viable for IKEA applications. IKEA will simultaneously focus on the development of capacity. When cost, performance, capacity and recyclability is achieved, we will have a good bio-based material that can be used as an alternative by IKEA, and hopefully by others in the future.

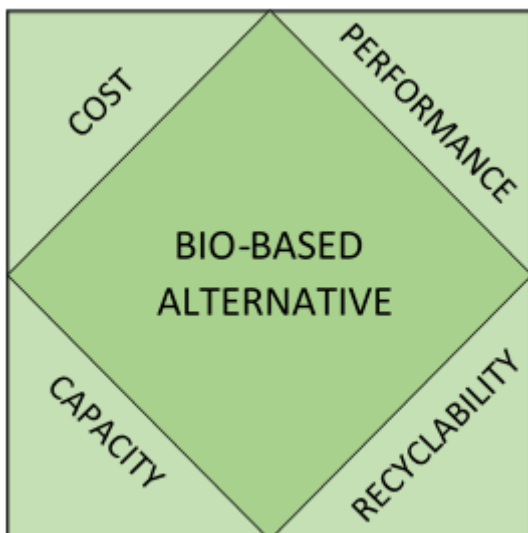


Figure 15. Aspects taken into account when developing bio-based alternative materials within IKEA.

To clarify the structure of this project, the three different stages will be described (Blends 1.0, 1.5, and 2.0). Since this is an ongoing project that has been progressing for several years, there is a lot of previous results. These are all part of the initial project, which will be referred to as Blends 1.0. These results have been evaluated

as further development in Blends 1.5 is made, and Blends 1.5 is the foundation for this thesis. To have a holistic view of the project, consideration must be taken, not only of material properties but also of the price, which is why the cost/performance matrix is introduced. Price is important since the primary goal is to replace the material in already existing products (Mammut and Trofast) where increasing the price, due to more expensive material is not an option. Within Blends 1.0, cost have not been considered, but rather technical aspects. As this thesis was initiated the project had reached a point where commerciality must be considered. Blends 1.5, which is the focus for this thesis, together with Blends 1.0 will serve as the foundation of Blends 2.0, in which several different biopolymers and novel materials will be further investigated, but with a cost and scalability perspective included. In the following section, the different parts of the project will be explained in more detail.

### Blends 1.0

Blends 1.0 was initiated as a pre-study project with the aim to understand the technical feasibility of polymer blends between biomaterials as well as bio/fossil-materials for IKEA products. To achieve this, IKEA developed a partnership with Fraunhofer ICT. Before IKEA settled on further evaluating the blends of PP together with PLA, PHB and PBS a substantial number of different biopolymers was investigated and information about these polymers, the suppliers and technology was gathered in an "IKEA master table". With this data, majority of the biopolymers were excluded for further testing. As the decision to investigate PLA, PHA and PBS was made, over 450 different blend compositions were examined, and a few was injection moulded into IKEA products. At this stage of Blends 1.0, IKEA decided that there was enough incentives to examine the commerciality of the project. The aim is to produce a blend with a minimum bio content of 20% with an approximate price of 2 €/kg (2 000€/ton), combining these facts with the prices of the individual polymers (Table 3) limit the possibilities of blending to some extent. In Figure 16, the relationship between bio content and price for the blends of only PP and biopolymer can be seen. From a cost point of view, it becomes clear that PLA is most favourable to use, followed by PHA and then PBS.

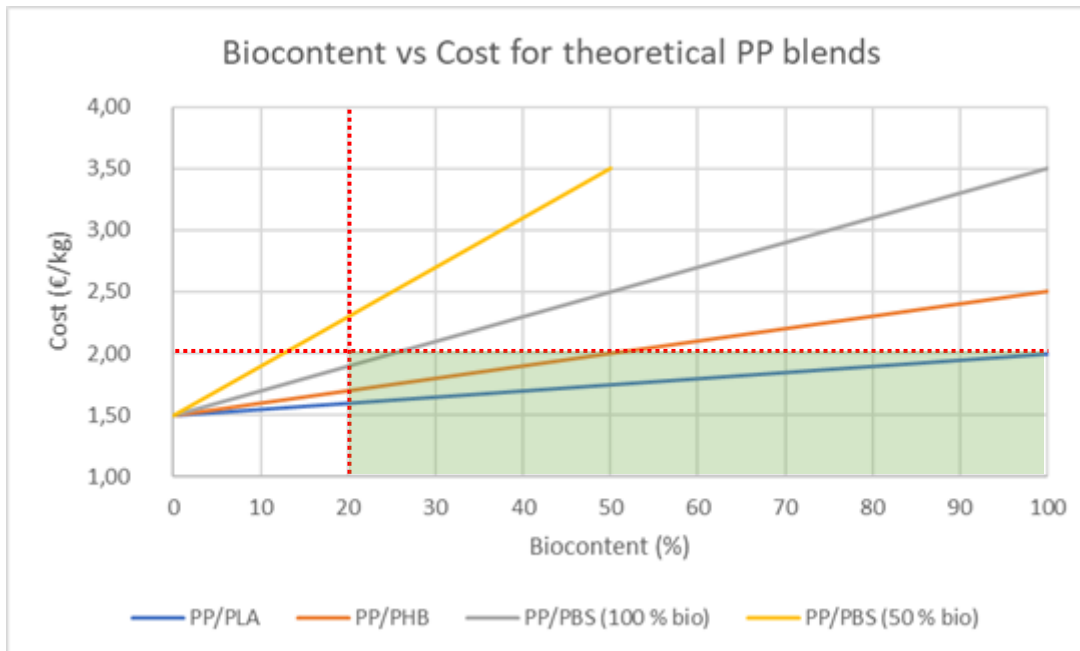


Figure 16. Price depending on bio-content for pure bio-fossil blends with varying bio content.

Results from Blends 1.0 imply that for PLA the drawbacks in HDT and impact properties are too pronounced to overcome, which is unfortunate due to the lower price compared to the other biopolymers. Also, for PLA mould temperatures must be high (>50°C), machines and tools are not normally designed for this. A PLA/PP blend is considered too far from reality for now [37] and therefore excluded from Blends 1.5.

PBS on the other hand has shown some promising properties. Even if the specifications are not fulfilled, it is likely that drawbacks could be solved by further development [37]. The main issue with PBS is the price and the fact that most commercially available PBS contain only 50% bio content. To reach a 20% bio-based blend, the content of PBS must therefore be doubled, price wise this cannot be motivated. For 100% bio content PBS, the price of this material would most likely be even higher, thus PBS is also excluded for Blends 1.5. This leaves PHA as the most promising biopolymers for blending with PP. Not only because of the drawbacks of the others, but also since PHA shows promising properties so far, hence we will continue with the blends of PHA/PP, in the Blends 1.5.

### Blends 1.5

As mentioned, Blends 1.5 will serve to give a holistic approach to see the different aspects of the business with focus on cost and performance. Hence, the thesis title was set as “*Analysing and concluding the cost/performance matrix for biopolymer blends with different renewable content*”. For the project to be a success, the performance, which was the focus of Blends 1.0 was put in context to the cost of the materials and processing.

Tests on initial PHA blend formulations already fulfil some properties in the specification but the blends need to be fine-tuned and processing parameters must be set. In Blends 1.0, majority of the blends that have been tested contained quite

high fractions of bio-content. Now, as price is taken into consideration, the focus will be on having a minimum of 20% bio-content (due to the IKEA sustainability goal of 2020). Different compatibilizers and additives are used to tune properties. Talc and chalk are introduced as fillers, hopefully improving the properties and at the same time decreasing the cost. In Blends 1.0 it was mostly the PHA grade PHBV that was evaluated, with promising results (the fact that PHBV was targeted was a combination of material properties and commercial availability). Other PHA grades could also have sufficient properties to blend and it could be interesting to investigate this also, and not only improving the PP/PHBV blends. Since it is difficult to predict how the PHA market will look like in the future several options should be investigated.

For this part of the project, compounding is important to consider both regarding properties, but also cost. So far, different compatibilizers were used to offset pronounced drawbacks in specific properties and to make the two different polymers homogenous. This option of using different additives will continuously be developed since we do not count on the blends to be functional straight away. When the properties are fulfilled, the polymer needs to be processable, with a high enough melt flow index (MFI). In addition to the use of a compatibilizer, using talc/chalk as a filler could both alter the properties and lower the price. Aiming for a filler content of 10-20% could make the cost of a blend more reasonable. This will be further evaluated.

Consideration might be taken to the use of different types of PP. We noticed that the previous blends were only conducted with one standard, PPCO2 named "PP C765-15NA", a high performance impact strength copolymer designed for injection moulding. Since different grades of PP differ in properties, changing the PP could outbalance/countervail insufficient values for a specific blend formulation. For example, PP of standard PPCO4 has a higher E-modulus than PPCO2 but at the same time a lower impact strength. Therefore, we want to evaluate the possibility of using a different PP material (PP material was supplied by BRASKEM).

## Blends 2.0

Looking forward, IKEA will use the information acquired from Blends 1.0 and 1.5 to once again investigate several alternatives to replace polypropylene in plastic products, where the aim is to replace more than the minimum of 20%. The PLA and PBS which were discarded for the Blends 1.5 might be revisited again in this stage of the process, however this is not included in this thesis. Even if the master thesis does not have the scope of capacity and recycling (end of life), it should be noted that for the long-term success of this project, these aspects are crucial to understand. The result from Blends 1.5 will give important information regarding which formulations to further develop.

## Method

### Price estimations

The prices found in Table 3 and Table 4 were estimated internally by IKEA for the Blends project, as well as the thesis. Additives are not named due to confidentiality, but their main chemical structures are described.

- For PP, the accuracy of the price is very good. IKEA has been using large volumes of PP for many years, the supply chain is well developed, and partnerships have already been established.
- For the additives and compatibilizers the prices were set by using Fraunhofer's knowledge and should reflect the market price. Since the volume for these materials within the blends is small, a potential error of the estimation would be less critical in this case. It is likely that if the purchased volumes would increase an even lower price could be used.
- IKEA has put in a lot of effort in trying to create a good estimation of the price regarding PHA. Two extensive feasibility studies were done together with Bio-on where development of a 10 000 t/a facility was examined, with the potential of scaling up to 30 000 t/a. The studies focused on feedstock, location, CAPEX and OPEX. Besides working together with Bio-on, IKEA hired Neste Jacobs as an external partner to validate the studies done by Bio-on. A base case, several alternative cases and a few optimized cases were presented, all with different outcome. It is important to understand that the price we use for PHA not necessarily reflect the current market price, but rather a price which IKEA predicts as plausible. We assume that the cost of producing PHBV would be the same as for producing PHB.

What is interesting, from a cost point of view, is that IKEA is a major consumer of plastic products, meaning several hundred thousand of tonnes annually. Because of this IKEA could challenge a bioplastic producer to increase their production dramatically. IKEA believe that this possibility of scalability could lead to a cost neutral scenario compared to fossil PP in the coming years. The price for PHA is still an estimation where several alternative scenarios have been evaluated, where location and feedstock are of major importance. The price also accounts for some process optimization such as higher total yields, continuous processes, process optimisation and stable feedstock prices. Cost breakdowns can be seen for the base case and optimal case in Figure 17 and Figure 18 below. For both cases, the raw material constitutes the major part of the expenses which naturally makes it very clear that the need for an inexpensive, easy to access and transport, feedstock is crucial. Choosing the right location if investing in a new plant will also have a big impact on the second and third biggest expenses, CAPEX and electricity.

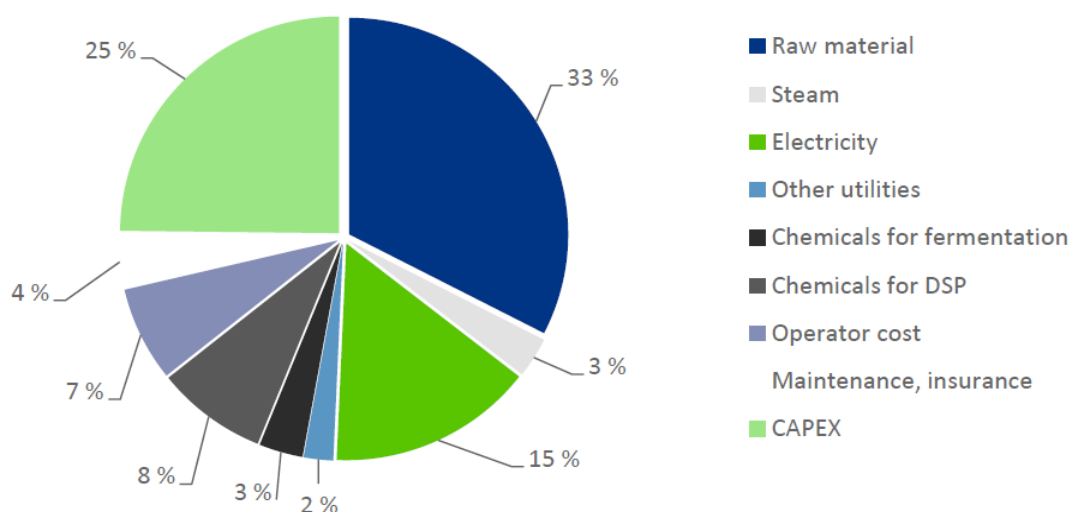


Figure 17. Cost breakdown for a "base case" of PHB compound net production, 4064 €/t [38].

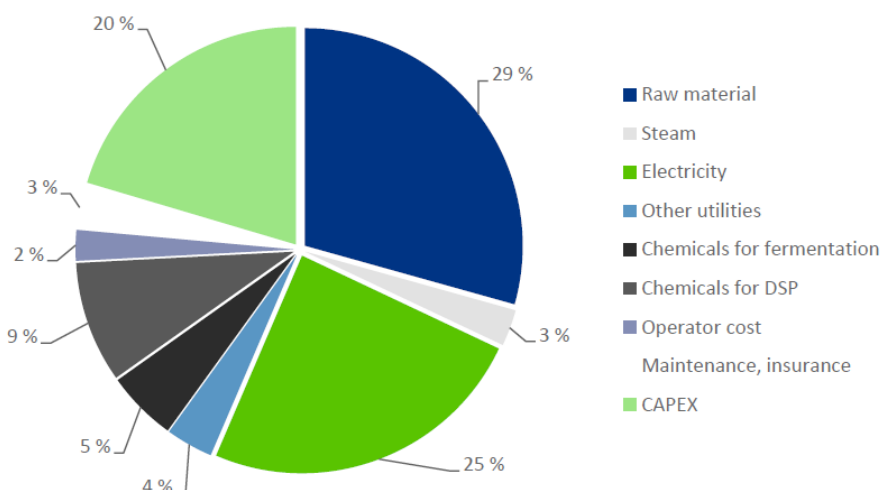


Figure 18. Total operation cost breakdown for an "optimal case" of PHB compound net production, 2696 €/t [38].

Compounding may add additional cost in an intermediate step between polymer production and injection moulding. For now, the cost of compounding is estimated by IKEA to 200 €/t [39], which will be used throughout the report.

Table 3. Price estimations used for the different polymers.

Polymer	Price estimation [€/t]
PHA (PHB)	2 500
PBS	3 500
PLA	2 000
PP	1 500

Table 4. Price estimations used for the different additives. Additives are not named due to confidentiality.

Additive	Price estimation [€/t]
<b>Filler A1:</b> SiO <sub>2</sub> -based talc (2 μm)	300
<b>Filler A2:</b> SiO <sub>2</sub> -based talc (0,7 μm)	500
<b>Filler B1:</b> CaCO <sub>3</sub> -based chalk (2,7 μm)	500
<b>Filler B2:</b> CaCO <sub>3</sub> -based chalk (2,5 μm)	500
<b>Compatibilizer A1:</b> Reactive ethylene based terpolymer with methyl acrylate	3 500
<b>Compatibilizer A2:</b> Reactive ethylene based terpolymer with butyl acrylate	3 500
<b>Compatibilizer B:</b> High molecular weight, linear polyester	4 000
<b>Compatibilizer C:</b> Random copolymer polypropylene, high grafted with maleic anhydride	4 000

Following equation was used for the price calculation:

$$\begin{aligned}
 & \textit{Total price of specific blend formulation} \\
 & = \textit{Biopolymer content in \%} * \textit{price of specific biopolymer} \\
 & + \textit{PP content in \%} * 1500 + \textit{Compatibilizer content in \%} \\
 & * \textit{Price of specific compatibilizer} + \textit{Filler content in \%} \\
 & * \textit{Price of specific filler} + 200 \textit{ (compounding)}
 \end{aligned}$$

### Compounding, extrusion, and injection moulding of test bars

At Fraunhofer ICT the different blends were compounded and pelletized using a twin-screw extruder connected to an underwater pelletizer. Multiple hoppers were connected to the extruder and loaded with the different materials, e.g. PHBV, PP, and compatibilizer, see Figure 19 (left). The feeding of components to the extruder was gravimetrically automated and controlled by computer.



Figure 19. Figure showing the extrusion setup at Fraunhofer ICT. Hopper (left) and extruder (right) [40].

In Figure 19 (right) the extruder is shown, the twin screw is located within the metal blocks, the different units allow certain temperature profiles along the extrusion. Temperature profile and other processing values can be found in Appendix B. Fraunhofer has been evaluating different screw designs for the compounding to ensure a good mixing of the materials. The design found in Figure 20 was used for compounding of the bio/petro blends.

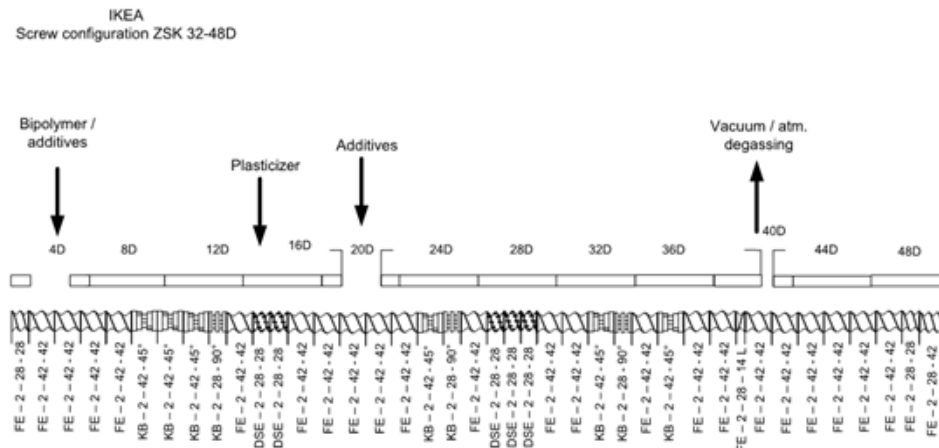


Figure 20. Screw design used for the bio/petro blends [40].

The extruder setup was connected to an underwater pelletizer, which is seen in Figure 21. After pelleting the compounded material, the granulates were dried for 3h at 80°C (water content max. 200ppm) before injection moulded into test bars for mechanical and thermal testing. The injection moulding machine used was an ENGEL ES200 and all process parameters can be found in Appendix E.



Figure 21. Underwater pelletizer [40].

Fraunhofer divides their work in two different parts, where one part is about finding suitable blends with good material properties. This part has been described



throughout the report. The other part is about processing the blends to create the IKEA products Mammut and Trofast and it is important that the compounding and injection moulding is done efficiently. Depending on the throughput rate as well as process parameters such as temperature and pressure, the estimated cost of the final blend could differ. For IKEA it would be favourable if the compounding was done by a PP supplier and not by an external compounder to lower the cost. Also, some PHA material is delivered as a powder and for this, an additional step is essential before having an effective compounding, where the powder is mechanically compressed. The compressed material can be compounded at a similar pace to that of the pellet version. Besides the compounding, it is critical that the moulding is done efficiently. Preferably with short cycle times and low temperatures. These are reasons why it is of such importance that the melt flow ratio (MFR) value is sufficient. According to Fraunhofer ICT, the MFR needs to have a minimum value of 10 but preferably closer to 15. If the cycle time for the blends end up being longer than those for PP this translates to a higher final cost which needs to be accounted for. However, the cycle time for a blend does not necessarily have to be longer and could in fact be shorter, this needs to be examined further at Plastitecnica (Italy) where Mammut and Trofast are produced normally and where all industrial sized equipment is located.

### Testing parameters

In Blends 1.0, test results from Fraunhofer was validated by doing similar testing at Swerea IVF. The result of this showed good conformity between Swerea IVF and Fraunhofer ICT, which led to the decision of letting Fraunhofer do the continued material testing. Tensile and mechanical parameters as well as different moulding machines/equipment were confirmed. The processes and testing parameters and descriptions can be found in Appendix C. To ensure a minimum of 20% bio-content in the final product, due to possible deviations, the amount of biopolymer was increased to 22% in the compounding.

### Cost/Performance matrix layout

The model which is presented below in Figure 22, Figure 23 and Figure 24 is an illustration of how we will present the cost/performance matrix. The blend formulation can be found in the top left corner of the figure. Below the matrixes are for the three PP specifications, PPCO2, PPCO4 and PPCO7. The properties on the different axis's range between the following values.

- Tensile Modulus: 0 - 2 000 MPa
- Elongation at yield: 0 - 10 %
- HDT: 0 - 200 °C
- Impact strength 0 - 20 kJ/m<sup>2</sup>
- Stress at yield 0 - 40 MPa
- Cost 0 - 4 €/kg

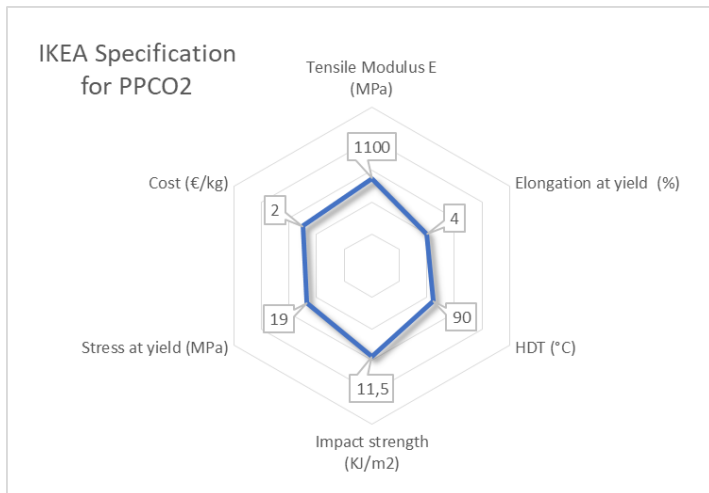


Figure 22. IKEA specification for PPCO2.

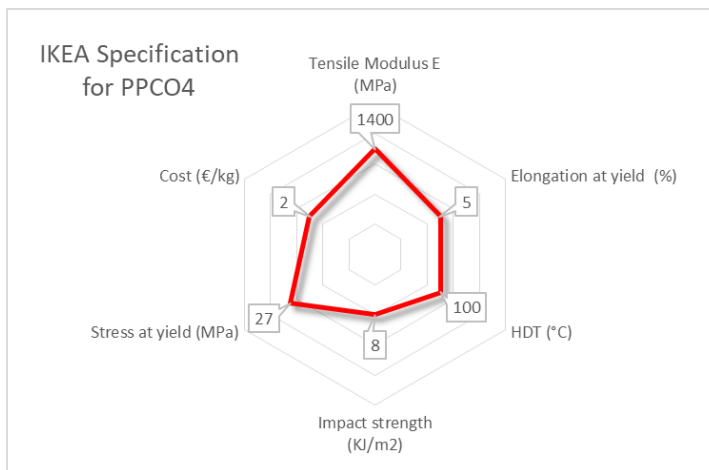


Figure 23. IKEA specification for PPCO4.

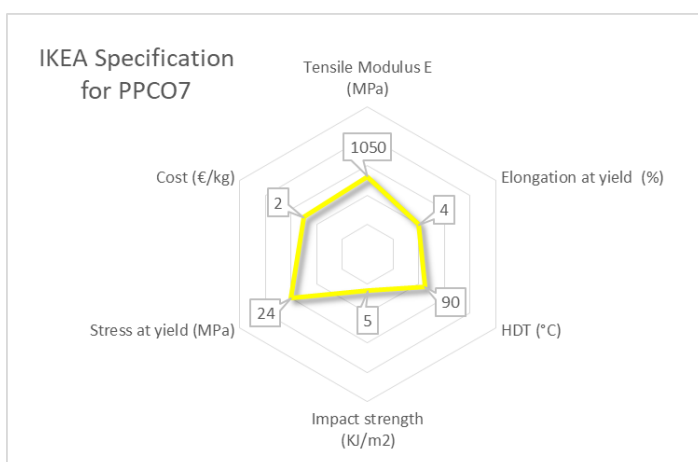


Figure 24. IKEA specification for PPCO7.

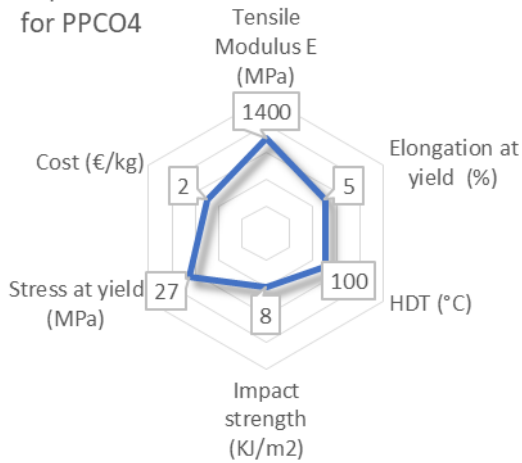
## Results

A blend between PHBV (22%) and PP (78%) without compatibilizer cannot reach any of the three PP specifications, but the only mechanical property not fulfilled for the PPCO7 is the elongation at yield where the value is 3,3 % (the required value is 4%). The similar blend with 25% PHBV also fulfills all values for PPCO7 except elongation at yield, where the value is 3,2%, just slightly less than the blend with 22% PHBV. The tensile modulus for these two blends is good with values over 1400 MPa. The addition of compatibilizers and fillers could not improve all the properties of the blend and the impact they have on the properties is explained below (and could also be found in [Appendix A](#)).

From previous trials it was shown that the blends of PP and PHBV post-crystallize for some time after the moulding (the material testing is done before this effect has diminished), where the effect is most pronounced in the first four weeks. The mechanical effects is a decrease in elongation at yield and impact strength, and an increase in tensile modulus. This is one reason why it becomes problematic to use blends with an already to low elongation at yield (e.g. the blend of PP/PHBV without compatibilizer) as this will become even lower in the actual product. The compatibilizer could counter compensate this effect and make a blend suitable a long time after processing as well. More importantly the compatibilizer homogenize the blend, without it the blend would delaminate when processed since PP is highly immiscible with PHA. For the low MFR values, Fraunhofer ICT acknowledges this as a problem, and they believe that the MFR value for PPCO7 (50 g/10 min) is out of reach. Still they believe that values of 10-15 g/10 min will be good enough for processing, and with the use of flow improvers the value could be increased further. Processing with given parameters specified in Appendix B and Appendix E give rise to pellets and test bars without problems of over-moulding and delamination. This indicates that the blend material will be processable in large scale production. Only exception was for the blends without compatibilizer where some delamination at the injection point could be seen. Sometimes surface irregularities were visible.

For the PHBV/PP blends, we have chosen to present the cost/performance matrix for nine different blends. We have evaluated the properties and cost for all blends of the different blend families (e.g. one family is for Compatibilizer A1 and another one is for Compatibilizer A2) within Blends 1.5 and chosen to present the best one for each of these. In Figure 25, the relevant specifications (PPCO2 was considered out of reach for these blends) are shown where the required values are displayed.

IKEA Specification  
for PPCO4



IKEA Specification  
for PPCO7

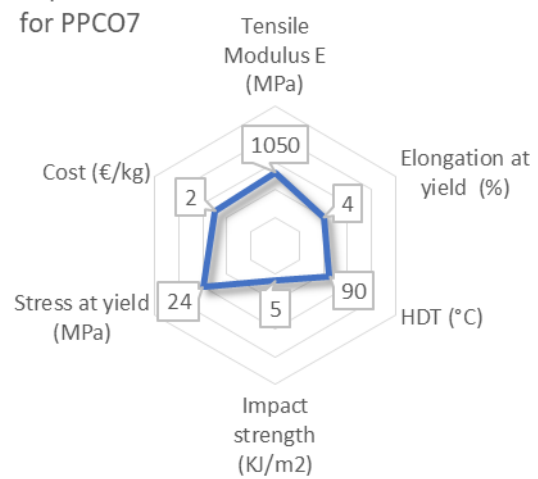
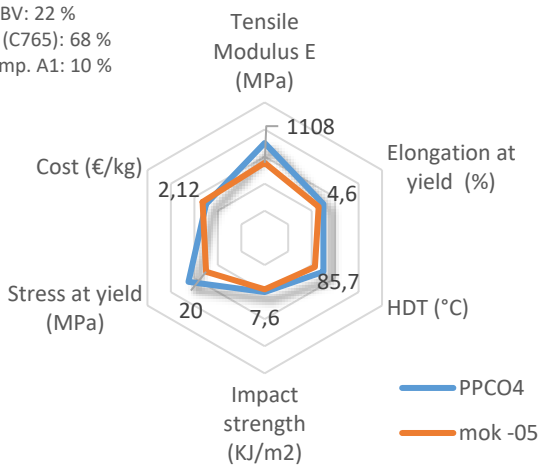


Figure 25. Specifications PPCO4 and PPCO7.

In Figure 26-Figure 34 the blend properties are plotted against the specifications, (note that the values seen in Figure 26-Figure 34, correlate to the blend and not the specification) the values are also documented in [Appendix A](#), where additional values for MFR also is shown. The names of the blends and the used specification are displayed together with the formulation of the blend in the top left corner of every diagram. Two of the blends are missing HDT measurements and are therefore left blank.

**MOK-05, PPCO4**

PHBV: 22 %  
PP (C765): 68 %  
Comp. A1: 10 %



**MOK-05, PPCO7**

PHBV: 22 %  
PP (C765): 68 %  
Comp. A1: 10 %

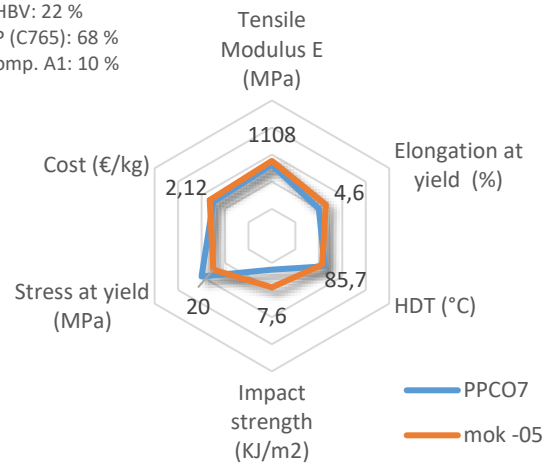
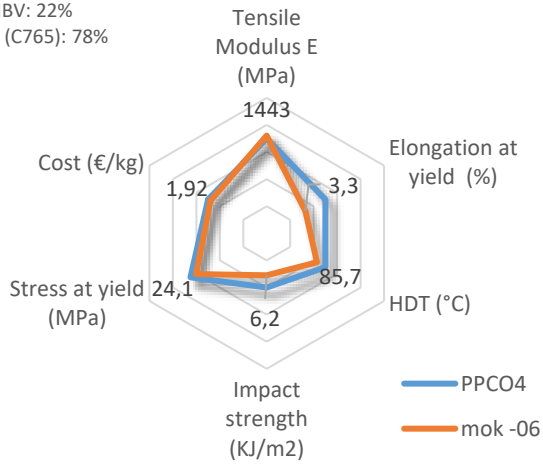


Figure 26. MOK-05.

**MOK-06, PPCO4**

PHBV: 22%  
PP (C765): 78%



**MOK-06, PPCO7**

PHBV: 22 %  
PP (C765): 78 %

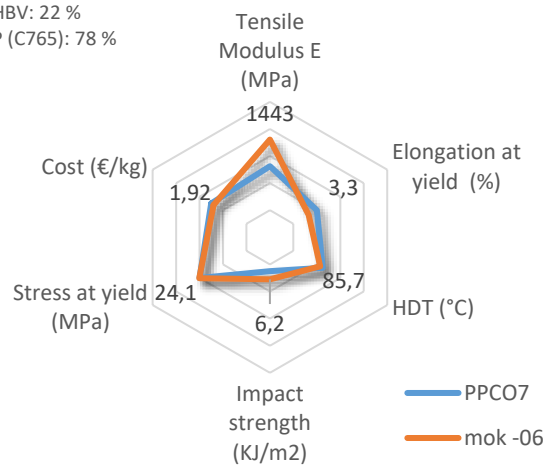
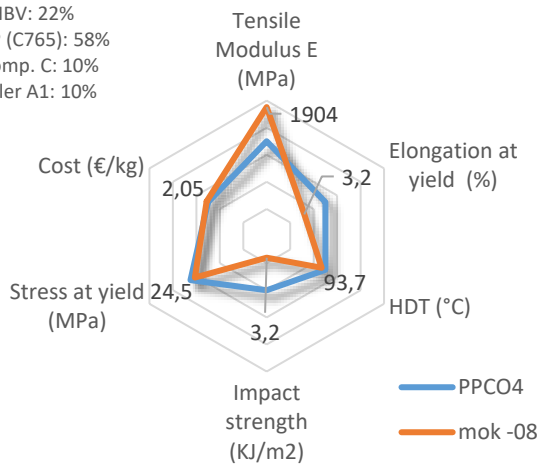


Figure 27. MOK-06.

**MOK-08, PPCO4**

PHBV: 22%  
PP (C765): 58%  
Comp. C: 10%  
Filler A1: 10%



**MOK-08, PPCO7**

PHBV: 22%  
PP (C765): 58%  
Comp. C: 10%  
Filler A1: 10%

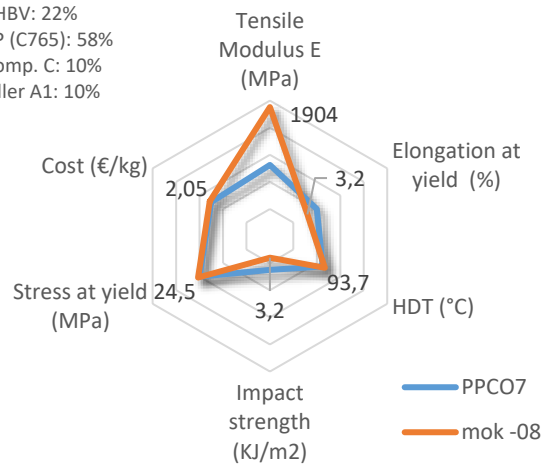
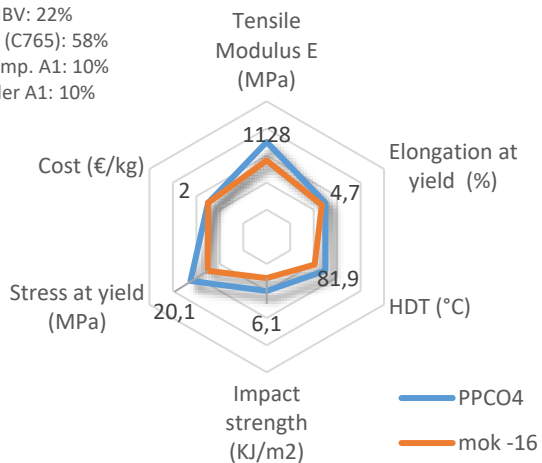


Figure 28. MOK-08.

**MOK-16, PPCO4**

PHBV: 22%  
PP (C765): 58%  
Comp. A1: 10%  
Filler A1: 10%



**MOK-16, PPCO7**

PHBV: 22%  
PP (C765): 58%  
Comp. A1: 10%  
Filler A1: 10%

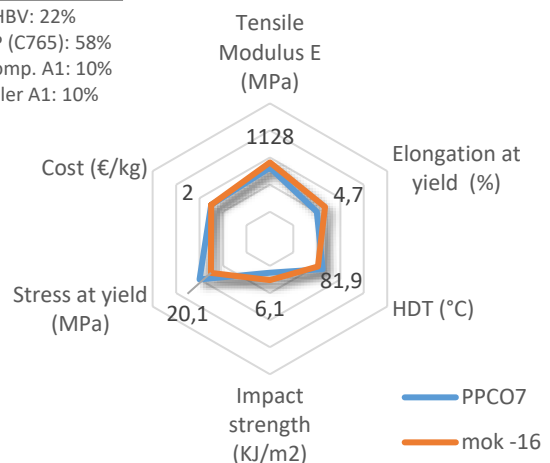
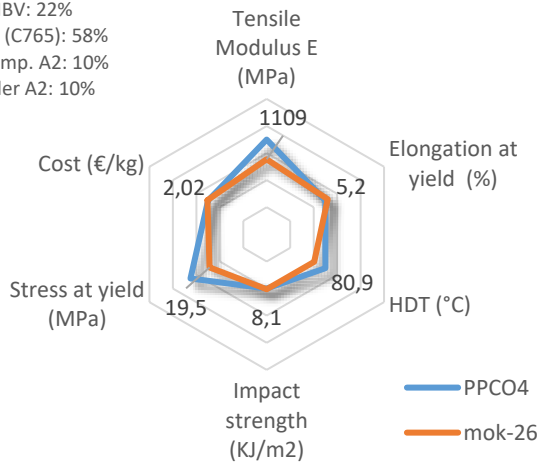


Figure 29. MOK-16.

**MOK-26, PPCO4**

PHBV: 22%  
PP (C765): 58%  
Comp. A2: 10%  
Filler A2: 10%



**MOK-26, PPCO7**

PHBV: 22%  
PP (C765): 58%  
Comp. A2: 10%  
Filler A2: 10%

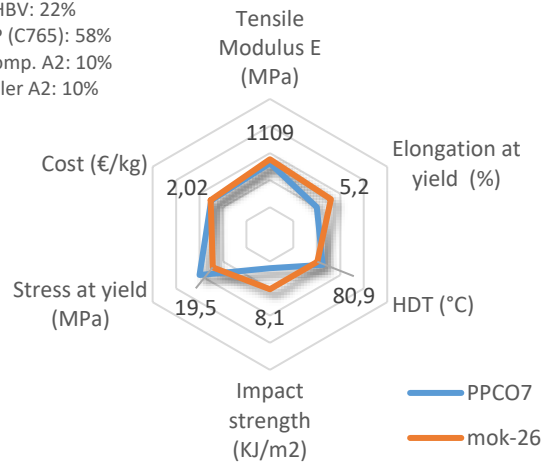
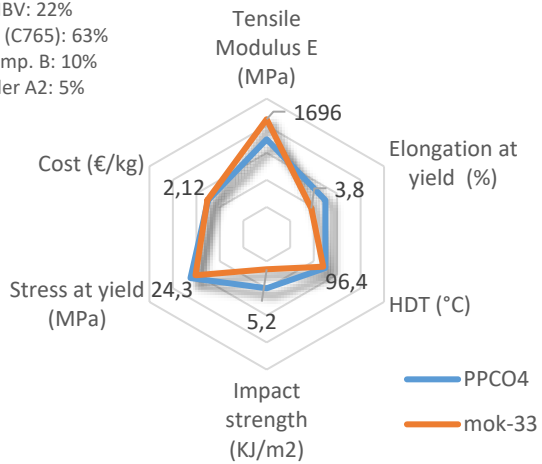


Figure 30. MOK-26.

**MOK-33, PPCO4**

PHBV: 22%  
PP (C765): 63%  
Comp. B: 10%  
Filler A2: 5%



**MOK-33, PPCO7**

PHBV: 22%  
PP (C765): 63%  
Comp. B: 10%  
Filler A2: 5%

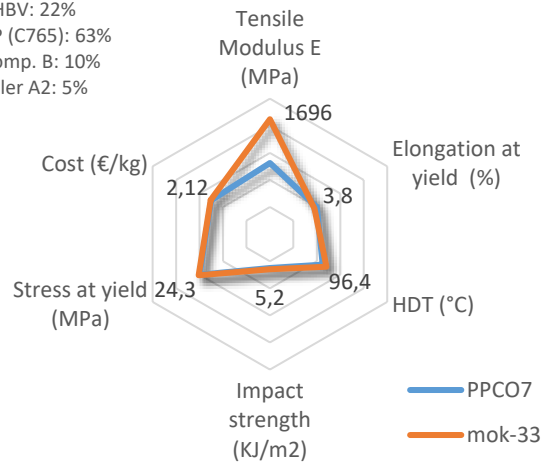
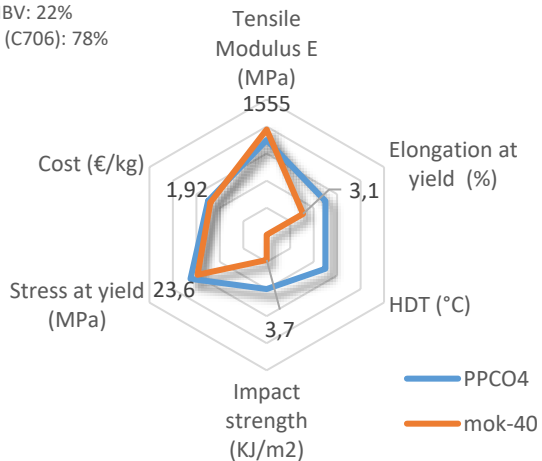


Figure 31. MOK-33.

**MOK-40, PPCO4**

PHBV: 22%  
PP (C706): 78%



**MOK-40, PPCO7**

PHBV: 22%  
PP (C706): 78%

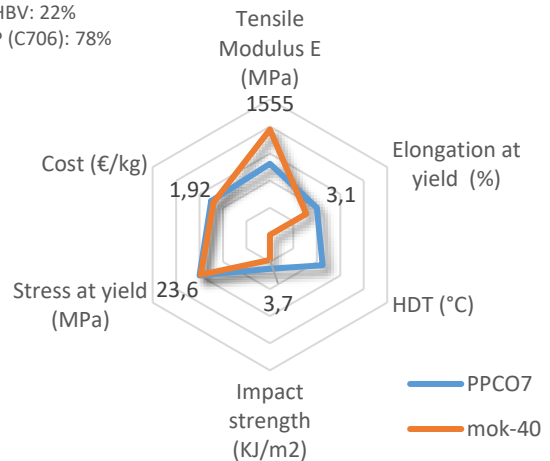
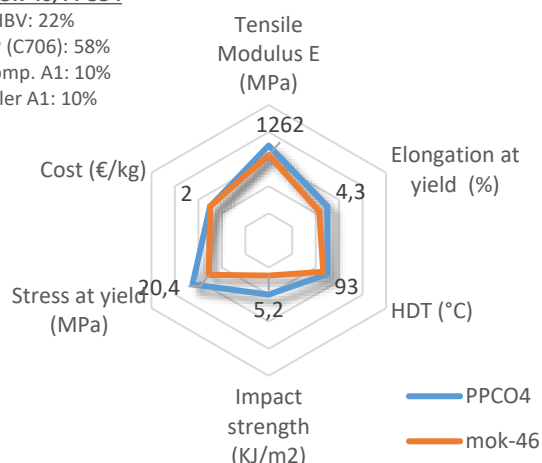


Figure 32. MOK-40 (HDT values missing).

#### MOK-46, PPCO4

PHBV: 22%  
PP (C706): 58%  
Comp. A1: 10%  
Filler A1: 10%



#### MOK-46, PPCO7

PHBV: 22%  
PP (C706): 58%  
Comp. A1: 10%  
Filler A1: 10%

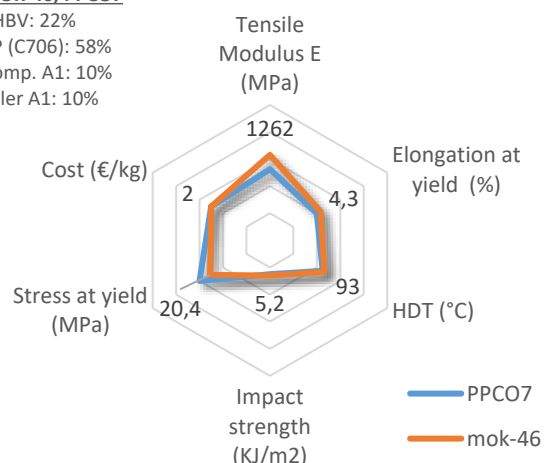
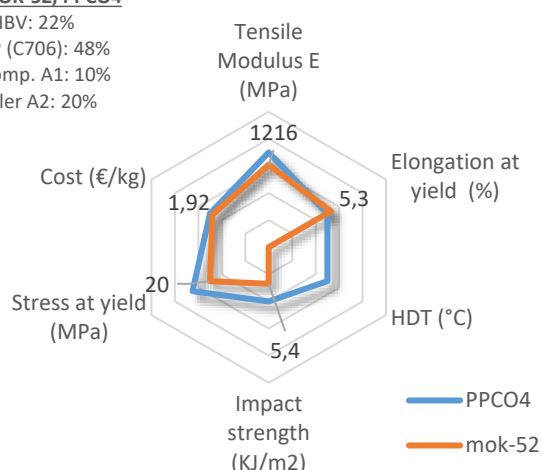


Figure 33. MOK-46.

#### MOK-52, PPCO4

PHBV: 22%  
PP (C706): 48%  
Comp. A1: 10%  
Filler A2: 20%



#### MOK-52, PPCO7

PHBV: 22%  
PP (C706): 48%  
Comp. A1: 10%  
Filler A2: 20%

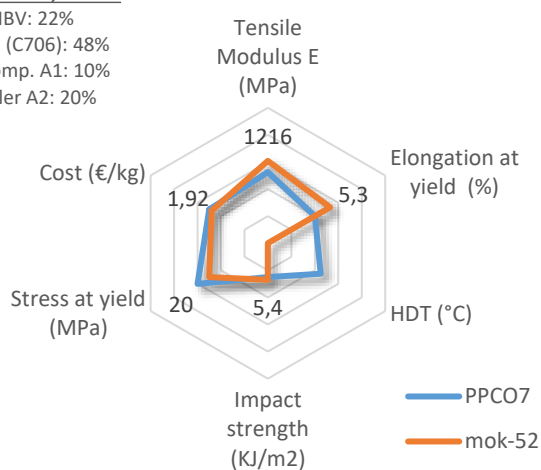


Figure 34. MOK-52 (HDT values missing).

Four different compatibilizers were investigated, Compatibilizer B, Compatibilizer C and two different grades of Compatibilizer A, 1 and 2. The mechanical and thermal properties of the different blends can be seen in [Appendix A](#). Some clear trends can be seen regarding the compatibilizers.

- Compatibilizer C could be used as an additive to reach every IKEA specification regarding the tensile modulus with values reaching as high as 1900 MPa. Stress at yield and HDT also show promising values for this compatibilizer. Comp. C also gives the highest MFR value of the four compatibilizer. Unfortunately, none of the blends containing Comp. C reach the lowest IKEA standard regarding impact strength, regardless of what talc/chalk material that is used.

- The blends of with Compatibilizer B have an overall good tensile modulus with values as high as 2200 MPa, and indications show that the HDT is good for these blends. The impact strength and stress at yield could reach the PPCO7 depending on what kind of additive is used and the amount of Comp. B. The major drawback lies in the elongation at yield with values between 2.7 - 3.8%.
- Compatibilizer A1 increases the impact strength of the blend but as the impact strength is improved the modulus drop. With the exception of one case, these blends with bio content of 20, 22 and 25% all reach the PPCO7 specification in terms of impact strength, tensile modulus and elongation at yield. The highest noted impact strength was 7,5 kJ/m<sup>2</sup> and highest tensile modulus 1128 MPa. The drawback for this Compatibilizer A grade lies within the stress at yield, HDT and MFR value.
- Compatibilizer A2 has similar effects as the Comp. A1, increasing the impact strength and lowering the modulus. However, results indicate that the Comp. A2 version is more favourable to use. The impact strength is increased to a greater extent and the drop of modulus is similar to the Comp. A1 version. Every blend reaches the PPCO7 standard in terms of impact strength, tensile modulus and elongation at yield when using the Comp. A2, and when using Filler A2 as an additive the PPCO4 is reached for impact strength. Comp. A2 has the same drawbacks as the Comp. A1 with insufficient stress at yield, HDT and MFR values.

The addition of compatibilizer does not improve the overall mechanical properties drastically, and in many cases the compatibilizer have a negative overall effect (compared to the blend without compatibilizer). Depending on the choice of compatibilizer some parameters are improved at the expense of another and there is no crystal-clear option. Evidently, it is very troublesome to improve the blends with a suitable compatibilizer.

The addition of chalk and talc to the blends seem to lower the impact strength and leave the modulus at similar values, meaning that the benefit of using these additives would only be the cost reduction. The increase between 5% and 10% of talc/chalk results in lower impact strengths for every blend, it is difficult to draw a conclusion about the modulus and the rest of the properties. In some cases, the values remain similar, in others they slightly change. Further examination of this would be interesting.

The prices for the formulations within Blends 1.5 can be found in [Appendix A](#), and the calculations can be found in Appendix D. With the estimated price of materials (supplied by IKEA and Fraunhofer) as well as the compounding cost, the material price ranges from roughly 1 900 €/ton to 2 150 €/ton. From a material property perspective, the amount of talc and chalk is limited to 5-10 %, which limit the cost reduction to some extent.



Two different grades of PP were examined (PP C765-15NA and PP C706-21) in blends together with the PHBV material in the compositions 20/80, 22/78 and 25/75 with the lower value being PHBV. The values of stress at yield, tensile modulus and elongation at yield is similar for both PP grades. Difference can be found in the impact strength and MFR values, with higher impact strength for PP C765-15NA and higher MFR for the PP C706-21. The PP C765-15NA is a better material for these types of blends, but further studies on additional PP grades could be interesting as these could be a better fit for the IKEA specification.

The blends are overall closer to fulfilling the PPCO7 specification than the PPCO4 where MOK-33 (Figure 31) currently is the blend closest to fulfilling all the material specifications with just a slightly to low value of the elongation at yield (3.8%). The price for MOK-33 is 2120 €/ton. Still it is important to have in mind that these matrices are created to give a quick overview of the blends in relation to the different standards, hence they do not give the complete picture of what is required for a blend to become commercial (the reader is encouraged to go through all the results in the [Appendix A](#)).

## Discussion

### Project discussion

As a PHA material (PHBV) was chosen for blending, PLA and PBS was discarded. PLA could prove to be useful for these blends in time, and companies like PURAC are looking into creating PLA materials with high crystallinity which could be interesting. PBS is definitely suitable from a performance point of view, but the commerciality of bio-based PBS is limited, with low volumes at high cost as major issues. On top of that, today most bio-PBS are only partly bio based which make it harder to reach the minimum of 20% bio-content.

As the PHA material is polymerized by microorganisms there is no need to use any additional catalyst. This is the case for PLA, where a metal catalyst often is utilized, usually it is tin-based and thereby hazardous. However, the extraction of polymer from the microorganism and purification of the PHA materials has proven to be troublesome and leads to significantly lower overall yields. Tianan claims to have a process for PHBV extraction which is a solvent free, water-based route [41]. To reduce the price of PHA it could be favourable to develop an effective continuous process, that could challenge the batch process which is commonly used for these types of conversions/polymerisation processes. The PHBV material was originally chosen for two main reasons, the sufficient properties seen in Blends 1.0 and the potential price of the material. The PHBV material “Enmat Y1000P” which was supplied by Tianan has a valerate content of 3% [41], another supplier could have a PHBV material with different content an varying molecular weight. According to Fraunhofer ICT the material properties of blends with PHBV would be similar if the valerate content varies with several percent. Because of this, different suppliers who supply PHBV could likely be used with little or no processing modification, still further

evaluation of this is required. Regardless if the final blend product ends up within the price range that IKEA is aiming for, the fact is that the supply of PHBV material is highly limited. According to Kevin Mooser, at Fraunhofer ICT, Tianan is currently the only PHBV supplier that can deliver a consistent material in somewhat larger volumes without issues. Even though capacity was left out of this thesis, this is something that should always be considered, especially when realizing the volumes of polymers that is currently being used at IKEA.

Talc and chalk are not considered biomaterials, they are mineral fillers and usually mined in large volumes then grinded into fine powder for processing. Even though not considered bio based, it could be seen as a better alternative as it replaces fossil PP. Still, the way the material is processed today might not be a sustainable solution and the circularity is questionable. Also, since these additives are mineral based, the density is often higher than that of the polymers, which in turn will affect the density. An increase in density would increase transportation costs and emissions of the finished product.

Throughout the project the blends were all created for intended use in “Trofast” and “Mammut”. This discussion aims to give as many angles to this as possible, it is important to reflect over the fact that this report is written from an innovative perspective. When discussing blends as a concept with the mechanical design engineer responsible for these products at IKEA, additional angles are revealed. Besides using different ISO standards (such as ISO-MAT-0054 for chemical requirements), within “Children’s” IKEA the products are classified as low, medium and high-risk products depending on how they interact with kids. Mammut and Trofast serves as good examples of how the products are classified as they are a part of children’s IKEA.

- Trofast, which is considered a low risk product, is not intended for direct and interactive contact with kids, meaning they will not eat something that has been in contact with the product or have direct skin contact for long periods of time.
- Mammut is intended for children between 3 to 6 years, as a stool. Therefore, skin contact is bound to happen, and it is regarded as a possible source of absorbing toxic substances through the skin, therefore it is classed as a medium risk product.
- A high-risk product would be in contact with food or something that a child would keep in its mouth, e.g. plates and cutlery.

The blends are more likely to be used in Trofast than in Mammut, due to the classification of low and medium risk. Furthermore, even if the compatibilizers and additives are considered nontoxic, these will have to be approved in the final products. The final blend which could be a mix of 4-5 different components (not

including UV-stabilizers) could very well not pass the internal demands besides the mentioned specifications (PPCO2, PPCO4 and PPCO7). Another thing, which is important for the blends to become commercial products, is to have products without any odour, bad smell or toxic additives/fillers. This is not within the scope of this thesis but is worth mentioning and could be difficult with certain compatibilizers etc. Comp. A1&2 is one of the best compatibilizer, but it has a distinct smell in its pure form and that is a concern for consumer applications. Investigation needs to be done on finished products in how much they smell. Another important aspect is colour, kaolin was examined as a filler with similar function as talc or chalk, however kaolin gave a yellow tone on the moulded product and it became difficult to colour with a colouring agent. Having a product with a white tone is easier to colour.

### Recyclability

For the recyclability, blending generally creates a problem. As a plastic product of PP only consists of one constituent, the sorting and categorizing is easier than for a blended product. To optimize the blends between polymers several additives will be used, e.g. compatibilizers, impact modifiers, talc, plasticizers. Understandably this will imply a more difficult reuse of the components, and a blended product would need a separate process to be effectively recycled. For IKEA it will become important to be crystal clear on the purpose of their “sustainable” products. Within the IKEA sustainability goals renewability and circularity is mentioned as two of the crucial driving factors. However, these might end up in conflict with each other for several product streams, where the blends could become one example. Introducing renewable content might prove to be troublesome for the recycling of the blends, since the material become more complex. Still there is a possibility to recycle blends but it is a very complicated question to address. The most well-developed system of recycling plastics is for PET bottles, where the food and beverage industry are consistently creating huge volumes of material due to the nature of the products, where the EoL is reached quickly. Materials other than PET could be separated in an integrated system using “NIR = Near Infrared Ray” technology [10], NIR can determine the chemical composition of different materials and hence separate in an efficient manner. Since biopolymers generally have a higher density compared to petrochemical polymers, theoretically they could also be separated using a mechanical technique such as floating or air funnel separator. However, currently the size of waste streams is too small for recycling of an individual plastic product. When addressing circularity, IKEA is in a different position than companies working with, for example, PET bottles, and perhaps another outcome than “traditional” recycling would be favourable. An advantage of IKEA products is the expected long lifetime, it is possible that a Mammut or Trofast is used closer to a decade in one household and they are likely still functional. At this point, the most favourable outcome would be further use after selling or donating the product, which is likely to happen for such a product. The second best alternative from a sustainable point of view would be recycling. As the final alternative, energy recovery by incineration is an option (done for most plastics today). As the option from a technical point of view is presented, then comes the regional aspects:

- In North America the absolute most common way of disposing waste, including plastic products is deposition in landfills. Which is neither sustainable nor is it driving the shift towards product circularity.
- For Northern Europe majority of the waste streams end up being incinerated for the heating of water and houses.
- In general, for Southern Europe management of waste and the system of collecting/treating it remains unclear, and ambiguous at best.
- For most parts of Asia (excluding the more developed regions) certain stages of the waste supply chain is connected to issues around child labour [10].

In a perfect world, it is possible to create a system which is sustainable and circular. However, with the stated facts above and a low price for petrochemicals, discussions about upcycling or downcycling is in fact not realistic. It is important to understand that the infrastructure of recycling is under development or even non-existing, and the regional differences is overwhelming. Right now, the best solution seems to be increasing the bio content as much as possible, and then when the product comes to its EoL, incinerate it and make use of the energy. A question could be why focus on blends at all? They just make an already difficult recycling even more complex. Would it not be better to use a pure material, than a blend material?

For the price estimations of PHA, we believe they are thoroughly done, but optimistic. For a price of 2500 €/ton, major processing improvements must be successful. To reach the price Neste Jacobs [38] concludes that higher yields and a more continuous fermentation should be developed. This price is based on building a new factory, this means large investments and several years of planning, construction and process optimization. Meanwhile, IKEA should talk to the producers of the material used today, asking them for a price estimation for purchases of large volumes. Tianan, that produces the PHBV, should have knowledge about their costs and future perspectives. In the event of IKEA requesting large volumes, there may be an opportunity for Tianan to extend their production. Hopefully, prices for bioplastics will decrease in the future as the scale of production increases and because of regulations and drive of companies considering and prioritizing the environment.

### General discussion

As mentioned in the introduction, there are companies who in the near future predicts a change within their organisations, moving towards the use of renewable feedstocks and sustainability. However, not everyone is prepared to do what is required and necessary. This has in many cases led to a standstill where only some dare to invest. It is crucial that development and future production of BBMC meet the demands for downstream application, and the consumers needs to push for the use of these materials. Still within every section of the value chain, actors will have to take a leap of faith in order to reach the needed transformational change.

The lower cost of the fossil material is continuously hindering the transformation towards the use of biomaterials. Also, these materials can be supplied at much larger

volumes. The high cost and small volumes for most biopolymers are correlating, and economies of scale could make some of the biopolymers commercially viable and competitive. Since a majority of producers are using fossil materials for their products, the incentives of producing high volumes of biopolymers are scarce and to produce high volumes of biopolymers is currently a high-risk investment. In terms of sustainability for future people and planet, IKEA is trailblazing with a bold strategy to reach the sustainability goals of 2020, 2025 and 2030. An interesting discussion, which will be critical to address more frequently soon, is the fact that renewable content and circularity might come at a premium price. As of today IKEA is reluctant to increase the price on commercially available products, which means that a more expensive material could end up suitable for only a few existing products or completely new ones. There is a possibility where the only way to reach the sustainability goals is through raising the product cost significantly, however a low cost is necessary for product availability to many people. As of today, IKEA has over 400 stores worldwide and are continuously expanding to new regions, and it is important to reflect over the fact that what might be available and affordable for a European customer might not be for someone living elsewhere. In order to target the many people in a worldwide context, the pricing must meet every customer and not only people in certain regions.

One of the major limitations for the upscale of BBMC is the feedstock availability and it is important to create a sustainable synergy between feedstock for the production of food and for chemicals. Since this planet is already overpopulated and starvation is a problem in many places [42], using first generation feedstock is not a good solution, even if it is just a fraction ( $<0,1\%$ ) of the arable land that is used for biopolymer production. The population is predicted to grow fast (9 billion by 2050 [43]). Even if it can be motivated to use food as feedstock right now, it might be problematic in the future when bigger volumes of polymers is a prerequisite and demand for food will be higher. Balance and weighing the care of people against the environment is a tough situation and something that hopefully can be avoided to the largest possible extent. Taking the exploitation of the rainforest and biodiversity into account, the use of palm oil and other similarly grown feedstocks needs to stop. Choosing the right feedstock for a specific area should also be a concern. Plantations of water needing feedstock where water is scarce or destroying nature to expose land for cultivation must be avoided. IKEA, being a global corporation, is continuously being watched from external actors, which has led to IKEA having very tough specifications, not only their products, but also on the origin of them. In practice feedstocks that is considered renewable, might be acquired through inhumane working conditions i.e. child labour and therefore not an option. The strict internal regulations on IKEA products could lead to a slower process, but as it is completed, other companies are likely to follow in the footsteps.

Looking forward, the production of PHA materials could get a boost if companies such as Oakbio and Newlight Technologies manages to commercialise a process which utilize gases such as carbon dioxide ( $\text{CO}_2$ ), carbon monoxide ( $\text{CO}$ ) and methane ( $\text{CH}_4$ ). Another interesting option, which has gotten a lot of attention without

leading to a commercial breakthrough, is the fermentation of waste streams to produce PHA. A mix of different PHA producing microorganisms could be used to convert the available carbon from different types of waste, still this has not reached commerciality due to low overall yields and availability of consistent waste streams.

## Conclusions

To start the conclusion, we return to the final part of the introduction where the four cornerstones of the blend was introduced; cost, performance, recyclability and capacity. With the early results of Blends 1.0 Fraunhofer concluded that multiple materials with ranging bio content fulfil or is very close to fulfilling the IKEA material specifications. However, most of these blends did not match the requirement of a final material where the cost limit is 2 000 €/ton. As cost and performance was the major focus PLA and PBS was discarded for the Blends 1.5.

- We concluded that PLA would not meet the IKEA performance requirements in blends with PP
- PBS showed promising material performance, but the price was considered too high.

The additional cost of hiring an external compounder would preferably be avoided. To effectively blend the polymers and possibly incorporate this process in the existing value chain could be crucial to achieve the price requirement. As external compounding most likely will lead to an additional cost (estimated to 200 €/ton). Introducing talc/chalk as a filler could reduce the cost. With the estimated prices given by IKEA and Fraunhofer, for every 10% talc/chalk that replace PP, the final price is reduced by roughly 100 €/ton depending on what additive is used. A conclusion is that no more than 10% of filler can be added if the desired properties is to be reached.

The different blends with 22% PHBV show different properties depending on what compatibilizer that is being used, with only values of elongation at yield and MFR not reaching the IKEA specifications. Besides the slightly too low mechanical properties of a blend without compatibilizer, due to post crystallization and delamination, a compatibilizer is needed. We believe MOK-33 (Figure 31) currently is the blend with the overall best properties. However, no blend fulfils a complete set of properties required for any of the different IKEA specifications. More importantly, a lot of these blends are still close to reaching PPCO7 with an affordable price, continuous testing is being performed. After working in close collaboration with IKEA and Fraunhofer ICT in this project, we can conclude that it is technically possible to use these blends for injection moulding, the question is whether these materials could compete commercially. We consider the individual cost of polymers, compatibilizers, additives and compounding and think that it is possible to create a blend with a price between 2000-2200 €/ton, although further testing on process parameters such as cycle time and compounding is needed.

Initially, the aim was to injection mould the IKEA products “Mammut” and “Trofast” with the most promising blends. This would have given valuable information on the commerciality in terms of processing and industrial scalability. We believe this is absolutely necessary, but as time was short it had to be excluded for this thesis.

Little is known about the properties and chemical interaction of these blends. IKEA is trailblazing in terms of commercial application, if this concept is improved and commercialized it could make a big impact for people and planet. However, the IKEA material specifications are based upon PP which is an impressive material, and to meet these requirements is no easy feat. As new biopolymer materials such as PHA are developed, the learnings and knowledge from this project will be increasingly important. Blending polymers enables the ability to tailor your material to great extent, but the variables are many and the number of material combinations is huge, and most is yet undone!

## References

- [1] J. Y. G.-Q. C. Ying Wang, "Polyhydroxyalkanoates, challenges and opportunities," *Current Opinion in Biotechnology*, vol. 30, nr 0958-1669, pp. 59-65, 2014.
- [2] Braskem, "Annual report 2016," Braskem, 2016.
- [3] Bayer, "Annual report 2011," Bayer AG, 2011.
- [4] D. H. Klusik, "Bayer," 04 2018. [Online]. Available: <https://www.bayer.com/en/sustainability.aspx>. [Använd 03 05 2018].
- [5] M. C. H. Corporation, "Pursuing Innovation and Sustainability to Build Corporate Value-Annual report 2011," Mitsubishi Chemical Holdings Corporation, 2011.
- [6] Coca-Cola, "2016 sustainability report," Coca-Cola Company, 2016.
- [7] Danone, "DANONE GOALS FOR A FOOD REVOLUTION BY 2030," [Online]. Available: <http://www.danone.com/en/for-all/our-mission-in-action/danone-goals-2030/>. [Använd 04 05 2018].
- [8] Nestle, "Improve packaging performance," [Online]. Available: <https://www.nestle.com/csv/impact/environment/packaging>. [Använd 04 05 2018].
- [9] IKEA, "People & Planet - IKEA Group Sustainability Strategy for 2020," IKEA, 2014.
- [10] P. Trehan, Interviewee, *Polymer Group Leader*. [Intervju]. 2018.
- [11] V. O. R. K. Gihan Hewage, "Global Biopolymer Outlook 2026: Forecasting Growth in the Next Decade," LUX Research, 2017.
- [12] P. W. A. L. W. C. J. S. S. S. A. D. W. M. M. L. G. V. J. H. H. H. V. A. C. A. D. Peter J. Mackey<sup>1</sup>, "Chemicals: 'Green is Good' – The Potential of Bioplastics," Morgan Stanley Research, 2012.
- [13] M. B. M. A. Y.-S. Y. N. W. J. A. Andrew Soare, "Quantifying Cost and Availability of Cellulosic Feedstocks for Biofuels and Biochemicals," Lux research, 2014.
- [14] A. S. M. B. M. H. Kalib Kersh, "Finding Feedstocks for the Bio-Based Fuels and Chemicals of Today and 2030," Lux reserach, 2012.
- [15] J. A. M. A. M. B. Andrew Soare, "Cellulosic Chemicals and Fuels Race to Compete with First-Gen Sugar Economics," Lux research, 2013.
- [16] T. B. Wim J. Groot, "Life cycle assessment of the manufacture of lactide and PLA biopolymers from sugarcane in Thailand," 2010.
- [17] I. f. B. a. Biocomposites, "Production diagram for Biopolymers," 2013.
- [18] NPTEL, "Stereoisomers of lactic acid," 08 16 2013. [Online]. Available: <http://nptel.ac.in/courses/116102006/16>. [Använd 16 02 2018].



- [19] S. D. K. B. Group, "http://www.showa-denko.com," March 2015. [Online]. Available: [http://www.showa-denko.com/wp-content/uploads/2015/03/Bionolle\\_2015.pdf](http://www.showa-denko.com/wp-content/uploads/2015/03/Bionolle_2015.pdf). [Använd 5 March 2018].
- [20] A. S. Meraldo Antonio, "Comparing the Performance and Addressable Markets for Biopolymers," Lux research, 2015.
- [21] K. M. Y. K. Chan Woo Lee, "Ring-opening polymerization of a macrocyclic lactone monomer isolated from oligomeric byproducts of poly(butylene succinate) (PBS): An efficient route to high-molecular-weight PBS and block copolymers of PBS," *Polymer*, vol. 55, nr 22, pp. 5673-5679, 2014.
- [22] JustJournal, "The Clinical Future of Polyhydroxyalkanoates," 16 04 2016. [Online]. Available: <http://justjournal.org/2016/04/16/biomaterials/>. [Använd 03 05 2018].
- [23] PT, "Plastic Technology-Compounding," Gardner Business Media, Inc., [Online]. Available: <https://www.ptonline.com/zones/compound>. [Använd 5 March 2018].
- [24] J. Bruck, "IKEA plastic material directions," IKEA, Älmhult.
- [25] R. K. V. O. Gihan Hewage, "Navigating the Web of Bio-based Performance Materials," LuxResearch, 2016.
- [26] J. Gotro, "Polymer Innovation Blog," Innocentrix, 8 April 2013. [Online]. Available: <https://polymerinnovationblog.com/polyethylene-furanoate-pef-100-biobased-polymer-to-compete-with-pet/>. [Använd 25 04 2018].
- [27] Y.-S. Y. Andrew Soare, "CO2 Conversion to Fuels and Chemicals," Lux research, 2015.
- [28] E. F. B. P. Erika Fekete, "Effect of molecular interactions on the miscibility and structure of polymer blends," *European Polymer Journal*, vol. 41, nr 4, pp. 727-736, 2005.
- [29] A. K. M. a. M. M. Michael R. Snowdon, "Miscibility and Performance Evaluation of Biocomposites Made from Polypropylene/Poly(lactic acid)/Poly(hydroxybutyrate-co-hydroxyvalerate) with a Sustainable Biocarbon Filler," *ACS Omega*, vol. 2, nr 10, 2017.
- [30] A. & G. M. & K. L. H. & C. L. P. & L. J.-Y. & W. C. & M. R.-I. & C. T.-C. Abay, "Preparation and characterization of poly(lactic acid)/recycled polypropylene blends with and without the coupling agent, n-(6-aminohexyl)aminomethyltriethoxysilane.," *Journal of Polymer Research*, vol. 23, nr 9, 2016.
- [31] S. S. R. W. W. F. A. M. Thabo Gcwabaza, "Morphology and properties of nanostructured materials based on polypropylene/poly(butylene succinate) blend and organoclay," *European Polymer Journal*, vol. 45, nr 2, pp. 353-367, 2009.
- [32] S. S. R. W. W. F. A. M. Thabo Gcwabaza, "Morphology and properties of nanostructured materials based on polypropylene/poly(butylene succinate) blend and organoclay," *European Polymer Journal*, vol. 45, nr 2, pp. 353-367, 2009.

- [33] J. K. M. W. T. Z. L. C. H. Jayven Chee Chuan Yeo, "Recent advances in the development of biodegradable PHB-based toughening materials: Approaches, advantages and applications," *Materials Science and Engineering:C*, 2017.
- [34] R. S. K. G. J. F. N. R. D. Roberta K Sadi, "Compatibilization of polypropylene/ poly(3-hydroxybutyrate) blends," *Journal of Applied Polymer Science*, vol. 123, nr 6, pp. 3511-3519, 2012.
- [35] A. H. Kevin Moser, "Renewable Blends potential 2 Project Final report," Fraunhofer-Institut für Chemische Technologie (ICT), Pfinztal, 2016.
- [36] IKEA, "www.ikea.com," [Online]. Available: [www.ikea.com](http://www.ikea.com). [Använd 16 02 2018].
- [37] K. Moser, Interviewee, *Development engineer at Fraunhofer*. [Intervju]. 11 04 2018.
- [38] NesteJacobs, "Optimum production process for bioplastic Project Report," 2017.
- [39] J. Martinsson, Interviewee, *Compounding cost*. [Intervju]. 11 04 2018.
- [40] FraunhoferICT, *IKEA project pictures*, Fraunhofer ICT.
- [41] TianAn, "TianAn Biopolymer ENMAT," TianAn Biologic Materials Co., 2017. [Online]. Available: <http://www.tianan-enmat.com/>. [Använd 18 04 2018].
- [42] WHO, "World hunger again on the rise, driven by conflict and climate change, new UN report says," World Health Organization, 15 09 2017. [Online]. Available: <http://www.who.int/en/news-room/detail/15-09-2017-world-hunger-again-on-the-rise-driven-by-conflict-and-climate-change-new-un-report-says>. [Använd 02 05 2018].
- [43] D. D. GUZMAN, "Sustainable Sourcing of Feedstocks for Bioplastics," Green Chemicals blog, 25 10 2016. [Online]. Available: <https://greenchemicalsblog.com/2016/10/25/sustainable-sourcing-of-feedstocks-for-bioplastics/>. [Använd 03 05 2018].
- [44] K. K. A. S. Mark Bünger, "Pruning the Cost of Bio-Based Materials and Chemicals," Lux research, 2012.

# Appendices

## Appendix A

### Results and price

Test No.	Notched impact strength kJ/m2	Stress at yield $\sigma$ std. in MPa	Tensile Modulus E std. in MPa	Elongation at yield $\epsilon$ std. in %	HDT std.	MFR std.	POLYMER (P/HR)	Loading [%]	Polymer 2 (PP)	Loading [%]	Compatibilizer [%]	Loading [%]	Filler	Loading [%]	Price €/ton
mxk00048301	6.3 0.1	24 0.2	1441 11	3.5 0.1	101.47	5.4	11.6 Emmat Y1000P	20	PP C765-15NA	20	80	10 A1	10 A1	1900	
mxk00048306	6.2 0.2	24.1 0.1	1443 15	3.3 0.1	85.7 2.11	12.1	Emmat Y1000P	25	PP C765-15NA	25	75	10 A2	10 A2	1920	
mxk00048302	5.7 0.1	24.3 0.2	1532 10	3.2 0.1	103.9 4.49	13	Emmat Y1000P	25	PP C765-15NA	25	75	10 A1	10 A1	1950	
mxk00048303	8.1 0.3	19.8 0.1	1071 15	4.9 0.2	84.73	1.5	4.3 Emmat Y1000P	20	PP C765-15NA	20	70 A1	10	10	2100	
mxk00048305	7.6 0.3	20 0.1	1108 5	4.6 0.1	85.7 1.45	3.8	Emmat Y1000P	22	PP C765-15NA	22	68 A1	10	10	2150	
mxk00048304	6.4 0.4	20.2 0.1	1168 7	3.7 0.1	84.73 2.27	3.8	Emmat Y1000P	25	PP C765-15NA	25	65 A1	10	10	2120	
mxk00048307	4.1 0.1	24.8 0.1	1708 13	3.3 0.1		15.37	Emmat Y1000P	22	PP C765-15NA	22	65 C	10 A1	10 A1	2110	
mxk00048309	3.2 0.4	24.5 0.2	1904 14	3.2 0.1		13.1	Emmat Y1000P	22	PP C765-15NA	22	58 C	10 A1	10 A1	2050	
mxk00048309	4.2 0.2	24.8 0.2	1629 14	3.3 0.1		14.7	Emmat Y1000P	22	PP C765-15NA	22	63 C	10 A2	10 A2	2070	
mxk00048310	3.8 0.2	24.9 0.1	1756 9	3.4 0.1		13.1	Emmat Y1000P	22	PP C765-15NA	22	58 C	10 A2	10 A2	2070	
mxk00048311	4.8 0.3	23.3 0.2	1456 8	4.4 0.1	93.73	4.6	16.36 Emmat Y1000P	22	PP C765-15NA	22	63 C	10 B1	10 B1	2120	
mxk00048312	4.3 0.1	23.7 0.1	1421 8	3.6 0.1	94.7 3.46	15.24	Emmat Y1000P	22	PP C765-15NA	22	58 C	10 B1	10 B1	2070	
mxk00048313	4.5 0.2	23.9 0.1	1378 11	3.8 0.1	95.77 3.88	15.66	Emmat Y1000P	22	PP C765-15NA	22	63 C	10 B2	10 B2	2120	
mxk00048314	4.2 0.1	22.9 0.3	1429 18	3.9 0.2	99.47 3.41	15.1	Emmat Y1000P	22	PP C765-15NA	22	58 C	10 B2	10 B2	2070	
mxk00048315	7.4 0.3	20.1 0.2	1103 9	4.9 0.2		6.86	Emmat Y1000P	22	PP C765-15NA	22	65 A1	10 A1	10 A1	2060	
mxk00048316	6.1 0.2	20.1 0.1	1128 22	4.7 0.1		6.04	Emmat Y1000P	22	PP C765-15NA	22	58 A1	10 A1	10 A1	2000	
mxk00048317	7.5 0.4	19.4 0.1	1056 17	4.9 0.1	81.87 1.65		6.8 Emmat Y1000P	22	PP C765-15NA	22	63 A1	10 A2	10 A2	2070	
mxk00048318	7 0.2	19.4 0.1	1065 5	5 0.1		5.95	Emmat Y1000P	22	PP C765-15NA	22	58 A1	10 A2	10 A2	2020	
mxk00048319	7 0.4	19.3 0.2	1013 12	5.1 0.2		6.97	Emmat Y1000P	22	PP C765-15NA	22	58 A1	10 B1	10 B1	2070	
mxk00048320	6.2 0.2	18.7 0.1	1056 19	5 0.1		7.2	Emmat Y1000P	22	PP C765-15NA	22	58 A1	10 B1	10 B1	2020	
mxk00048321	6.2 0.2	19.5 0.1	1094 24	5.2 0.1		6.69	Emmat Y1000P	22	PP C765-15NA	22	63 A1	10 B2	10 B2	2070	
mxk00048322	5.3 0.2	18.7 0.1	1115 10	5 0.1		7.17	Emmat Y1000P	22	PP C765-15NA	22	58 A1	10 B2	10 B2	2020	
mxk00048323	7.6 0.5	19.9 0.1	1129 22	5.2 0.1		7.9	Emmat Y1000P	22	PP C765-15NA	22	65 A2	10 A1	10 A1	2060	
mxk00048324	6.6 0.4	19.5 0.1	1194 6	4.9 0.1		6.78	Emmat Y1000P	22	PP C765-15NA	22	58 A2	10 A1	10 A1	2000	
mxk00048325	8.6 0.4	19.8 0.1	1119 19	5.2 0.1		7.4	Emmat Y1000P	22	PP C765-15NA	22	65 A2	10 A2	10 A2	2070	
mxk00048326	8.1 0.3	19.5 0.1	1109 3	5.2 0.1	80.87 0.91		6.3 Emmat Y1000P	22	PP C765-15NA	22	58 A2	10 A2	10 A2	2020	
mxk00048327	7.8 0.2	19 0.2	1070 25	5.2 0.1		7.9	Emmat Y1000P	22	PP C765-15NA	22	65 A2	10 B1	10 B1	2070	
mxk00048328	6.3 0.2	19 0.1	1163 20	5.1 0.2		7.8	Emmat Y1000P	22	PP C765-15NA	22	58 A2	10 B1	10 B1	2020	
mxk00048329	6.6 0.3	19.2 0.1	1125 14	5.1 0.1	81.47	4.2	7.9 Emmat Y1000P	22	PP C765-15NA	22	65 A2	10 B2	10 B2	2070	
mxk00048330	5.9 0.2	18.7 0.1	1150 23	5.1 0.2	85.3 0.44		8.2 Emmat Y1000P	22	PP C765-15NA	22	58 A2	10 B2	10 B2	2020	
mxk00048331	4.8 0.4	21.9 0.1	1763 18	3.2 0.1		8.59	Emmat Y1000P	22	PP C765-15NA	22	65 B	10 A1	10 A1	2110	
mxk00048332	4.3 0.3	24.3 0.4	2231 10	2.7 0.3		8.31	Emmat Y1000P	22	PP C765-15NA	22	58 B	10 A1	10 A1	2050	
mxk00048333	5.2 0.4	24.3 0.1	1696 31	3.8 0.1		8.77	Emmat Y1000P	22	PP C765-15NA	22	63 B	10 A2	10 A2	2120	
mxk00048334	4.6 0.2	24.8 0.2	2047 18	2.7 0.1	96.37 2.51		8.37 Emmat Y1000P	22	PP C765-15NA	22	58 B	10 A2	10 A2	2070	
mxk00048335	5.2 0.3	23.5 0.1	1823 19	3.4 0.1		9.2	Emmat Y1000P	22	PP C765-15NA	22	65 B	10 B1	10 B1	2120	
mxk00048336	4.5 0.2	22.9 0.1	1602 23	3.2 0.1		8.62	Emmat Y1000P	22	PP C765-15NA	22	58 B	10 B1	10 B1	2070	
mxk00048337	4.6 0.3	23.1 0.1	1483 12	3.6 0.1		8.8	Emmat Y1000P	22	PP C765-15NA	22	65 A1	10 B2	10 B2	2120	
mxk00048338	4 0.1	22.4 0.1	1608 19	3.1 0.1		8.58	Emmat Y1000P	22	PP C765-15NA	22	58 B	10 B2	10 B2	2070	
mxk00048339	3.7 0.1	22.4 0.3	1526 29	3.2 0.1		22.28	Emmat Y1000P	20	PP C765-21	20	80	10 A1	10 A1	1900	
mxk00048340	3.7 0.1	23.6 0.1	1555 29	3.1 0.1		19.89	Emmat Y1000P	22	PP C765-21	22	75	10 A1	10 A1	1920	
mxk00048341	3.8 0.1	24.7 0.1	1646 17	3 0.1		19.24	Emmat Y1000P	25	PP C765-21	25	75	10 A1	10 A1	1950	
mxk00048342	5 0.3	20 0.4	1083 30	4.6 0.2		13.945	Emmat Y1000P	20	PP C765-21	20	70 A1	10	10	2100	
mxk00048343	4.9 0.3	20 0.1	1107 16	4.5 0.1		12.42	Emmat Y1000P	22	PP C765-21	22	68 A1	10	10	2120	
mxk00048344	4.7 0.4	20.3 0.1	1200 21	4.2 0.1	93.43 1.79		8.909 Emmat Y1000P	25	PP C765-21	25	65 A1	10	10	2150	
mxk00048345	5.5 0.3	20.3 0.2	1182 10	4.6 0.1		10.72	Emmat Y1000P	22	PP C765-21	22	65 A1	10 A1	10 A1	2060	
mxk00048346	5.2 0.3	20.4 0.1	1262 24	4.3 0.2	93.03 2.75		8.933 Emmat Y1000P	22	PP C765-21	22	58 A1	10 A1	10 A1	2000	
mxk00048347							deleted								
mxk00048348	4.2 0.1	20.1 0.1	1422 23	4.5 0.1		5.65	Emmat Y1000P	22	PP C765-21	22	48 A1	10 A1	10 A1	1880	
mxk00048349	5.3 0.4	19.8 0.1	1136 26	4.4 0.1		12.2	Emmat Y1000P	22	PP C765-21	22	65 A1	10 A2	10 A2	2070	
mxk00048350	5.6 0.3	20.1 0.2	1185 31	4.8 0.1		10.5	Emmat Y1000P	22	PP C765-21	22	58 A1	10 A2	10 A2	2020	
mxk00048351							deleted								
mxk00048352	5.4 0.3	20 0.1	1216 23	5.3 0.2		4.77	Emmat Y1000P	22	PP C765-21	22	48 A1	10 A2	10 A2	1920	

**Key for additives**  
 Comp. A1: Reactive ethylene based terpolymer with methyl acrylate  
 Comp. A2: Reactive ethylene based terpolymer with butyl acrylate  
 Comp. B: High molecular weight linear polyester  
 Comp. C: Random copolymer polypropylene, high grafted with maleic anhydride  
 Filler A1: SiO2-based falc (2 µm)  
 Filler A2: SiO2-based falc (0.7 µm)  
 Filler B1: CaCO3-based chalk (2.7 µm)  
 Filler B2: CaCO3-based chalk (2.5 µm)

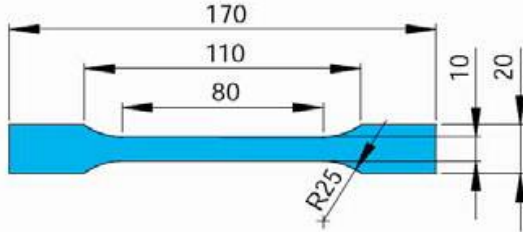


## Appendix C

### Testing parameters

The sample dimensions for the testing bar can be seen in the figure below (numbers given in mm). All the samples have been stored for at least 3 hours at atmospheric pressure,  $23 \pm 2$  °C and  $50 \pm 5$  % relative humidity before testing.

Thickness: 4 mm



Tensile testing was done according to the ISO 527-2 standard. For the tensile modulus and stress at yield 10 specimens were used respectively. The tensile modulus was measured with a test speed of 1 mm/min between 0.05-0.25 % strain. The stress at yield and elongation at break was determined by using a test speed of 50 mm/min until break.

Charpy notched impact test was done according to the ISO 179/1eA, where e stands for an edgewise blow direction. A is for a notch base radius of  $0.25 \pm 0.05$  mm and the remaining width of  $8.0 \pm 0.2$  mm. For this test 20 samples for each material was tested.

HDT was settled according to DIN 53461, with a load of 0.45 MPa.

Rheological measurements were done by studying the melt flow index (MFI) according to DIN 53735. Depending on the melting temperature of the polymer material, different temperature and loads were used.

-PHB based materials: Temp. 180-190 °C; load: 2,16 kg.

-PP based materials: Temperature: 190-200 °C; load 2,16 kg.

# Appendix D

## Price calculations

Formulation Price	PHBV % (Enmat Y1000P)	PP %	1500	3500	3500	4000	4000	4000	300	500	500	500	200	COST (€[t]
			Compatibilizer A2 %	Compatibilizer A1 %	Compatibilizer B %	Compatibilizer C %	Filler A1 %	Filler A2 %	Filler B1 %	Filler B2 %	Comounding			
mk100418-01	0,2	0,8	0	0	0	0	0	0	0	0	0	0	0	1900
mk100418-02	0,25	0,75	0	0	0	0	0	0	0	0	0	0	0	1950
mk100418-03	0,2	0,7	0	0,1	0	0	0	0	0	0	0	0	0	2100
mk100418-04	0,25	0,65	0	0,1	0	0	0	0	0	0	0	0	0	2150
mk100418-05	0,22	0,68	0	0,1	0	0	0	0	0	0	0	0	0	2120
mk100418-06	0,22	0,78	0	0	0	0	0	0	0	0	0	0	0	1920
mk100418-07	0	0	0	0	0	0	0	0	0	0	0	0	0	200
mk100418-08	0,22	0,63	0	0	0	0,1	0,05	0	0	0	0	0	0	2110
mk100418-09	0,22	0,58	0	0	0	0,1	0,1	0	0	0	0	0	0	2050
mk100418-10	0,22	0,63	0	0	0	0,1	0	0,05	0	0	0	0	0	2120
mk100418-11	0,22	0,58	0	0	0	0,1	0	0,1	0	0	0	0	0	2070
mk100418-12	0,22	0,63	0	0	0	0,1	0	0,05	0	0	0	0	0	2120
mk100418-13	0,22	0,63	0	0	0	0,1	0	0	0,1	0	0	0	0	2070
mk100418-14	0,22	0,58	0	0	0	0,1	0	0	0	0,05	0	0	0	2120
mk100418-15	0	0	0	0	0	0	0	0	0	0	0	0	0	2070
mk100418-16	0,22	0,63	0	0,1	0	0	0,05	0	0	0	0	0	0	200
mk100418-17	0,22	0,58	0	0,1	0	0	0,05	0	0	0	0	0	0	2060
mk100418-18	0,22	0,63	0	0,1	0	0	0,1	0	0	0	0	0	0	2000
mk100418-19	0,22	0,58	0	0,1	0	0	0	0,05	0	0	0	0	0	2070
mk100418-20	0,22	0,63	0	0,1	0	0	0	0,1	0	0	0	0	0	2020
mk100418-21	0,22	0,58	0	0,1	0	0	0	0	0,05	0	0	0	0	2070
mk100418-22	0,22	0,63	0	0,1	0	0	0	0	0	0,05	0	0	0	2070
mk100418-23	0	0	0	0	0	0	0	0	0	0	0	0	0	2020
mk100418-24	0,22	0,63	0,1	0	0	0	0,05	0	0	0	0	0	0	2070
mk100418-25	0,22	0,58	0,1	0	0	0	0,1	0	0	0	0	0	0	2060
mk100418-26	0,22	0,63	0,1	0	0	0	0	0,05	0	0	0	0	0	2000
mk100418-27	0,22	0,58	0,1	0	0	0	0	0,1	0	0	0	0	0	2070
mk100418-28	0,22	0,63	0,1	0	0	0	0	0	0,05	0	0	0	0	2070
mk100418-29	0,22	0,58	0,1	0	0	0	0	0	0,1	0	0	0	0	2020
mk100418-30	0,22	0,63	0,1	0	0	0	0	0	0	0,05	0	0	0	2070
mk100418-31	0	0	0	0	0	0	0	0	0	0	0	0	0	2020
mk100418-32	0,22	0,63	0	0	0	0,1	0,05	0	0	0	0	0	0	200
mk100418-33	0,22	0,58	0	0	0	0,1	0,1	0	0	0	0	0	0	210
mk100418-34	0,22	0,63	0	0	0	0,1	0	0,05	0	0	0	0	0	210
mk100418-35	0,22	0,58	0	0	0	0,1	0	0,1	0	0	0	0	0	2070
mk100418-36	0,22	0,63	0	0	0	0,1	0	0	0,05	0	0	0	0	2120
mk100418-37	0,22	0,58	0	0	0	0,1	0	0	0,1	0	0	0	0	2070
mk100418-38	0,22	0,63	0	0	0	0,1	0	0	0	0,05	0	0	0	2120
mk100418-39	0	0	0	0	0	0	0	0	0	0	0	0	0	200
mk100418-40	0,2	0,8	0	0	0	0	0	0	0	0	0	0	0	200
mk100418-41	0,22	0,78	0	0	0	0	0	0	0	0	0	0	0	1900
mk100418-42	0,25	0,75	0	0	0	0	0	0	0	0	0	0	0	1920
mk100418-43	0,2	0,7	0	0,1	0	0	0	0	0	0	0	0	0	1950
mk100418-44	0,22	0,68	0	0,1	0	0	0	0	0	0	0	0	0	2100
mk100418-45	0,25	0,65	0	0,1	0	0	0	0	0	0	0	0	0	2120
mk100418-46	0,22	0,63	0	0,1	0	0	0,05	0	0	0	0	0	0	2150
mk100418-47	0,22	0,58	0	0,1	0	0	0,1	0	0	0	0	0	0	2060
mk100418-48	0	0	0	0	0	0	0	0	0	0	0	0	0	2000
mk100418-49	0,22	0,48	0	0,1	0	0	0,2	0	0	0	0	0	0	200
mk100418-50	0,22	0,63	0	0,1	0	0	0	0,05	0	0	0	0	0	1880
mk100418-51	0,22	0,58	0	0,1	0	0	0	0,1	0	0	0	0	0	2070
mk100418-52	0	0	0	0	0	0	0	0	0	0	0	0	0	2020
mk100418-53	0,22	0,48	0	0,1	0	0	0	0	0	0	0	0	0	200

# Appendix E

## Injection moulding parameters

Test	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18						
Date	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18						
Material	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP	PHBV/PP					
Trial no.	mk-01	mk-02	mk-03	mk-04	mk-05	mk-06	mk-07	mk-08	mk-09	mk-10	mk-11	mk-12	mk-13	mk-14	mk-15	mk-16	mk-17	mk-18	mk-19	mk-20	mk-21	mk-22	mk-23	mk-24	mk-25
<b>Injection moulding machine</b>																									
<b>ENGEL ES200</b>																									
Closing force	kN	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
<b>Temperature</b>																									
Entry	°C	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Zone 4	°C	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Zone 3	°C	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170
Zone 2	°C	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Zone 1	°C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nozzle	°C	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190
<b>Tool temperature (de vice)</b>																									
	°C	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
<b>Pull back</b>																									
	mm	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
<b>Dose path</b>																									
	mm	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
<b>Number of revolutions</b>																									
	1/mm	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96
<b>Back pressure</b>																									
	bar (hydr.)	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
<b>Cooling time</b>																									
	s	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
<b>Dozing delay</b>																									
	s	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
<b>Injection pressure</b>																									
	bar (hydr.)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
<b>Injection pressure at UP</b>																									
	bar (hydr.)	31.0	29.3	33.8	31.4	32.6	31.9	29.6	30.0	29.5	30.3	28.0	28.4	29.0	35.2	36.1	35.1	34.7	35.2	36.7	35.1	36.3	36.6	35.6	34.2
<b>Injection speed</b>																									
	mm/s	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
<b>Shift pilot/switchover</b>																									
	mm	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
<b>After pressure</b>																									
	bar (hydr.)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
<b>Pressure time</b>																									
	s	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
<b>Cover</b>																									
	mm	3.2	2.8	3.3	3.2	2.9	2.9	3.0	2.9	3.5	2.9	3.4	3.0	3.3	3.1	3.6	3.2	3.4	3.3	3.6	3.4	3.5	3.3	3.4	3.4

Date	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	05.18	
Material	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP	FHVB/PP
Trial no.	mok-26	mok-27	mok-28	mok-29	mok-30	mok-31	mok-32	mok-33	mok-34	mok-35	mok-36	mok-37	mok-38	mok-39	mok-40	mok-41	mok-42	mok-43	mok-44	mok-45	mok-46	mok-48	mok-49	mok-50	mok-52	
Injection moulding machine	ENGEL ES200																									
Unit	Unit																									
Closing force	kN	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
Temperature																										
Entry	°C	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Zone 4	°C	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160
Zone 3	°C	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170
Zone 2	°C	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Zone 1	°C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nozzle	°C	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190
Tool temperature (device)	°C	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0	60,0
Pull back	mm	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Dose path	mm	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Number of revolutions	1/min	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96
Back pressure	bar (hydr.)	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Cooling time	s	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Dosing delay	s	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Injection pressure	bar (hydr.)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Injection pressure at UP	bar (hydr.)	35,2	33,8	35,6	34,5	34,6	35,2	34,9	36,2	34,8	35,7	34,5	35,5	27,1	25,9	25,8	28,2	27,8	29,5	31,8	33,	35,2	29,8	31,6	35,0	
Injection speed	mm/s	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
Shift piont/ swichover	mm	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
After pressure	bar (hydr.)	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Pressure time	s	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0	10,0
Cover	mm	3,2	3,5	3,6	3,7	3,5	3,6	3,5	3,7	3,8	3,4	3,4	3,5	2,2	1,9	2,5	2,1	2,2	2,8	3,3	3,4	3,3	2,7	3,1	3,4	3,4