Chapter 16

From Restorative Building to Regenerative Economy: A Model-Theoretical Analysis on Bio-based Plastics for the Construction Industry

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Abstract With the introduction of the Construction Products Directive EU305:2011, architects are more than ever required to select products with a high proportion of renewable raw materials. Only then will it be possible to internalise, hence to compensate, for environmental damage caused by technologies that do not conserve resources and are energy-intensive. Using a novel bio-based wood-plastic composite (WPC) as an example, this chapter shows that internalisation can be successful if conventional fossil plastics are “greened” by adding renewable biomass. The results show that this is only the case if the bio-content is not too high but exceeds a minimum value. The degree of sustainability depends on the assessment of the extent of damage to the environment and society. The optimal level of internalisation can then become allocatively efficient, meaning that the costs of avoiding plastics do not increase more than the damage costs decrease. The findings demonstrate that environmental protection can also be economically meaningful and potentially contributes to increasing social welfare in society. A paradigm shift towards restorative economy in construction should take this principle into account.

Keywords Bio-based plastic composites · Internalisation · Environmental damage · Abatement technology · Crude oil preservation

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16.1 Introduction

The European construction industry is one of the largest sectors of the economy. In 2017, it accounted for approximately 10% of the gross domestic product within the European Union (Statista, 2020). After the packaging segment, the construction sector consumes 10 million tonnes of plastic, making it the second largest consumer of fossil resources in the form of polymers. This represents about 20% of the total EU-wide plastics consumption (PlasticsEurope, 2020). The advantages of plastics are undoubted. It is durable, tough, easy to shape, and shows special properties that are hard to match by alternatives in construction applications (Youssef & El-Sayed, 2018). These include isolation against electricity, heat retention to increase energy savings and waterproofing. Another important property is recyclability. Through reuse, waste plastic can be converted back into new products of the same quality or lower performance characteristics, thereby significantly extending the entire life cycle of polymers (Hao et al., 2019). But also compared to packaging, the use of plastic in construction has clear advantages. While the former are mostly disposable materials that are either incinerated or recycled immediately after purchase, the question of the end-of-life use of plastics in the construction industry usually only arises after decades. Nevertheless, many building products are offered in a packaging on the market or delivered to the building site wrapped in a plastics foil. Thus, the use of plastic in the construction segment is not generally advantageous and the use of fossil-based polymers in short-lived packaging only makes sense if the packaging is collected and specifically taken for reuse as recycling. In Germany, for example, the recycling rate of bulky waste, such as furniture and inventory is 53%, electrical appliances are 100% recycled, and 99% of construction and demolition waste is recovered (Destatis, 2020). Obviously, efforts are already being made to recycle waste materials in general. However, these do not necessarily meet the criteria of a restorative economy, which consists in the use of renewable resources and not in the exploitation of limited raw materials even if this takes place in several life cycles.

It appears that, in contrast to other industries, the use of fossil resources in construction is comparatively less harmful to the environment only because products show a comparatively longer life span (Álvarez-Chávez, Edwards, Moure-Eraso, & Geiser, 2012). This is not to say, however, that this type of using increasingly scarce raw materials is fundamentally justified and should therefore be raised to status quo. Rather, it must be examined at each stage whether the current exploitation of fossil resources is justifiable. A continuation as before would still be acceptable if the linear use of oil, i.e., the extraction, application and degradation into individual components, which are then deposited in the ground as carbon or introduced into the atmosphere as carbon dioxide, did not lead to damages to the environment and mankind. On the other hand, the question arises as to whether the benefit of plastic as packaging or as a product in a component or building is still high enough if it is balanced against the environmental damage that arises simultaneously or afterwards. This net benefit would then often be too small to justify the current

application. This consideration therefore goes beyond the pure life-cycle analysis and increasingly doubts the current use of polymers even in long-life applications. Finally, the criticism is also justified that the refining of crude oil into plastics as today's standard technology and the loss of fossil resources deprives future generations of a potential. It is to be assumed that with progressive development, future technologies that use this source of raw material might be of far greater benefit to mankind than is the case today. Then the continuation of the current status quo, despite alternatives, would be all the more of a pure egoism of today's generation.

What a possible alternative looks like and whether it is then at all reasonable to substitute all plastics is to be discussed in the further course of this paper. The remainder is as follows: (1) first, sustainability principles will be explained, (2) then a new type of bio-based composite material will be presented, which could play an increasing role as a representative for greener technologies and (3) finally, this particular material will be used to show how an efficient avoidance of fossil-based plastics in the construction industry could look like.

16.2 Sustainability Principles

The literature on the goals of sustainability considers ecological and human capital to be worthy of protection in principle. Wackernagel et al. (1999) see the former as the maintenance of habitat, and Heckman (2000) understands the latter as the sum of human knowledge and skills in just this habitat worth protecting. It can therefore be assumed that the loss of eco-capital is accompanied by a loss of human capital. This can be explained by the fact that inductive research in particular is inspired by natural phenomena, meaning that observing nature expands the available knowledge. There are different views on how to maintain the eco-potential while humans use natural resources. The intensity with which such a sustainability strategy leaves eco-capital unchanged therefore determines the type of strategy. Consequently, a distinction is made between the weak sustainability principle and the strong one (Bjørn & Hauschild, 2012; Ryberg et al., 2018). This means that lost eco-capital is substituted in any way, e.g., oil consumption is offset by reforestation (Turner, 1993). It is easy to see that this only maintains the sum of capital, but not resource diversity. Ultimately, mankind cannot exist in an environment that is monotonous and homogeneous in its nature. In contrast, strict sustainability aims not only to maintain the quantity of total capital but to apply this principle to each species and resource, so that diversity is also maintained (Daly, 1991). This presupposes that human intervention in the natural cycle is regenerative, i.e., that the harvest is not greater than the output that results from natural growth. To stay with the example of reforestation, this would demand that deforested rainforest must be replaced by the same species at the same location and the felling of trees must not be greater than naturally growing back, so that the quantity of rainforest remains constant. In order to be able to exploit resources on a larger scale and to limit the damage from the loss of eco-capital, the concept of critical sustainability has been established (Ekins,

Simon, Deutsch, Folke, & De Grootl, 2003). This means that the only compromise to be pursued is the conservation and restoration of at least critical stocks of the same species. Anything beyond this may be substituted in whatever way possible. Here too, it is clear that this principle must not become the rule and should apply on a case-by-case basis.

The problem of the use of fossil resources by plastics can therefore at least follow the weak principle of sustainability, because a similar recovery of consumption is not possible since there is no regeneration. Hence, the only principle remaining is to minimise consumption. This can be achieved by applying avoidance technologies, as shown next using the example of Wood-Polymer Composites.

16.3 Alternative Technologies to Preserve Resources

16.3.1 *Bio-based Materials*

It is out of question that plastic, and the associated exploitation of fossil resources, is often used below its potential as it is the case with packaging, where polymers represent a rather convenient and cost-effective option for protecting goods from external influences, such as sunlight, moisture and mechanical forces, at least during transport (Hao et al., 2019). If the use of plastics was limited only to applications in which this material has no alternative, then resource preservation would be already well advanced. As a consequence, from falling demand, the costs for plastic would rise. Since plastic is currently a low-cost material, it is difficult for alternatives to compete in the market (Pal & Gander, 2018). If sustainable alternatives still managed to compete with more expensive plastic, then any further substitution by the alternative material would counteract a loss of eco-capital. The alternative material would thus have an internalising effect, as its use reduces environmental damage (Mason, 2012).

16.3.2 *Wood-Plastic Composites*

It is obvious that especially bio-based materials are internalising. If they are taken from nature under the strict sustainability principle, the application of the weak form of sustainability would be limited to a few exceptions. One such bio-based material is Wood-Polymer Composites, called WPC (see Fig. 16.1). This composite material still consists of fossil-plastic, in which, however, up to 80% by volume plant fibres are embedded (see Fig. 16.2, left). The latter is usually a wood fibre as waste material from the sawmill industry (Carus, Müssig, & Gahle, 2008). This fibre has an aspect ratio of 1:50, hence, it is a longer fibre which, in combination with the thermoplastic matrix, leads to a higher load-bearing capacity of the

Fig. 16.1 Wood-Plastic Composites (WPC) as a transition technology towards purely bio-based plastics

Fig. 16.2 Left: Wood fibres encapsulated in a thermoplastics-matrix; right: brushed WPC surface before and after one year of outdoor weathering

material, just like steel reinforcement in concrete (Monteiro, Calado, Rodriguez, & Margem, 2012). The matrix is usually polyethylene (PE), polypropylene (PP) or polyvinyl chloride (PVC). It can also be a recycled plastic.

WPC has been available in the construction sector for 20 years, and the main applications are decking and façade panels (Carus & Eder, 2015). In 2015, for example, 66,000 tons of WPC were produced in Germany (Statista, 2020). According to the author’s opinion, this bio-based material is also becoming increasingly interesting for the packaging industry. To stay with the example of the construction sector, in 2011, the EU Regulation No.305 (CPR, 2011), known as the Construction Products Regulation, was issued. In this regulation, the EU Commission

demands that construction products must also use environmentally friendly and renewable raw materials. A substitution of plastic-based construction products by WPCs would therefore also be in line with legal requirements. Nevertheless, this only makes sense if technical equivalence is assured. Here it becomes obvious that a replacement of plastics by wood or cardboard is only possible in well-selected cases. Especially in the building industry, construction elements are often exposed to weather, so they must be resistant to moisture. This works well for wood when it is surrounded by air and can dry out regularly (Tamrakar & Lopez-Anido, 2011). In the case of WPC, the wood fibre is embedded in the plastics-matrix and thus protected from both moisture and UV-radiation. The water absorption capacity of WPC averages 3%–5% and makes the material even suitable for façade applications. However, the fact that WPC contains biodegradable components may lead to the conclusion that it is not equivalent to conventional building materials in terms of durability. Indeed, investigations with artificial weathering or long-term tests under natural environments confirmed a significant load drop after only one year (Beg & Pickering, 2008). This is accompanied by a degradation of the polymer-matrix in the outer profile layers which translates into polymer chain scissions (Seldén, Nyström, & Langström, 2004). The short-chain polymers then reduce the load capacity. At the same time, the bond with the wood fibre weakens. The latter are eroded out and this degradation process then starts again in the polymer layers behind. The WPC material is thus gradually destroyed, which is associated with a reduction in cross-section and impairs the static load-bearing capacity in the component (Fig. 16.2, right).

According to studies by the author, the characteristic mechanical values would have to be reduced by at least 50% in order to be able to use them as design values in structural analysis (Friedrich, 2016). The final design value thus depends on the characteristic test result from the mechanical resistance test, assuming the flexural strength is the decisive criterion for the applicability of WPC in structural components, such as a façade panel. In this case, this characteristic value should be as high as possible so that after subtraction of material degradation due to ageing, there is still sufficient strength to satisfactorily guarantee the application for a predetermined service life, e.g., 50 years as cladding. In the case of WPC, the characteristic bending strength depends on the fibre content. The more wood fibres are embedded in the plastics-matrix, the higher the sustainability and thus the degree of internalisation of the material. The high fibre content also has a positive effect on mechanical strength, as this makes the plastic more loadbearing (Hung, Chen, & Wu, 2012). It therefore seems to make sense to embed as many fibres as possible. However, degradation increases with the fibre content, i.e., the degree of ageing-related deterioration is higher. From this point of view, it may not make sense to embed as many fibres as possible. On the other hand, the manufacturing costs of WPC rise, because the production speed of extruded WPC profiles decreases with increasing fibre share, i.e., fewer linear metres of profiles can be produced per time unit. This makes the fabrication of WPC elements more expensive, especially since capital costs are comparatively high due to the equipment-intensive production processes. Using too few wood fibres in WPC is not ecologically effective and too many wood fibres are

uneconomical. Hence, there must be an optimum where the wood fibre content is efficient, i.e., economical, and yet internalisation remains effective.

16.4 Macro-Economic Analysis Regarding the Effectiveness of WPC

16.4.1 Model-Theoretical Framework

According to neoclassical theory, the effects of economic factors can be modelled on the basis of a normative analysis. For this purpose, a graph is used in which the market demand $P(Y)$ is represented as a straight line falling in Y , which is the quantity of the product (Xu, Cho, & Lee, 2016). If the production of the good causes damage to the environment or society (Fig. 16.3, left: grey area), then this damage should actually be paid by the producer, which is reflected in higher production costs, so-called marginal costs c . Such damage could occur in the case of oil consumption for plastics due to the exploitation of natural fossil reserves (Pal & Gander, 2018). After use of the plastic, CO_2 would be released into the atmosphere and contribute to global warming (Strimitzer & Höher, 2015). In order for a producer to avoid this compensation payment, other materials can be chosen. However, these are most likely more expensive, since bio-based materials from renewable resources do not cause such damage. Assuming that a governmental regulator would force the producers to pay the compensation fees, e.g., through a CO_2 -tax, as investigated in a study by Convery, McDonnell, and Ferreira (2007). The amount of this tax would then have to be at least equal to the proportionate damage costs in order to make producers indifferent in their choice of more environmentally friendly alternatives. If the producer previously produces with marginal costs of c_1 , the optimal supply

Fig. 16.3 Left: Internalisation of damage cost through reduction of output Y and price increase; right: Price-stimulating effect through change from fossil-plastics to bio-based plastics (WPC)

quantity according to Fig. 16.3 (left) is Y_{real} . It is optimal because it maximises its profit. In doing so, the producer will demand the highest possible price, P_{real} , if the market is willing to pay it.

If now production becomes more expensive, hence reaching a level c_2 due to the punishment fee for pollution, then the producer would only offer Y_{int} , i.e., a smaller quantity. This results in less environmentally harmful goods being produced overall, which internalises environmental damage. For the market this has consequences, because now the producer will demand a higher price P_{int} to keep his profits stable. This should not bother him at first, because his business is still profitable. But this will not last very long, because consumers might look for alternative products in response to higher prices. If all oil-based plastic products are taxed, then the remaining alternatives should always be more environmentally friendly. The market will thus turn to these substitutes, increasing the pressure on producers to use renewable raw materials instead of paying the tax and freeing themselves from claims of pollution. Overall, the average bio-based products on the market will increase, which has a positive impact on the environment (Amacher, Koskela, & Ollikainen, 2004). The taxation of fossil-plastics in products is effective, i.e., it achieves its goal. However, it is also clear that crude-oil cannot be saved completely because, on the one hand, there are still no alternatives for some applications, which will make them increasingly more expensive in the long term. On the other hand, some companies can pay this tax without any problems because of their financial strength, as this tax applies to the entire industry. Nevertheless, the effect is noticeable and is currently being aimed for with the introduction of the CO₂-tax in Germany. In this context, a more polluter-related taxation of less environmentally friendly products is more and more under discussion, as a so-called damage tax, DaVAT. This tax could be based on product-specific life-cycle analyses and should then encourage consumers to buy more tax-privileged, environmentally friendly products (Timmermans & Achten, 2018).

16.4.2 *Model-Fit with WPC Technology*

The example shows that internalisation can only work by increasing costs. In the case of WPC, a switch from neat plastics to wood fibre-reinforced plastics would also mean an increase in costs. And yet, as a transitional technology, WPC does have the potential to internalise the market for plastic products without state intervention. As explained so far, the transition to environmentally friendly alternatives must be attractive for the producer. This is the case if it at least maintains the previous profit or even increases it. WPC could certainly be an incentive for manufacturers. Klaiman, Ortega, and Garnache (2016) demonstrated in a consumer study that customers show a higher willingness to buy and pay if they are aware that they act in an environmentally friendly manner when making a purchase. According to Feucht and Zander (2018), eco-labels, and in particular on CO₂-emissions, can encourage consumers to pay up to 20% higher prices than for less ecological

alternatives. Obviously, awareness of environmentally friendly behaviour alone is sufficient for the $P(Y)$ curve in Fig. 16.3 (right) to shift upwards, i.e., to show higher willingness to pay on the market. This can be interesting for manufacturers, because sales increase with higher prices, even if the output decreases due to higher costs. This allows higher profits to be achieved. Klein, Emberger-Klein, Menrad, Möhring, and Blesin (2019) found that a higher willingness to pay is difficult to achieve for bio-based plastics as well, especially if they are visually indistinguishable from their counterparts made entirely of plastic. However, the advantage of WPC is that the wood fibres are clearly visible, especially when the surface is brushed (Fig. 16.2, right). This also explains the market success of WPC decking in recent years. This is all the more true when WPC has a high fibre content, for example over 50% (Fig. 16.3, left). Then it would not only save plastic and avoid CO_2 emissions but also the existing emissions from the plastic still contained in the WPC would be partially compensated by the CO_2 -sink resulting from the wood fibres. As a consequence, if the consumer is aware that WPC is included in the product, this would be equivalent to a curve-shift from $P_{\text{fossil}}(Y)$ to $P_{\text{WPC}}(Y)$, which is accompanied by a price increase to P_{WPC} (Fig. 16.3, right). This can at least compensate for higher production costs resulting from the plastic transition. It is obvious that WPC also has an internalising effect because it substitutes plastics, even if it still contains a small proportion of it. Contrary to the tax, however, the market volume does not decrease, because the profit can remain the same despite higher costs. On the consumer side, the transition is not disadvantageous either, because a better conscience, known as the warm-glow effect, represents an additional benefit for the customer, which he or she purchases together with the product and will pay for additionally.

16.4.3 Optimality Considerations

Finally, the question remains about the optimal extent of bio-ingredients in plastics. Or, in the case of WPC, what is the optimum fibre content. As already explained, the manufacture of WPC profiles becomes more expensive with increasing fibre content due to lower production speed. On the other hand, a too small proportion is less economical, because the transition to WPC technology is associated with sunk costs from investment. Economics considers a change in technology towards environmentally friendly products to be worthwhile if the cost savings on environmental damage increase at least as much as the costs of the new technology. This means that for the optimal amount of internalising technology, the slope of the damage-saving-curve must be equal to the slope of the cost-curve when the new abatement technology is applied. This is shown in Fig. 16.4 for WPC, assuming that the wood fibre-content corresponds to the degree of use of the internalising technology “WPC”. This means that the more fibres embedded in plastics, the higher the degree of internalisation. Figure 16.4 represents an economic analysis and shows what the optimal internalising wood fibre-content depends on. The X-axis illustrates the proportion of plastics and, on the Y-axis, the marginal costs ($\text{cost}_{\text{marg.}}$) of plastic

Fig. 16.4 Economically efficient content of plastics in WPC for effective internalisation of environmental damage caused by plastics

avoidance are plotted, which corresponds to the production of WPC. This is described by the curve of the marginal abatement costs ($AbC_{\text{marg.}}$), which decreases with increasing plastic content. Also shown are the marginal damage costs ($DC_{\text{marg.}}$) to the environment through oil exploitation for plastic production. Marginal abatement costs ($AbC_{\text{marg.}}$) at 100% plastic consumption are minimal, because no wood fibres are embedded and thus no WPC is produced (= Point 1). On the other hand, the marginal damage costs ($DC_{\text{marg.}}$) to the environment are maximal. It can also be seen that in the case of a maximum proportion of wood fibres of 80%, which corresponds to the value of 20% plastic on the X-axis, the marginal abatement costs ($AbC_{\text{marg.}}$) become maximal (= Point 2). Then the marginal damage costs ($DC_{\text{marg.}}$) are also minimal. It should be stressed that WPC needs at least 20% wood fibres to be considered WPC at all. Figure 16.4 contains several scenarios of internalisation by WPC, shown as three different marginal damage curves, $DC_{1,\text{marg.}}$, $DC_{2,\text{marg.}}$, and $DC_{3,\text{marg.}}$. Each of them intersects with the $AbC_{\text{marg.}}$ -curve. The corresponding amount of remaining plastic content (PC) in the WPC is $PC_{1,\text{int.}}$ to $PC_{3,\text{int.}}$. The following applies to these plastic contents: the degree of damage reduction corresponds to the degree of avoidance cost increase, since all curves are marginal values of the original cost functions. If even less plastic than $PC_{\text{int.}}$ was to be incorporated, i.e., if the fibre-content was to be further increased, the avoidance would be too expensive compared to the damage savings. Therefore, the result is efficient.

However, it can also be seen from Fig. 16.4 that the steeper the marginal damage curve, the lower the proportion of plastic in order to internalise optimally. It is evident that the additional benefit ΔU for the consumer, which is described as warm-glow, increases. Finally, it also becomes clear that it cannot be economically viable to substitute almost the entire plastic, because then the avoidance becomes too

expensive for society. This should only be the case if the environmental damage is rated extremely high.

The analysis makes it clear that WPC internalises ideally because the plastic content can be flexibly adjusted according to the extent of damage caused by plastic in nature. According to the author's opinion, currently about 30% of wood fibres ($=PC_{2,int.}$) should already internalise optimally (Friedrich, 2018). However, in the future, with even more realistic estimates of the extent of damage, higher fibre-content will certainly be required. It is also understandable that this avoidance technology must be used consistently in all products containing plastics in order to develop its internalisation potential at all. If the average fibre content in all plastics applications were already 30% today, the effects from internalisation would certainly be noticeable.

16.5 Conclusions

The aim of this chapter was to show how new materials based on biomass help to reduce environmental damage from less sustainable materials. Plastics, which become an internalisation technology through the addition of wood-fibres, were used as an example. It was shown that it is not economically efficient to replace almost all plastic material, because then the transition would be too expensive. The socially optimal degree of biomaterial integration depends on the assessment of the extent of damage caused by petrochemical polymers. The higher the prognosis, the more natural fibres need to be embedded to compensate. Also, the optimum fibre-content increases with decreasing production costs with the new avoidance technology. This means that in the future, costs will continue to fall with higher utilisation, which will then lead to even "greener" plastic materials. The plastics transition in the construction industry must first be initiated, then the change towards a regenerative economy will gain in momentum. The technology already exists, the industry commitment and consumer demand are now required. This internalisation model can also be applied to other sectors, such as the energy industry, where the optimal internalising share of energy from renewable sources can be calculated in the same way.

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