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Sustainability study of fibre-reinforced plastics in an industrial environment

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Abstract

Project background lies in a development project of a walkway end element made from fibre-reinforced plastics for Valmet’s OptiConcept M paper and board machines by the author during summer of 2018. Several unanswered questions about using fibre-reinforced plastics remained after the development project, so some of the questions were formulated as a thesis subject. The research problem was giving a sustainability-centered recommendation whether a broader usage of fibre-reinforced plastics is commendable or not. This was done by answering four research questions and providing a synthesis from the conclusions of each question which were 1) How a structure built from fibre-reinforced plastics compares against one made from steel, 2) How usage of fibre-reinforced plastics fit into ambitious sustainability goals such as Valmet’s, 3) How sustainability of fibre-reinforced plastics can be enhanced today, and 4) How future development will shape sustainability of fibre-reinforced plastics.

Both qualitative and quantitative methods were used with an emphasis on life cycle assessment methodology covered in ISO 14040/44, performing short case study interviews, conducting a comprehensive literature review and compiling internal information about sustainability and fibre-reinforced plastics at Valmet and its suppliers. Results from each of the research questions support the conclusion that replacing steel and similar materials with fibre-reinforced plastics can be a significant improvement from sustainability point of view in heavy industrial environments like Valmet’s. Most importantly, fibre-reinforced plastics generate less CO_2 emissions and have lower energy consumption during their product life cycle. Their use is not only justifiable but also recommendable in technically demanding long life-cycle industrial applications, given that their manufacturing and end-of-life treatment is carried out in socially and environmentally sustainable fashion.

Keywords/tags (subjects)

Fibre-reinforced plastic, life-cycle assessment, LCA, LCI study, case study

Miscellaneous (confidential information)

Chapter 5 and appendices 5, 6 and 9 are confidential and they have been removed from the public thesis. Grounds for secrecy: Publicity law 621/1999 24§, 17, Business or professional secret. The period of secrecy is five years and it ends in five (5) years after the publication.

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Tiivistelmä

Tutkimuksen tausta on kesällä 2018 tehdyssä tuotekehitysprojektissa, jossa suunniteltiin lujitemuovinen versio OptiConcept M paperi- ja kartonkikoneiden hoitosiltojen päätyelementistä. Materiaalin käyttöön liittyi useita ratkaisemattomia kysymyksiä, joista osa muotoiltiin opinnäytetyön aiheeksi. Tutkimusongelmaksi määriteltiin suosituksen antaminen sen suhteen, onko lujitemuovien nykyistä laajempi käyttö suositeltavaa kestävän kehityksen näkökulmasta. Tutkimusongelma ratkaistiin luomalla synteesi neljän erillisen tutkimuskysymyksen johtopäätöksistä. Tutkimuskysymykset olivat 1) Miten lujitemuovinen rakenne vertautuu teräksestä tehtyyn vastaavaan, 2) Miten lujitemuovien käyttö istuu yhteen Valmetin kestävän kehityksen ohjelman kanssa, 3) Miten lujitemuovien käytön vastuullisuutta voidaan parantaa olemassa olevilla menetelmillä ja 4) Miten kehitys tulee vaikuttamaan lujitemuovien vastuullisuuteen tulevaisuudessa.

Työssä hyödynnettiin sekä määrällisiä että laadullisia tutkimusmenetelmiä. Painoarvoa annettiin erityisesti ISO 14040/44:ään pohjautuvaan elinkaari-inventaarioselvitykseen, lyhyille case-tutkimushaastatteluille, perusteelliselle kirjallisuuskatsaukselle ja Valmetin kestävän kehityksen ohjelmaa ja käytössä olevia lujitemuoviosia koskevan sisäisen tiedon koostamiselle. Kaikkien tutkimuskysymysten tulokset tukevat päätelmää siitä, että teräksen ja muiden vastaavien materiaalien korvaaminen lujitemuoviosilla on kestävä toimintamalli. Tärkeimpiä tähän liittyviä huomioita ovat lujitemuoviosien pienemmät hiilidioksidipäästöt ja energian kulutus koko elinkaaren aikana. Lujitemuovien käyttö teknisesti haastavissa, pitkän käyttöiän kohteissa on kestävän kehityksen näkökulmasta paitsi perusteltavissa myös suositeltavaa edellyttäen, että niiden valmistus ja loppusijoitus hoidetaan ympäristö- ja työturvanäkökulmasta tarkasteltuna kestävällä tavalla.

Avainsanat (asiasanat)

Lujitemuovi, elinkaariarviointi, LCA, elinkaari-inventaarioselvitys, case-tutkimus

Muut tiedot (salassa pidettävät osuudet)

Opinnäytetyön luku 5 ja liitteet 5, 6 ja 9 ovat salassa pidettäviä ja piilotettu julkisesta versiosta. Salassapidon perusteena on Julkisuuslain 621/1999 24§, kohta 17, mukainen yrityksen liike- tai ammattisalaisuus. Salassapitoaika on viisi (5) vuotta.

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Glossary of terms

Carbon fibre reinforced plastic, CFRP. Polymer matrix reinforced with carbon fibres. Forms relatively small portion of the total plastic composite production, but a major portion of their market value.

Composite. Combination of two or more materials that are not dissolved or blended in.

Fibre (fiber). Reinforcing component of FRP, where the length is considerable bigger than the other two spatial dimensions.

Fibre-reinforced plastic, FRP. Polymer matrix reinforced with fibres.

Filler. Added to FRP to adjust its properties. Can be included directly in the resin or mixed in separately.

Glass fibre reinforced plastic, GFRP. Polymer matrix reinforced with glass fibres. Forms majority of plastic composite production.

Hardener. One of the two main components of thermoset plastics in liquid state. Forms thermosets when combined in and cured with a resin.

LCA study; Life Cycle Assessment Study. Consists of four phases: definition of goal and scope, inventory analysis (LCI), impact assessment and interpretation.

LCI study; Life Cycle Inventory Study. The same as LCA study, excluding impact assessment phase of it. Not to be confused with the LCI-stage of an LCA study.

Life cycle; Product Life Cycle, PLC. Consecutive stages of a product from extraction to raw materials to the final disposal.

Life Cycle Assessment, LCA. Compiling, quantifying and evaluation of products potential (environmental) impacts thorough its life cycle.

Life Cycle Thinking, LCT. Shifting of the focus beyond production to environmental, social and economic impacts of a product over its entire life time.

Matrix. Binding material of the composite.

Plastic composite. Composite material with a polymer matrix.

Polymer (plastic). Usually a petro-chemical -based material, produced through polymerization: formation of long molecular chains. Can be divided between thermosets and thermoplastics according to their malleability.

Resin. Liquid component of a thermoset that is mixed in with a hardener.

Sustainability. Support without collapse. Most commonly divided to three major aspects, also called as the triple bottom line of *Business sustaniability*: economic, social and environmental.

Thermoset. Type of plastic produced by combining resin and hardener in a liquid state. Consists of chemically interconnected polymer chains that prevent reshaping of the material with heat or pressure.

Thermoplastic. Type of plastic. Consists of polymer chains that are not interconnected, allowing repeated reshaping of the plastic by using heat and pressure.

Waste hierarchy. Order of priority for disposal of solid waste: prevention, prepare for reuse, recycle, other recovery and disposal.

1 Project definition

1.1 Lead-up

The background for this thesis is in a product development project started during Summer 2018 as part of the authors’ full-time job as Industrial Design Trainee at Valmet Oyj. **Curved end element for walkway platforms of the OptiConcept M paper- and board machines needed a redesign**. Even though possible to manufacture in a fashion that meets all the set quality requirements, there had been recurring issues in its manufacture and finding multiple suppliers capable of producing such quality. This led to pressure in developing an alternative version of the element in way where good quality would be ensured in every piece with reasonable expenses. Since the element is one of the most visible eye-catchers in a paper or board production lines, the demands for the visual quality played a huge part in the redesign.

The existing structure of the walkways is illustrated in figure 1 with the end element framed with red lines. The picture was taken early 2018 in the pre-assembly hall of Valmet’s Rautpohja-unit located in Jyväskylä, Finland and was the latest available reference of it during the time of starting this thesis. The picture is taken at the ground level with the angle of the view being the most typical for observing the structure.

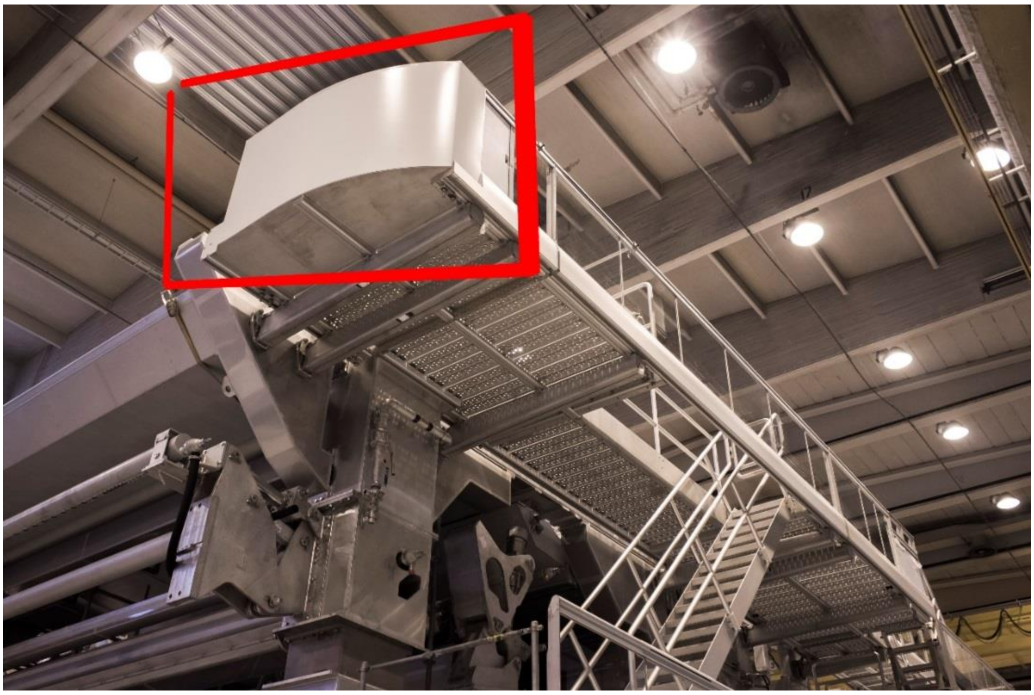


Figure 1. Assembled walkway with a steel end element

Fibre-reinforced plastic (FRP) was chosen as the material-to-go for the redesign, since it would be relatively cheap to produce and as a moulded product, its quality-control would be easy. The preliminary design was carried out during the Summer of 2018 (figure 2), but when the design was ready enough to start contacting possible suppliers for producing the prototype and possibly doing the actual production later, it was identified that there were several unanswered questions with the new material.

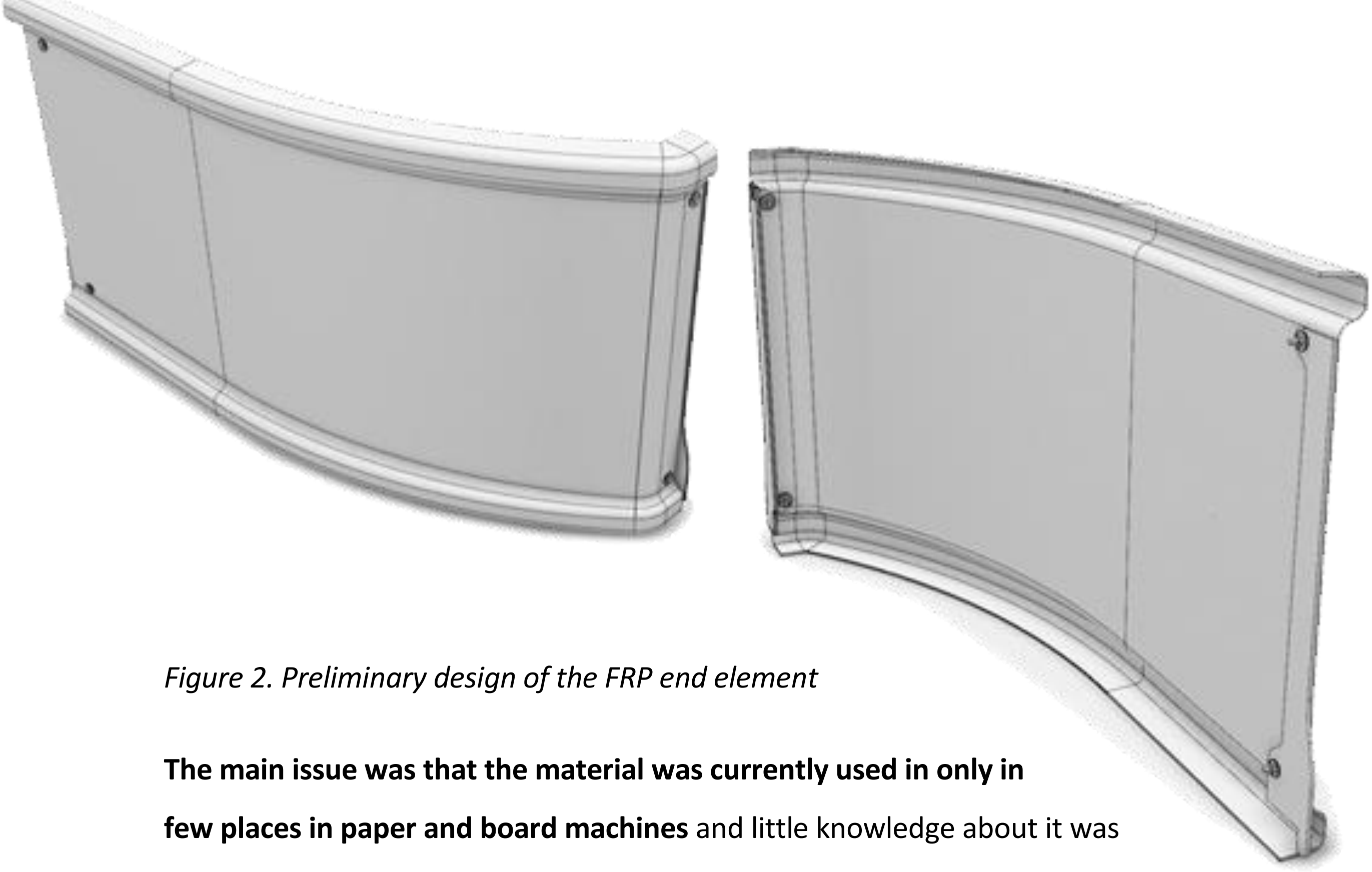


Figure 2. Preliminary design of the FRP end element

The main issue was that the material was currently used in only in few places in paper and board machines and little knowledge about it was readily available. There hadn't been any previous studies regarding sustainability of the material inside the company either. Broader usage of plastics could be widely considered to be in direct conflict Valmet's brand with possible attitudes of stakeholders towards usage of plastics seen another possible issue. The product would need to also comply with the corresponding safety regulations and the moist, corrosive and chemically challenging high-temperature environment of paper and board machines. Due to these reasons, it was decided to study deeper in to the material.

1.2 Valmet

Valmet is a Finnish technology company producing technologies, services and automation primarily for paper and energy industries (About us 2018). Profitability and revenue of the company has been growing clearly for the past several years, with revenue reaching all-time-high of 3 300 M€ and approximately 12 500 employees on the latest published financial statement of 2018. Contrary to expectations, the amount of revenue generated in the Paper business line has stayed way higher (1000 M€) than initially projected (650 M€) for two consecutive years. (Valmet strategy info 2018-2020; Annual Review 2018. 2019, 5, 8.)

This all aligns well with the authors general conception as employee of Valmet that the paper industry is doing well, despite the constant fear and predictions of its decline. The combined global consumption of paper and board has, in fact, increased by 7% from 2006 to 2016 (Production volume of paper and cardboard worldwide 2006 to 2016 (in million metric tons). 2018) and continues to increase mainly because of increased demand of board grades and tissue generated by eCommerce, urbanization and higher standards of living. The growth of these two compensate and even exceed the declining demand of *Printing&Writing and Newsprint* paper grades. This is further supported by environmental issues, that are driving the transition from plastics to fibre-based packaging. (Mandell & Virtanen 2019.) Restrictions and prohibitions on plastics-based products will increase in the future, which may well open massive new markets to other pulp-based products in addition (Immonen 2019).

1.3 A broader view

The title of this thesis could well include the term “plastic composites” instead of “fibre-reinforced plastics” that is only one category of the aforementioned. These terms, defined alongside other plastics-related terminology in chapter 3.1, are largely interchangeable in this context, as every plastic composite project at Valmet utilize fibre-reinforced plastics exclusively. Because of this, the work was narrowed down to FRPs that are considered having the best mechanical properties (Saarela et al. 2003, 19), but its findings are largely applicable to any other plastic composites.

Figure 3 outlines the thesis in the bigger picture as a Venn diagram. The selected umbrella term is Sustainability at Valmet, a major focus area in the company. A good representation of the strong stated commitment to this is the company’s mission: C*onverting renewable resources into sustainable results*. Usage of Fibre-Reinforced

Plastics at Valmet is perceived to largely fall inside the sustainability-agenda, while the topic of the thesis forms a notable part of usage of FRP at Valmet. Product development project of the end element was considered hardly relevant and as such barely intersects the thesis, although knowledge gathered from its development like the FEM-analysis of it proved helpful at later stages.

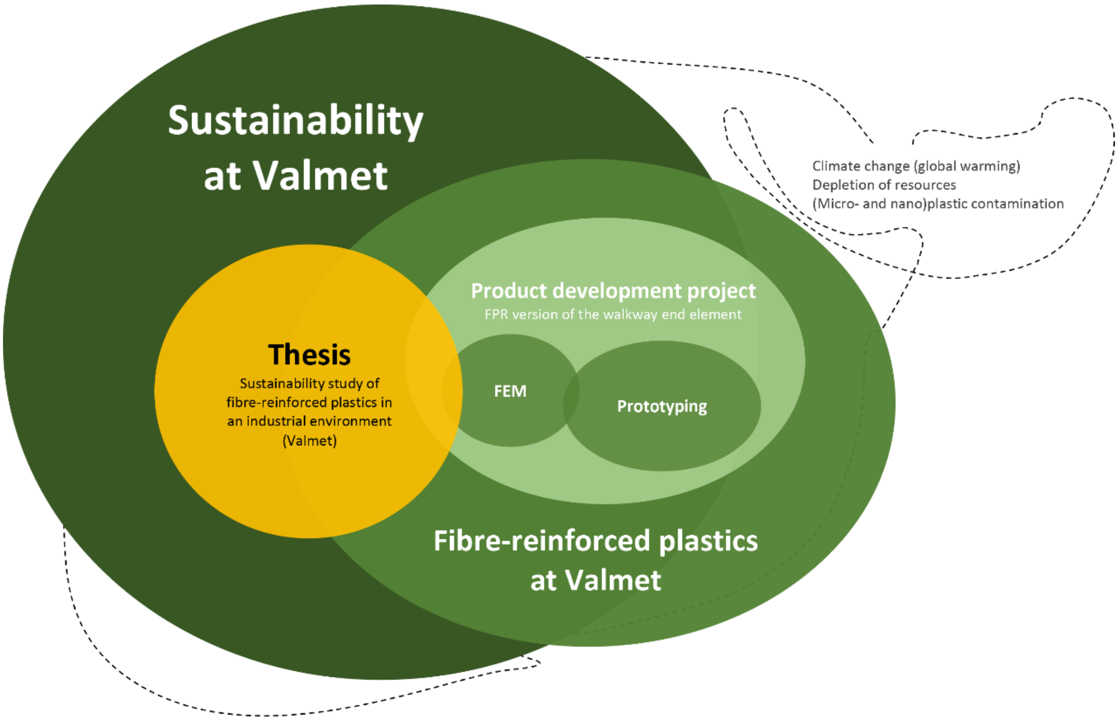


Figure 3. This thesis as part of a bigger picture

Even though material technology was viewed as inseparable part of the thesis, its importance relative to sustainability-driven aspects was consciously diminished due to the managements take that the topic of this thesis is well-grounded if it’s done with primary focus on sustainability. Additionally, there was a direct conflict of interests between the operational and the strategic level of the organization: On the strategic level, a decision in favor of reduction the use of all plastics in Valmet’s products was made during summer of 2018 (Puustjärvi 2018). On the operational level, there was major pressure to increase the cost-effectiveness and quality control by replacing metal structures with ones produced from fibre-reinforced plastics. In the end, it was decided that it is far more important for the company to focus on the environmental friendliness of the paper-making process itself rather than the machines running the process; whereas studying higher usage of plastics in the process would’ve been more questionable, the strive for better cost-competitiveness in the machinery by utilizing plastics was seen relevant (Saario 2018). The best way to minimize risks in using plastics such as ones related to sustainability and brand image of Valmet is doing research alike this thesis. One of the most important presumptions of this work is that there is enormous potential to increase cost-competitiveness of Valmet's products by utilizing FRP but replacing steel structures with FRP-composites of presumably questionable sustainability needs solid argumentation to be strategically acceptable.

In the grand scheme of things, three problem areas in sustainability of plastics pop up frequently: *climate change* (global warming particularly), *depletion of resources* and *plastic contamination* (micro- and nanoplastics particularly). Whereas Valmet's business strategy leans strongly on mitigating and adapting to climate change and depletion of resources (Saario 2017, 2), plastic contamination can be seen almost equally or even more important; Microplastics are being even cited as "number one threat" to humankind with a prospect of extinction unless urgent steps are taken (The Global Plastic Calamity 2019, 4).

IPCC (Intergovernmental Panel on Climate Change) published its special report SR15 around the time of starting this thesis. It addressed confining the global warming around +1,5 °C level compared to the pre-industrial age, provoking major concerns on sustainability of actions of humankind with wordings such as being "the most disturbing description of humanity's destruction of the planet" (Dans 2018). Figure 4 illustrates the situation until 2017 and the future predictions in different scenarios. They all forecast the global warming to peak at alarming +1,5…2 °C with "high confidence" between 2030 and 2052 and either start decreasing or becoming steady after that (Global Warming of 1,5 °C – Summary for policymakers 2018, 5), but this requires radical measures. Our legal and economic systems responding normally only to immediate and certain threats (Theodore & Theodore 2010, 153) instead of also foreseeable ones, combined with evidences of those in power having the higher likelihood of denying climate change and the science behind it (Klein 2014, 46) form a formidable challenge in fighting climate change. Pivotal points to it include reduction of greenhouse gas emissions, eliminating the already-accumulated greenhouse gases from the atmosphere, ceasing the use of fossil fuels and improving energy efficiency and use of natural resources in general (Dans 2018). The latter applies also to depletion of resources alongside with focus on renewables, as stated in the very mission of Valmet.

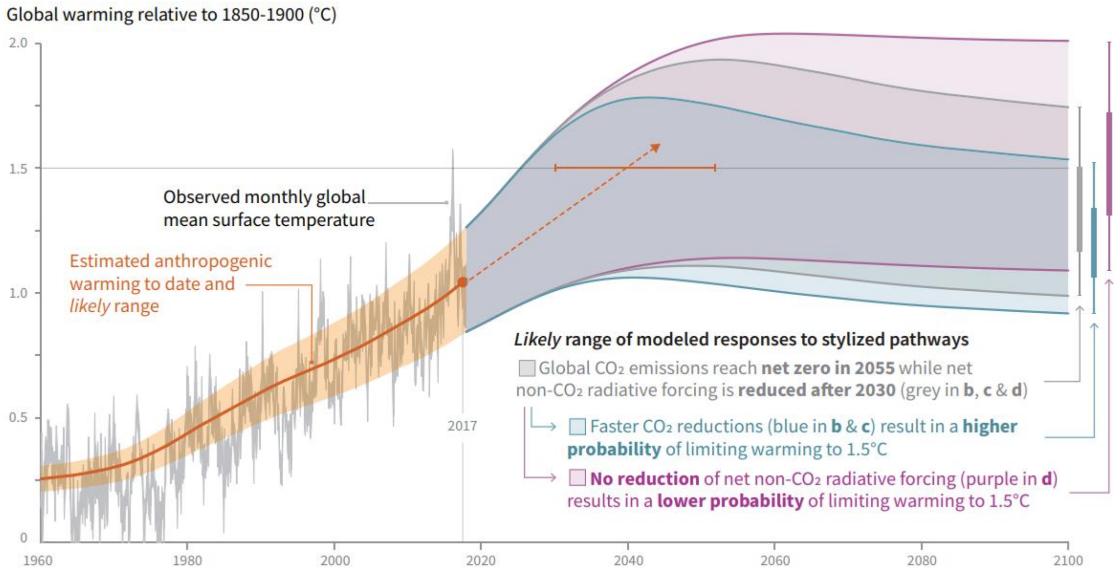


Figure 4. Predictions on global warming (Global Warming of 1,5 °C – Summary for policymakers 2018, 8)

The year 2018 brought huge media-attention on the problems of plastic contamination, especially when it comes to marine debris formulated from plastics, with video and photographs circulating in what seemed to be all over social media at the time. While climate change is being stated as one of the greatest challenges the world is facing (SFS-EN 14067:2018, 5), marine litter was one of the most important news topics of 2018 alongside it (HS-työryhmä 2018). As such, being able to formulate well-articulated, facts-based views around these topics is something all engineers might need to be able to do in a very near future. According to Smith (2011, 25-43), the upcoming few decades will be mostly shaped by four megatrends that are all at the very core of sustainability: *Climate change*, *Overuse of natural resources*, *Growth of population* and *Globalisation*.

Engineers as developers of products and processes have a major influence in affecting the ecological footprint of the products and services being consumed. Importance of careful planning and design is emphasized by the nation that the design phase of the product is the only one during which natural resources are not consumed (Kamrani, Azimi & Al-Ahmari 2013, 3). The influence of the product design to the end result is approximately 70 % where as costs of the product development stage are only around 5 % of the total expenses as famously stated by Munro & Associates (History of Lean Design® 2013). Ulrich and Eppinger (2012, 5) exhibit similar numbers with development costs forming of 1 – 3 % the total sales of each product example presented. With ratios like this, everything else being done right at every possible later step is next to trivial, underlining the importance of strategic planning and product developers understanding well implications of their decisions.

1.4 Objectives

The **research problem was to provide a comprehensive, sustainability-driven argumentation whether a broader usage of fibre-reinforced plastics is commendable in an industrial environment**. In addition to answering the question solely regarding health, safety or environmental aspects of sustainability, the research sought to factor in business competence to provide meaningful results (Welford 2004, 152): whether the assumed higher cost-efficiency of FRP compared to steel, the most used material of paper and board machines, outweigh its assumed sustainability drawbacks. Subsequently, **the primary research question** for solving it was defined as

1. **How a structure built from fibre-reinforced plastic compares to a one made from steel, with the most relevant sustainability-metrics possible?** (RQ1)

In order to answer this question, **what the most relevant metrics are needs to be defined** first. It was deemed obvious that steel fares in many indicators of environmental sustainability but loses to plastics in some regards and they're being discussed far too little. For instance, when it comes to energy-intensiveness of different materials in construction industry, aluminum – another material used widely at walkway platforms – and steel are the absolute worst according to Toiviainen (2008, 27). On the other hand, fibre-reinforced plastics are notorious materials when it comes to their recyclability. In general, sustainability-driven discussion and decision making was viewed as being based too much on opinions and misconceptions instead of facts due to absence of practical, ground-level data. Solving the research problem was considered helpful for strategic purposes and developing Valmet's sustainability program further. Should the findings the work support recommending additional usage of FRP a quick, well-visualized draft on how to proceed identifying the most plausible applications for FRP, as well as composing design guidelines were considered for secondary practical benefits. At later stage these were reduced to a list of helpful questions in determining whether

FRP is an advisable material from sustainability point of view for an intended application (chapter 8.2). In case of a non-recommendation, the argumentation behind it would have been be equally important.

The primary research question was not expected to provide a satisfactorily broad answer to the research problem. Consequently, following **auxiliary research questions** were specified

2. **How usage FRPs fit into Valmet's sustainability goals?** (RQ2)
3. **How sustainability of FRPs can be enhanced today?** (RQ3)
4. **How future development will shape sustainability of FRPs?** (RQ4)

Even though initially not considered as important as RQ1, these three were added **to be covered at least briefly due to their high potential to produce significant added value** to Valmet. This was viewed to be the case particularly regarding the future predictions, as factors such as environmental load of the production and possible negative effects on the brand image of the company using FRPs concern present day, but ultimate disposal – aspect widely considered the most problematic in plastics – is issue only at the end of the life cycle. Considering that paper and board machines have a typical life-span of 30 – 50 years (Immonen 2019), it is relevant to look not only at the current state of sustainability of fibre-reinforced plastics but also the future of them. If a paper machine with non-recyclable FRP parts would be built today, would they be efficiently recyclable at the end of the machine life time? In addition to recyclability, other aspects on the sustainability of FRP in future were considered briefly.

Studying RQ2 required not only finding out the details of Valmet's sustainability agenda and its metrics at Valmet, but also the current situation. These questions included examining how widely such materials are used, how their usage has been justified, whether past studies had been made, how big impacts their use currently have on the company and do these aspects collide somehow with the sustainability agenda of the company. RQ3 and RQ4 were purely about the material itself. As the work went on, importance of RQ2 and RQ3 were considerably heightened in favor of RQ1 due data availability, know-how and perceived significance of the findings.

The research questions were subject to few assumptions. As for RQ1, whether the material should be used more or not was expected to culminate on which metrics the answer is based on. Coming up with objective comparisons between purely quantitative factors and those depending on ones’ values was also perceived challenging, with the pitfall of biased selection of metrics to produce the supposedly desired outcome.

Productional and financial factors were expected to support the use of FRPs, but fitting the material with Valmet’s ambitious sustainability goals (RQ2) was anticipated being difficult. Finding more sustainable ways to produce FRPs with what is available already in comparison to industry standards (RQ3) was thought to be not only possible but also highly probable. Means to it were expected to turn out very limited as the most commendable materials and technologies might near the cost of a comparable steel structure. Sustainability of plastics was expected to be enhanced greatly with nearly every possible metric in the future, but finding relevant information regarding upcoming technologies and breakthroughs was expected to be laborous, leaving expectations from conclusions of RQ4 to be very shallow or uncertain in nature.

To further clarify thesis workflow, the research questions with their respective priorities, mutually agreed between the author and representatives of Valmet, and thesis objectives were compiled as a flowchart (figure 5). Another way of defining the thesis process would have been to answer RQ1 exclusively but the now-selected process – even though challenging, extensive and multi-staged in nature – was perceived to maximize the practical benefits of the work while doing so in a sufficiently vertical, scientific manner. Adding the auxiliary research questions and follow-up stages just meant considerably more horizontal study instead of predominantly a vertical one. A component of conscious risk-taking was present, where the reserved time for answering the primary research question might turn out to be insufficient. This risk was minimized by pedantic project management, scheduling and tracking of working hours.

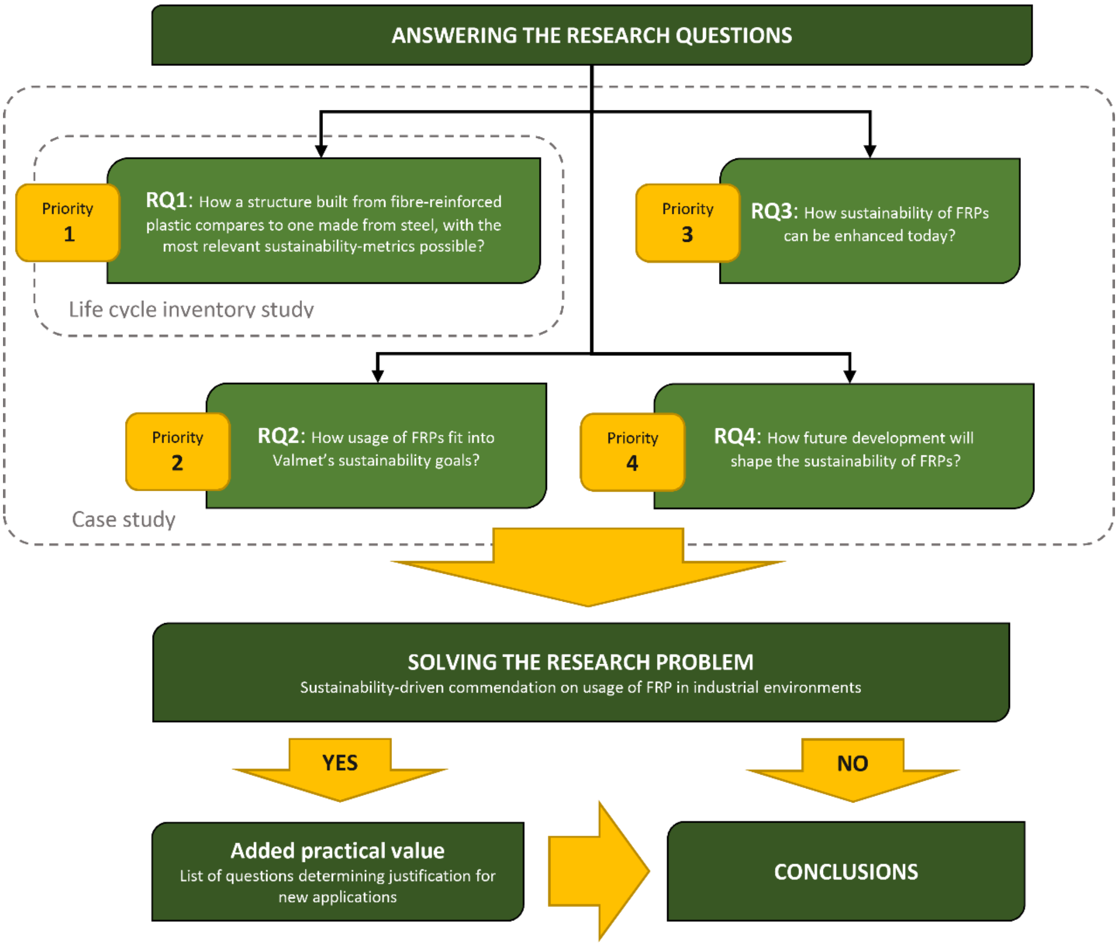


Figure 5. Flowchart of the thesis progress

2 Methodology

The best way to solve the research problem was perceived as conducting a **case study** (Sahari 2019), research that aims to gather in-depth, thorough knowledge of the research subject by empirical investigation, studied in its natural context and by utilizing multiple sources of evidence (Kananen 2013, 54). Selection of case study as the research strategy was justified due to manifold research problem that was hard to break down to its components due to its complexity – the very definition of how a case study should be chosen as a research method (Ibid., 59). Additional indicator was found from the nature of the research questions dominated by *How*-questions (Yin 2014, 191). This thesis can be viewed not only as a case of purely technological study conducted from an engineering point of view, but a combination of technological, social, environmental and economic aspects (Sahari 2019). Hence, the **research object** that **was** approached from all these four angles is not the end element examined in RQ1 but **Valmet's and its stance on sustainability in relation to FRP**.

Case study is viewed primarily as qualitative research but can include quantitative methods in addition (Yin 2014, 19). Quantitative methods used primarily in answering RQ1 stress quantification, numbers, generalization and prediction (Kananen 2013, 24). Qualitative research, utilized in assessment of the LCI study results for RQ1 and solving RQ2, RQ3 and RQ4, emphasizes comprehension, themes, open questions, text and descriptions (Ibid). The **stages of work** in a case study are the same as in qualitative and quantitative research methods (Ibid., 59), illustrated in table 1 alongside their practical meaning in this thesis.

Table 1. Research stages

No	What	Practical meaning
1	Definition of the research problem	Should FRP be utilized to a greater extent?
2	Definition of the research questions	RQ1, RQ2, RQ3, RQ4
3	Choosing the research object	Valmet and its stance on sustainability in relation to FRP
4	Choosing analysis and information collecting methods	ISO 14000, OpenLCA, six sources of evidence (documentation, archival records and themed interviews in particular), references
5	Implementation of the research	LCI study, conducting interviews and the literacy review, personal messages and discussions, triangulation
6	Interpretation and analysis	Spreadsheets, mindmaps, flowcharts, critical review session
7	Documentation	Thesis report with its appendices

Solving RQ1 was mainly based on methodology of **life cycle assessment**, LCA, covered in ISO 14040/44 and defined in detail in chapter 3.6. The selected tool within the methodology, to which the work is based on but does not fulfil the requirements of, was a life cycle inventory study, LCI study, where the environmental performance of the FRP and steel end elements were assessed and compared against each other. It was mutually agreed between the author and Valmet representatives that without having an example product to reflect upon, the work could have been too abstract and as such, not useful enough for Valmet to justify commissioning of the work.

The walkway end element as the examined product was selected as a combination of several factors. There were possible rivals for the product (chapter 5.2) but the considered factors aligned best with the end element, most importantly

- **The product didn’t include confidential aspects**, so better public availability of this thesis was ensured by selecting it
- **Currency as a freshly developed product**, as results of this thesis might affect directly in the decision to continue with its development and possible future production.
- **Good data availability and familiarity** of the selected product(s) to the author

Table 2 presents an overview of the number of items per sources of evidence and categories of reference in relation to which research question studying of them aimed to answer. The line between classifying items as *evidence* or *reference* was a very thin and artificial one but was drawn with items of internal information of Valmet, personal messaging and data gathered personally by the author categorized as evidence, where other publicly available information was labeled as references. The amount of information on each item varied at large and a lot of the data was handled in bundles with some of the items consisting of several subitems. Therefore, the absolute numbers in the table should be interpreted only directionally as what kind of sources were utilized, instead of definite conclusions of respective priorities purely based on the number of each cell. A detailed breakdown of each item is organized in spreadsheets and presented in appendices 1-2. Appendix 1 also contains more comprehensive information on how the evidence was treated, most importantly basic principles upon which the interviews were planned, executed, documented and verified.

Table 2. Utilized sources of evidence and references per research question

Source	**Research question**			
	RQ1	RQ2	RQ3	RQ4
Evidence				
Documentation	4	12	3	3
Archival record	3	10	0	1
Themed interview	0	2	6	3
Direct observation (passive observer)				
Participatory observation (active observer)	0	2	0	0
Physical artifact				
References				
Scientific publication	5	0	10	4
Book	2	0	1	3
Other digital publication	3	1	1	3
Article	1	0	3	1
Website	1	0	8	0

The research questions were primarily answered through interpretation of the collected evidence (chapters 4-7, while references were mostly leaned on when collecting evidence wasn’t viable. This was mostly true in the case of answering RQ3-4, where lots of scientific papers on the disposal of FRP now and in the future was browsed through. Most of the studied material overlapped significantly in terms of research questions. This meant that conclusions for individual research question are, for structural clarity of this document, presented at the end of respective chapters dedicated for each of the research questions. Overall conclusions, as a synthesis of answers from the four research questions, are presented in chapter 8.

Lots of references not listed in table 2 were used in addition. Those included items that were helpful in determining methodology and definitions, but also for background data, statistics, legislation and classifications. The evidence was classified according to the six major sources of evidence in a case study according to Yin (2014, 106-118), out of which all were collected or considered. The goal was to collect as extensive amount evidence as possible to achieve comprehensive triangulation of evidence – validating the consistency of data through cross verification and deepening understanding of the topic (Ibid., 241).

A particularly heavy emphasis was put on the themed interviews, which were planned as short case study interviews as defined by Yin (Ibid., 110-111) – done at one sitting with an average length of 56 minutes and a rather tight focus on the defined stream of questions. All the used interview questions are presented in appendix 3 (in Finnish) with the key takeaways from each interview included in appendix 4 (in English).

3 Key definitions

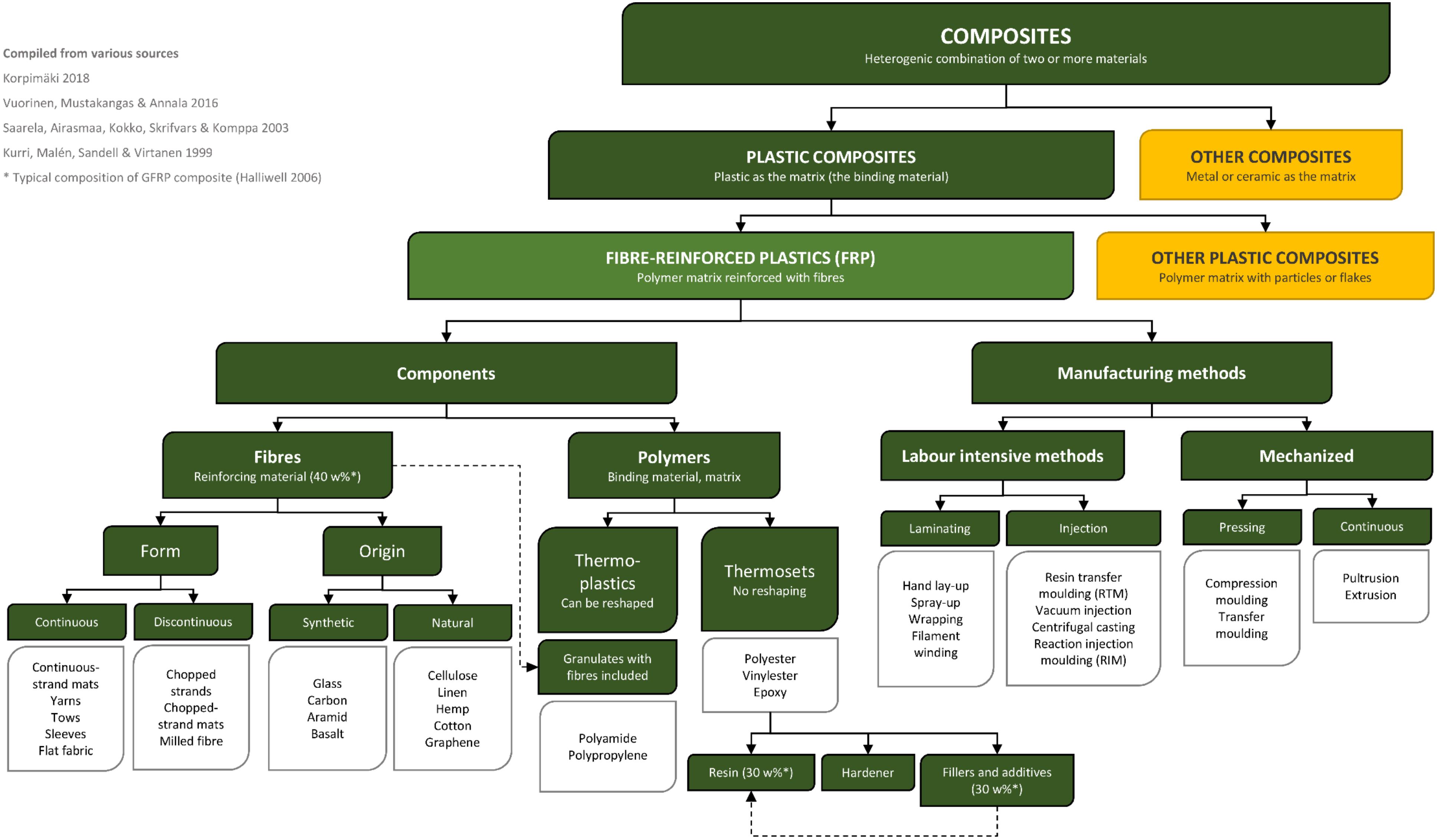
3.1 General definitions on plastic composites

Composites are combinations of two or more different materials where the materials are working together but are not dissolved or blended in. The binding material of the composite, called **matrix**, can be either metal, ceramic or plastic. A material is called **plastic composite** when its matrix is plastic, usually an oil-based product achieved through polymerization. (Vuorinen, Mustakangas & Annala 2016, 3, 16; Saarela, Airasmaa, Kokko, Skrifvars & Komppa 2003, 17; Polymerization: How plastic materials are made 2018.) A visual representation that compiles key terminology from the various sources referred to in this chapter is presented in figure 6. The hierarchy of how components of FRP are structured varies greatly based on the source, so whenever they were contradictory, definitions of Vuorinen et al. (2003) were followed.

Fibre-reinforced plastics are a form of plastic composites that consists of a polymer matrix blended in with fibres (Vuorinen et al. 2016, 5). The matrix serves as the base material that binds the composite, as well as passes the external forces for the fibres to carry (Keskinen & Mannermaa 2019). Amount of each of the components in FRP is most precisely stated as weight content w% or volume content v% (Saarela et al. 2003, 453, 456) that vary depending on the manufacturing method and desired properties.

Fibres, are added to enhance the mechanical properties of the composite. They are usually produced from synthetic minerals, but ones of natural origin can also be used. Fibres are defined as a form of reinforcement where one of the spatial dimensions is considerable bigger than the other two. Reinforcement can be alternatively provided in the form of flakes (two of the dimensions are bigger than the third) or particles (all three of the dimensions are relatively equal). In such cases, the composites are not FRP but other forms of plastic composites. (Vuorinen et al. 2016, 5.) Approximately **95 % of all reinforcing fibres used are glass fibre, from which 99 % is E-glass** that has good electrical and mechanical properties and good corrosion resistance, especially considering its low price (Saarela et al. 2003, 14, 74). Due to broad use of glass fibres as reinforcement, glass fibre reinforced plastics are referred as **GFRP** across the literature. Carbon fibre-reinforced plastics are referred with similar logic as **CFRP**.

Polymers (plastics) in FRP can be divided between thermoplastics and thermosets according to their malleability, with FRPs being made almost exclusively from the latter (Saarela et al. 2003, 14). **Thermoplastics** are formed from long chains of polymer that are not chemically bonded and as such, can be repetitively molded by utilizing heat and pressure. **Thermosets** cannot be reshaped with heat and pressure or by dissolving due to their polymer chains being chemically interconnected. (Ibid., 18).



Compiled from various sources

Korpimäki 2018

Vuorinen, Mustakangas & Annala 2016

Saarela, Airasmaa, Kokko, Skrifvars & Komppa 2003

Kurri, Malén, Sandell & Virtanen 1999

* Typical composition of GFRP composite (Halliwell 2006)

Figure 6. Key FRP terminology, multiple sources

Thermoset polymers consist mainly of two components in liquid state: **resin** and **hardener** (Vuorinen et al. 2016, 4). They're combined by the end-user during the manufacture to achieve the polymerization of the plastic. **Fillers** and **additives** for adjusting their properties according to the use are also usually included, either directly in the resin or mixed in separately (Saarela et al. 2003, 18, 53, 57). Polymers in FRP are typically polyester, epoxy or vinylester. Roughly half of it is typically from the resin and hardener while the rest is fillers. (Halliwell 2006, 25; Saarela et al. 2003, 35.) While the polymerization of the thermosetting plastics is done during the manufacture of FRP, thermoplastics are fully polymerized when they're being shipped from the raw material producer. They come usually in the form of plastic granulates, which are they're and impregnated to the reinforcing material during manufacture of thermoplastic products. (Saarela et al. 2003, 53.)

Production of plastic composites is material additive in nature (Huikuri 2019). Manufacturing methods can be divided roughly to labor intensive – typically wet lay-up and various injection methods, both relevant in the case of the walkway end element (Korpimäki 2018) – and mechanized such as pressing or continuous processes like pultrusion (Saarela et al. 2003, 13, 153). In wet lay-up, fibre layers are placed to the mould manually with resin being added between each layer manually. Vacuum injection utilizes a vacuum bag placed around the mould after the reinforcing material is added. Subsequently, the used resin is fed and cured by vacuum. (Saarela et al. 2003, 154-155, 167, 447.) Between the two, wet lay-up demands more reinforcing material to achieve similar technical performance, resulting in higher material consumption. Additionally, it exposes the worker more to hazardous fumes as the resin is being added manually in an open space (Korpimäki 2018).

A significant portion of FRP-products are **laminates** (typical products of wet lay-up and vacuum injection particularly) that are formed by combining two or more layers of reinforcing material and aligning them relative to each other to produce an anisotropic product, one having different physical properties depending on the measurement direction (Saarela et al. 2003, 456- 457).

Benefits of plastic composites in comparison to metals (FRP vs traditional materials 2017, 2-3; Saarela et al. 2003, 13; Kurri, Malén, Sandell & Virtanen 1999, 139) are

- Good weight-to-strength/stiffness ratios
- Possibility for aligning mechanical properties (non-isotropic structures)
- Freedom of shape
- Possibility to produce large one-piece parts
- Good chemical durability
- Cheap moulding costs
- Easy-to-repair structural damages
- Low electrical and thermal conductivity

Although each point on the list is relative – depending on plastic composite, metal and/or methods of manufacture like freedom of shape in cast or 3D-printed metal – it serves as a good basis in understanding strengths of plastic composites in general.

3.2 Consumption and waste of plastic composites

Usage of plastic composites has been on a rise thorough 2000s with the global consumption accelerating considerably year by year. The global market value at 37 billion € in 2016 is estimated to reach 51 billion € in 2021, boasting average annual rise of 8 % in value (Anane-Fenin & Akinlabi 2017, 1). In Europe, production of composites is approximated to be 1 000 000 tons each year, with the amount of waste composites being around 300 000 tons, roughly being doubled in ten years between 2005 – 2015. Due to the typically long life-cycle of waste composites, the high amounts of production transition in to high amounts of waste with a long delay. (Blom & Dufva 2016, 20.)

Global consumption of CFRP has been on a particularly steep rise, as it has gone from almost 35 000 tons in 2008 to estimated 120 000 tons per year in 2020 and estimated to continue rapidly for the foreseeable future. A similar amount of waste that is produced currently is expected to become due for scrapping around 2041, with an average of 22 years delay. (Anane-Fenin & Akinlabi 2017, 1; Pickering & Turner 2013, acc. Melendi-Espina, Morris, Turner & Pickering 2016, 2.). Whereas CFRP has been used almost exclusively by the aerospace industry in the past, the rise in demand is mainly explained by interest from other industries like automotive and transport industries where usage of more traditional materials is simply not enough anymore in terms of performance. Usage of typically more expensive composites shift the focus from investment to life cycle costing, as the usually-higher costs of lightweight composite structures can be compensated manifold in the use-phase by faster handling times and reduced energy consumption a lot of times. (Huikuri 2019; Mannermaa 2015, 32, 34.) Whereas carbon composites form only a fraction of the production, they form extremely high portion of the value of all composites. For example, Job (2010, 3) cites the values being 2 % of production but 40 % of value in UK around 2010.

Sources of waste composites are two-fold: primarily products reaching their end-of-life (80 % of all composite waste), secondarily process waste in the manufacture (20 %). The absolute amount of process waste has stayed level for several years, whereas products reaching their end-of-life is on a steady rise. (Blom & Dufva 2016, 16, 20.) This emphasizes the problem being more severe in the ultimate disposal rather than directly in the manufacturing industry. The problem is further highlighted due to process waste being easier to recycle than end-of-life products as they're typically cleaner, dryer and pre-sorted (Blom 2019).

3.3 Micro- and nanoplastics

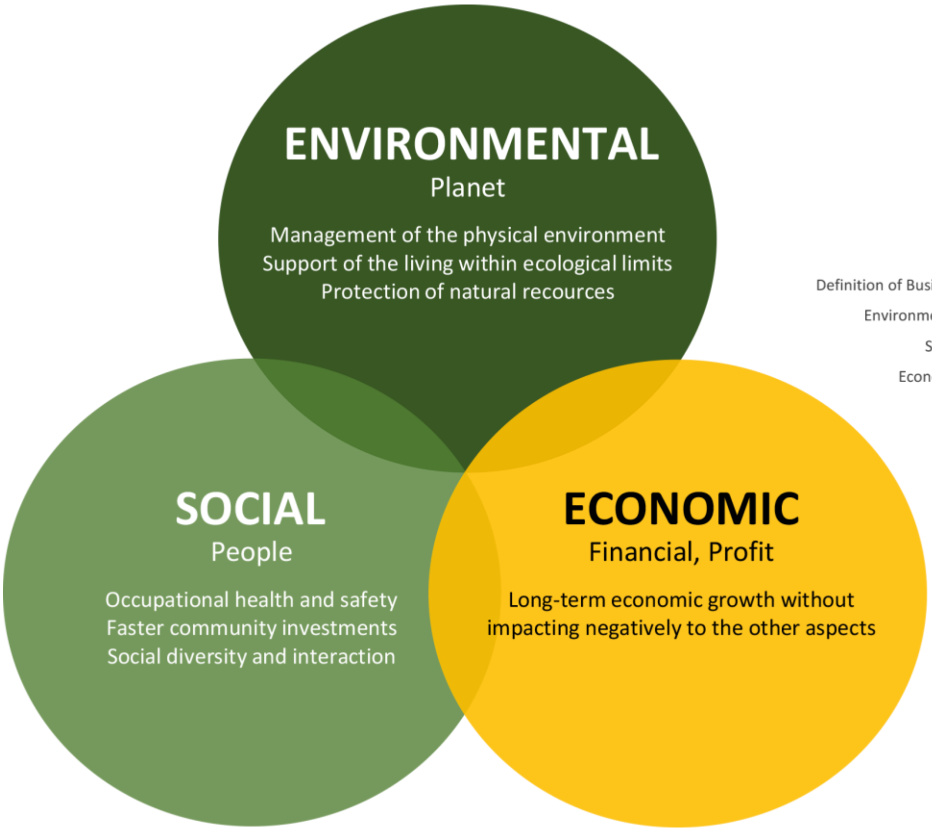
Microplastics are synthetic, micron-scaled solid polymers that cause potential risk when their particles don't disappear by dissolution or degradation (Verschoor 2015, 29). During the past few years, they have been a major talking point and one of the biggest concerns regarding usage of plastics in general due to their synthetic nature and chemicals used in them. Whereas most sources dub climate change as the single biggest environmental challenge today, micro- and nanoplastic contamination is – if not on par with climate change – at least the concern that comes right after it (Jokinen 2019a). The most important sources of micro- and **nanoplastics**, plastic particles of less than 1 micrometer in size, are pre-production plastic granulates of the thermoplastic industry, synthetic fibres used in fabrics, degrading plastic waste and microbeads added to health and beauty products. Nanoparticles, being able to enter internal organs and bloodstream, are a particularly deep concern. Whereas marine microplastic pollution is a problem of particularly intense media attention, terrestrial microplastic pollution is estimated to be 4 - 23 times higher in weight. (The Global Plastic Calamity 2019, 7, 8.)

Microplastic pollution has already been identified as a problem in some of the most unexpected places like underground freshwater sources, remote mountain areas and even the air we breathe with only little known about how they affect the human health (e.g. George & Roberts 2019; Panno, Kelly, Scott, Zheng, McNeish, Holm, Hoellen & Baranski 2019; Piirainen 2018). However, some studies indicate that they may have a profound impact on hormones affecting fertility, immune systems, blood pressure and building up multiple diseases such as cancer (The Global Plastic Calamity 2019, 4). All this increases the pressure to ban short-lived plastic application and establish effective recycling practices and infrastructure for plastics (Jokinen 2019a).

3.4 Sustainability

Sustainability has a very broad range of definitions that vary according to context and author. Most consistently it is viewed as supporting without collapse (short and long-term interests alike) or with a similar wording. (Theodore & Theodore 2010, 107; Kamrani et al. 2013, 4.) **Sustainable development** is ensuring the needs of the present while not compromising the support of future generations as defined by United Nations (acc. Theodore & Theodore 2010, 117). This is in tangent to the ideal of *intergenerational justice*: not burdening the future generations with depletion of resources, ecological degradation, increased dept, disorder and insecurity, but ensuring conservation of options instead. Gibson, Holtz, Tansey, Whitelaw and Hassan (2012, 52) point out that sustainable development is a dangerous concept, since it fails to recognize that our planet's capacity to withstand our impositions is already overstrained and as such, can be used in promoting enterprises that stress this capacity even further.

Business sustainability (figure 7) comes down to managing *the triple bottom line.* It divides sustainability in to three aspects which are **economic**, **social** and **environmental** (Definition of business sustainability 2013). In general, this seems to be the most frequently used model for addressing sustainability as they are the exact same used in, for example, Dow Jones Sustainability Indices (DJSI) and the ISO 14 000 family of standards. Other major areas of sustainability that are frequently used include technological and cultural (e.g. Theodore and Theodore 2010, 107; Areas of sustainability 2015).



Multiple sources
Definition of Business sustainability 2013
Environmental sustainability 2015
Social sustainability 2015
Economic sustainability 2015
Vargas 2018

Figure 7. Definition of business sustainability

This thesis addresses primarily environmental sustainability and only secondarily social and tertiarily economic aspects. This was due to deemed higher importance of environmental aspects combined with the substantially better availability of resources. Much of this had to do with the fact that life cycle assessment, the chosen methodology for RQ1, has typically an environmental focus that does not address financial or social aspects (SFS-EN ISO 14040:2006, 13).

3.5 Product life cycle and waste hierarchy

Life cycle is defined as the consecutive stages of a product – any goods or service – from extraction of the raw materials to the final disposal (SFS-EN ISO 14040:2006, 13, 15). **Product life cycle**, PLC, is used as a synonym. While the wording varies, it typically consists of the five following stages (SFS-EN ISO/TR 14062:fi:2003, 23)

1.	**Pre-Production**	Extraction/processing of raw materials to manufacturable ones
2.	**Production**	Manufacturing and assembly
3.	**Distribution**	Transportation
4.	**Operation**	Use and maintenance
5.	**Disposal**	Processing back to raw materials and returning to environment

Product life cycle can be approached through various methods, from which the most consistently brought up along with Life cycle assessment (LCA) is **Life cycle thinking** (LCT) – a decision-making tool in shifting of the focus beyond production to environmental, social and economic impacts of a product over its entire life cycle (Life Cycle Thinking 2018; What is Life Cycle Thinking? 2012).

Disposal stage of the PLC can be examined further via the concept of **waste hierarchy.** The prime purpose of the waste hierarchy is establishing an order of priority for optimizing resource efficiency and minimizing adverse environmental impacts, especially greenhouse gas emissions. Directive 2008/98/EC on waste by European Commission, also called as Waste Framework Directive, introduces this priority (figure 8). The distinction between *Other recovery* and *Disposal* is somewhat relative. Operations like incineration (thermal treatment of waste) with no or only limited levels of energy recovery are interpreted as disposal alongside landfilling, whereas “a high level of energy recovery” is expected for the method to be classified as *Other recovery*. (The role of waste-to-energy in the circular economy 2017, 4.)

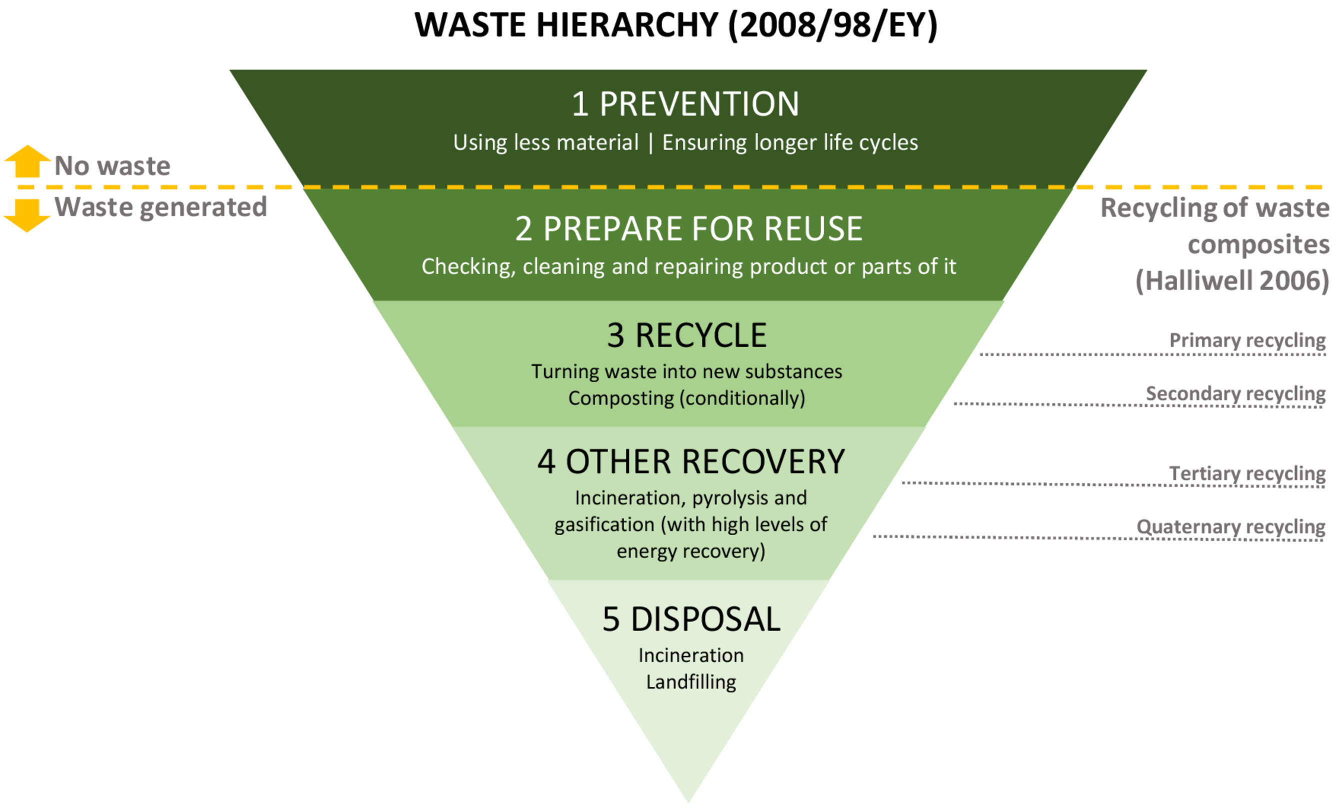


Figure 8. Waste hierarchy with recycling of waste composites, multiple sources (The role of waste-to-energy in the circular economy 2017, 4; Directive 2008/98/EC on waste 2016; Halliwell 2006, 19-20.)

Primary recycling is done when conversion of waste to *recyclate* is achieved while the properties of the recycled material equal those of the virgin material. When they are lesser, process is classified as secondary recycling. Tertiary recycling includes material conversion into fuel or chemicals. Quaternary recycling encompasses conversion into energy. The classification between primary and secondary recycling is also relative, with the question being *to what degree* degradation of properties is permitted. When defined literally, primary recycling is almost only a theoretical option in plastics, implying possibility of infinite recycling circuits. (Halliwell 2006, 19-20). The classification of primary recycling is used in this thesis when the use of recycled material doesn't compromise properties of the second life product. Typically, this means confining the amount of recycled material below a certain threshold, like 20-30 % of ground thermoset granulates in compression moulding compounds (Job 2010, 19-20).

3.6 Life cycle assessment

Life cycle assessment, LCA, is a method for identifying areas of environmental stress and evaluating their impacts on various stages of the product life cycle. This includes quantification of the used impact metrics, as called for in formulation of RQ1. (Kamrani et al. 2013, 9; Theodore & Theodore 2010, 112; Welford 2004, 138). Four stages of LCA, also referred as LCA study, are presented in figure 9 that combines the ISO-definition to selected practical remarks.

The goals of an LCA can be sometimes met without including the LCIA-stage to the study, in which cases the correct ISO-term for it is **life cycle inventory study**, LCI study *(SFS-EN ISO 14040:2006, 9)*. Due to the perceived relatively low depth needed in answering RQ1 and acknowledging it being only a part of this thesis, conducting LCI study instead of LCA study was deemed more appropriate allocation of resources.

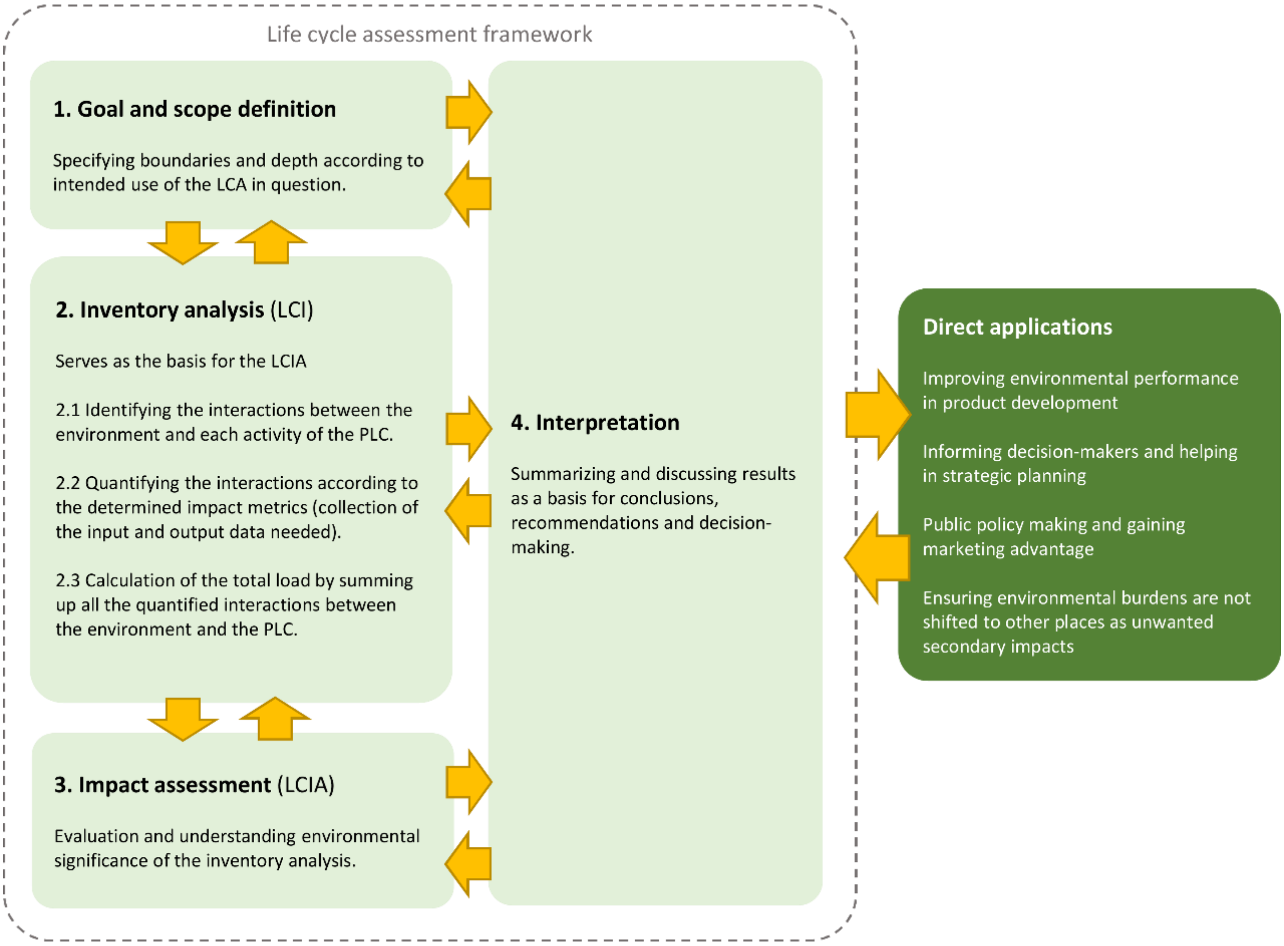


Figure 9. Stages of an LCA study according to ISO 14040/44, modified (SFS:EN ISO 14040:2006, 9, 13, 19, 25, 27, 35; Kamrani et al. 2013, 9; Theodore & Theodore 2010, 112)

3.7 Environmental impacts

Environmental impact is any change to the environment caused as result of activities taken within the product system. They cover inputs and outputs alike and can be either adverse or beneficial, although only the adverse ones are usually covered. Impacts can be addressed to **impact categories** such as climate change, global warming potential, acidification potential, eutrophication potential, depletion of resources and alteration and reduction of habitats and biological delivery. (SFS-EN ISO 14067:2018, 9; ISO/TR 14062:fi: 2003, 11, 23; Environmental impact categories 2016.)

Inputs form what can be categorized broadly as the material and energy flow from environment into the product system. Most stages of PLC consume energy, which can be further classified by source with each types of energy sources having identifiable impacts on environment. Outputs are the flow of releases from the product system into environment. In addition to the product itself, they can be various intermediates, co-products and by-products of the product life cycle. (ISO/TR 14062:fi: 2003, 23, 25.) The smallest elements for which the input and output data (elementary flows) is quantified in are called unit processes. Combined with the stages of product life cycle they form the product system. Its system boundaries are the set of criteria that specify which unit processes are accounted for. (SFS-EN ISO 14040:2006, 19; SFS-EN ISO 14044:2006, 19.) Measurement of impact metrics is done in functional units, that are the quantified performance of the assessed system (SFS-EN ISO 14044:2006, 17).

There is no single set of impact metrics available, so they need to be defined case by case (Welford 2004, 152). Even though there are no absolute rules on what to measure, some basic principles on choosing the impact metrics apply. Based on the listings by several authors (Welford 2004, 152-153; Dahl, Hak & Moldan 2007, 56-57; Golachowska-Poleszczuk & Topolska 2015, 18), the most essential ones factored in were

- **Measurability** – they must be measured easily and represent the reality well-enough
- **Controllability** – there must be a clear connection between each measure and actions for improving them
- **Credibility** – measures need to be acknowledged stakeholders (employees and environmental groups particularly), while being feasible in terms of key areas, not just the ones easiest to deal with
- **Understandability** – they must be understandable to those who act upon them
- **Constraining their amount to low enough** to ensure adequacy of resources

3.8 Sustainable design and development

Primary benefits in integrating environmental aspects into design and development as defined in ISO/TR 14062 are enhanced potential to new business possibilities, stimulation towards innovation and significantly improved cost-efficiency and product quality. Emphasizing life cycle approach and thinking about each of the stages in the PLC systematically is vital in understanding environmental impacts of any given product system. It can help ensuring that all the environmental characteristics and most relevant environmental impacts – including those generated by co- and by-products – are accounted for and that consideration is given also to any arbitrarily insignificant elements that may ultimately turn out to have significant environmental impacts. In addition, it helps focusing on the system in which the product is performing in, not only the product itself and that environmental impacts are not shifted from one life-cycle phase or material to another. (ISO/TR 14062:fi: 2003, 7, 25, 27)

Changing or influencing any single input or output might affect other inputs and outputs. These are called sustainability *trade-offs* which – in the context of sustainable design and development – are presented in relation to environmental aspects. They can be categorized as following (ISO/TR 14062: fi 2003, 29, 31):

- **between environmental aspects**; e.g. using FRP in favor of steel for more optimal consumption of energy and raw materials in pre-production, manufacturing, distribution and operation but having more challenges in disposal of the material

- **between environmental, social and economic aspects**; e.g. using an environmentally friendly fibre instead of glass fibre for more efficient incineration at end of life cycle (environmental aspect), healthier working conditions and a better public image (social aspects), but resulting to increased initial costs (economic aspect)

- **between environmental, technical and/or quality aspects**; e.g. using FRP in favor of steel for better visual quality and quality control, but resulting into a product that might break more easily

3.9 Other related terminology

Global warming is caused by the greenhouse effect which refers to the increased amount of greenhouse gases (GHG) in our atmosphere that prevent heat from escaping the planet (Mann 2018), most importantly CO_2 and methane (Global Greenhouse Gas Emissions Data 2017). Up to 19,5% of all GHGs produced to the atmosphere can be traced directly down to industrial sector, excluding transports and waste management related to it, making it a considerable contributor to global warming (Sectoral greenhouse gas emissions by IPCC sector 2016).

GHG emissions are widely quantified in a common unit of carbon dioxide equivalent, CO_2e. It describes how much CO_2 would be needed to have the equivalent impact on global warming for any given amount of any other greenhouse gas or sets of different gases. This is the very reason of CO_2e being considered so useful: bundles of different gases can be not only expressed in a single number, but also compared against each other for their total significance on global warming. (SFS-EN ISO 14067:2018, 12; Brander 2012, 2,3.)

Carbon footprint of a product is formulated when all the GHG emissions and removals expressed as CO_2e are summed up. An LCA where only the carbon footprints are considered would be a single impact category study of *climate Change*. (SFS-EN ISO 14067:2018, 9), typically referred also as *Global Warming Potential*, GWP (Environmental impact categories 2016). Whereas climate change is considered one of the key impact categories, any evaluation should be broadened beyond that to avoid misleading results and subsequently mislead decisions as achieving genuinely sustainable consumption and production requires consideration of all relevant environmental impacts (Carbon footprint– what it is and how to measure it 2007, 1-2).

4 RQ1: Comparison between steel and FRP end elements

4.1 Conducting the LCI study

4.1.1 Definition of goal and scope

The intended goal – including application, target audience and reasons for carrying out the LCI study – are the same as for this thesis in general. Based on source literature and internal discussions, the used **functional units were *CO_2 emissions*, *Energy consumption* and *Amount of waste to landfill***. These three were the only ones that fulfilled the principles laid out for impact metrics in chapter 3.7, are constantly brought up as important metrics, had good enough public data availability, were considered reasonable choices by the interviewed sustainability specialist at Valmet and are well-aligned with Valmet's quantitative environmental metrics (chapter 5.1). CO_2 emissions instead of CO_2e emissions were chosen due to the combination of simplifying the scope of the study and only the first being stated as a main quantitative metric at Valmet. Water consumption was also considered but rejected in the late phases as finding reliable-enough data with the given resources turned out to be impossible.

Product system models – that were iteratively updated during the data collection as suggested in SFS-EN ISO 14044 (2006, 35) – for FRP and steel end elements are illustrated in figures 10 and 11. The size of the arrows in inputs and outputs are roughly representative of the scale of their impacts.

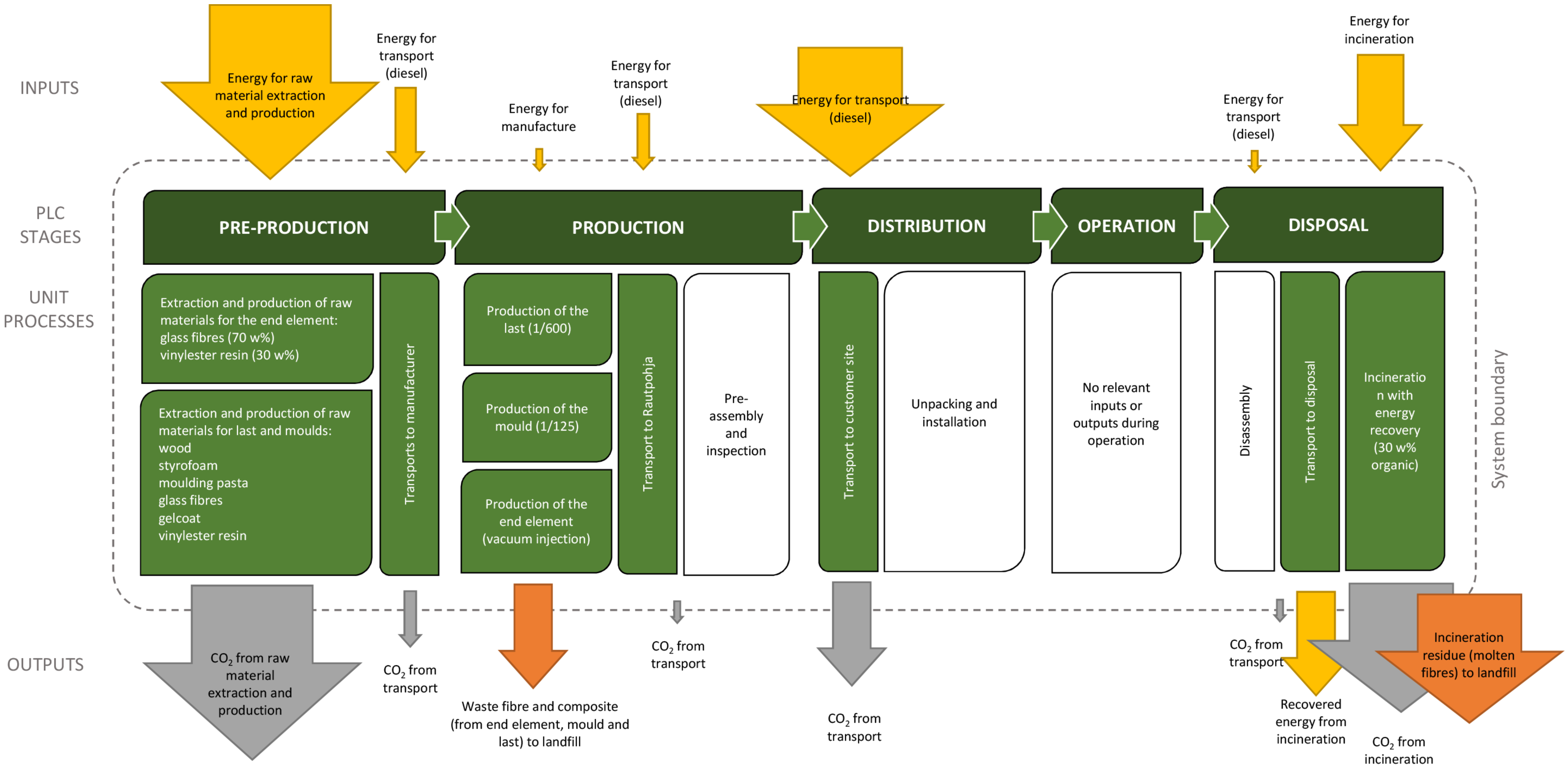


Figure 10. Product system model for FRP end element

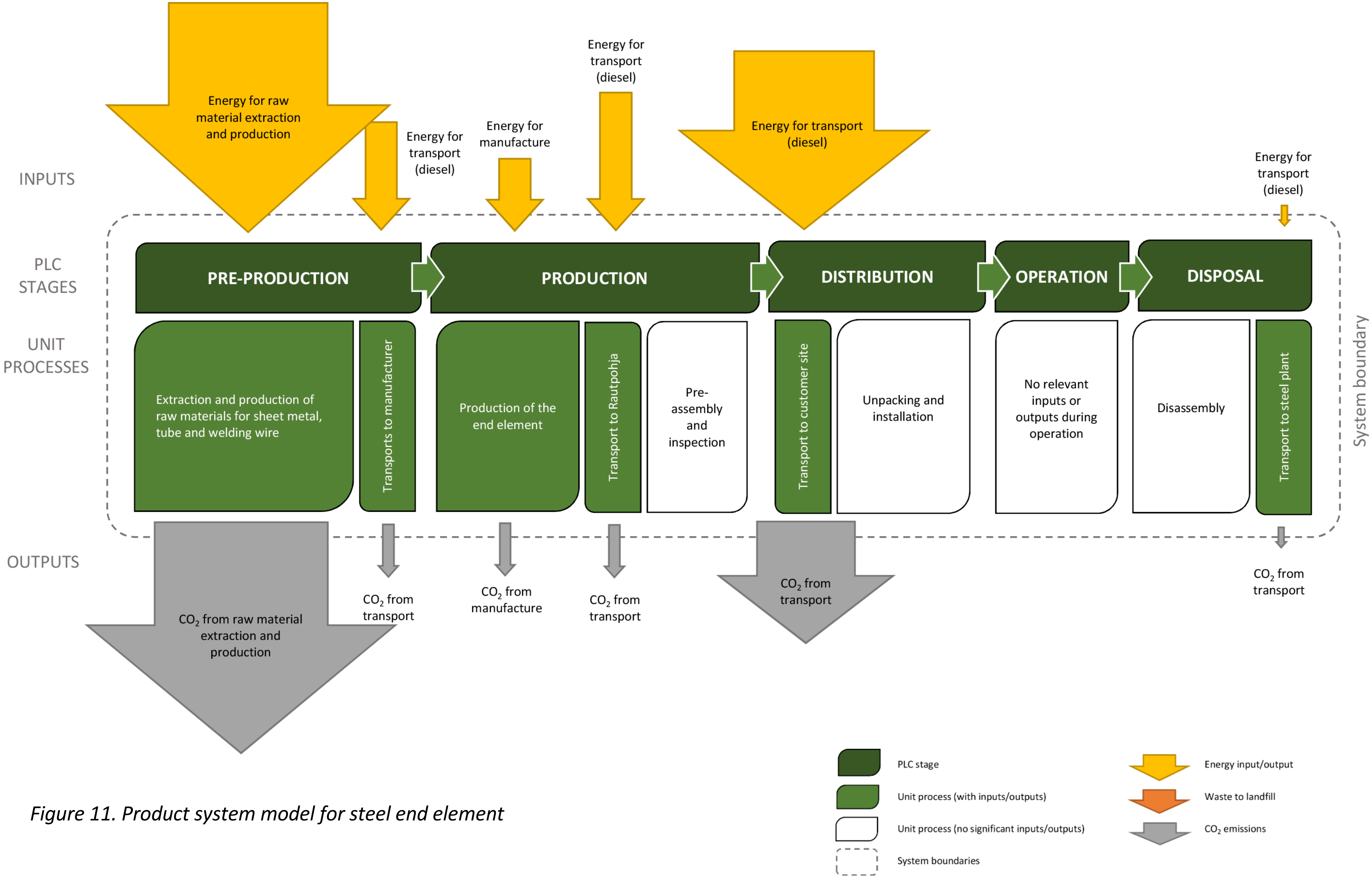


Figure 11. Product system model for steel end element

Only primary processes and impacts were accounted. Factors left out from the study were all secondary operations and impacts, including storage of moulds and the last for FRP end element. Emissions and energy consumption of producing and logistics of the packaging materials, as well as any other materials that would be consumed during the PLC of the end elements that were not directly used in their manufacturing were also disregarded. Materials with only minor consumption like painting of steel version were also left unaccounted for simplicity.

Specification for the FRP end element was chosen based on the most used, and therefore most probable, choices for end element to get the most universal and applicable results possible. This meant choices in favour or E-glass as fibres, thermosetting vinylester as the polymer, vacuum injection as the manufacturing method and incineration with energy recovery as the disposal method. Detailed specifications with the most important data points, used sources and values for each end element are included as appendices 5-6.

4.1.2 Inventory analyses (LCI)

LCI data sheets for inventory analyses of each end element are presented in tables 3-4. **No specific tools or databases apart from spreadsheet calculation were utilized in the making of analyses**. Consequently, the process of making the LCIs was a very straightforward, manual listing of properties and quantifying them to environmental impacts according to publicly available data. As for logistics, an internal expert was consulted to construct a “typical case” of Valmet’s paper or board mill delivery including distances per used transportation means.

Alternatives for spreadsheet calculation were sought after until the very last moment possible. An LCA expert was consulted for the work, after which obtaining a license for LCA software SimaPro was attempted unsuccessfully and OpenLCA – another software for making life cycle assessments – was tested out in combination with the freely available ELCD database. Eventually, given the combination of restricted time frame, no prior experience in using such software, ELCD database turning out to be inadequate for FRP materials and no know-how from JAMK or Valmet on making LCAs available, use of mere spreadsheets was leaned on.

Table 3. LCI data sheet for FRP end element

	PLC stage and unit process	Functional unit		
		CO2 emissions [kg]	Energy consumption [MJ]	Waste to landfill [kg]
1	**Pre-production**	Extraction and processing of raw materials		
	Material extraction and production	59	486	N/A
	Transports	5	48	0
2	**Production**	Manufacturing and assembly		
	Last and mould (for one piece)	0	1	1
	Manufacturing	0	9	11
	Transport to Rautpohja	1	8	0
3	**Distribution**	Transportation		
	Transport to site	21	353	0
4	**Operation**	Use and maintenance		
	Lifts	0	0	0
5	**Disposal**	End of life management		
	Transport to disposal	0	5	0
	Incineration with energy recovery	39	12	23
TOTAL		125	922	35

Table 4. LCI data sheet for steel end element

	PLC stage and unit process	Functional unit		
		CO2 emissions [kg]	Energy consumption [MJ]	Waste to landfill [kg]
1	**Pre-production**	Extraction and processing of raw materials		
	Total	173	1480	N/A
	Transport to manufacturer	3	46	0
2	**Production**	Manufacturing and assembly		
	Manufacturing	4	24	0
	Transport to Rautpohja	5	65	0
3	**Distribution**	Transportation		
	Transport to customer site	58	997	0
4	**Operation**	Use and maintenance		
	Lifts	0	0	0
5	**Disposal**	End of life management		
	Transport to recycle	0	1	0
TOTAL		243	2614	0

Comparison between inventory analyses in terms of total loads per functional unit for each PLC stage is presented in table 5. **FRP end element accumulated 2,0-times lower CO_2 emissions and consumed 2,8-times less energy thorough the PLC**, with respective saves of 118 kg in CO_2 and 1 692 megajoules in energy. **Steel end element produced 35 kg of less material to landfill, while performing all-around better in disposal.**

Table 5. Comparison of LCIs

	Functional unit	End element	
		FRP	Steel
1	**Pre-production**		
	CO_2 emissions [kg]	64	177
	Energy consumption [MJ]	534	1526
	Waste to landfill [kg]	Removed (N/A from FRP)	
2	**Production**		
	CO_2 emissions [kg]	0	8
	Energy consumption [MJ]	17	89
	Waste to landfill [kg]	12	0
3	**Distribution**		
	CO_2 emissions [kg]	21	58
	Energy consumption [MJ]	353	997
	Waste to landfill [kg]	No relevant impacts	
4	**Operation**	No relevant impacts	
5	**Disposal**		
	CO_2 emissions [kg]	39	0
	Energy consumption [MJ]	17	1
	Waste to landfill [kg]	23	0
6	**Totals**		
	CO_2 emissions [kg]	124	243
	Energy consumption	922	2613
	Waste to landfill [kg]	35	0

4.1.3 Interpretation

No single overall scores or numbers from the LCIs were produced, as it would have required weighting of the used metrics relative to each other. This would've came down to value choices and given a possibility to adjust weights of each metric according to the desired outcome, taking off the scientific basis of the LCA (SFS-EN ISO 14040:2006, 27; SFS-EN ISO 14044:2006, 23). As for GHG emissions, only CO_2 was factored in. Numbers might have turned out somewhat different if CO_2e would have been used, but this wouldn't have probably changed conclusions of the LCI to either direction.

FRP end element has a significant advantage in global warming potential through its CO_2 emissions and energy consumption, which come rather directly from the fact that the FRP end element is also around 2,8-times lighter than the steel version. It is important to note that the LCI results are based on very conservative figures in favor of steel end element. Whenever conflicting values from negative impacts were found, the bigger ones were used for FRP end element whereas smaller figures were used for the steel version. Leaving out impacts from painting also favored steel end element. Consequently, **it is highly likely that the numbers would be clearly more advantageous in favor of the FRP version if more accurate data and system model would’ve been used.**

Steel version accumulated no waste to landfill during its PLC (with the assumption that 100 % of the steel used during the PLC will be recycled), which was 35 kg less than from the FRP version. This figure is deceptive, though, as figures from raw material extraction and production were unaccounted for due to not finding comparable data points from glass fibre production. The steel melting process is a considerable source of landfill-waste through its slag; according to 2018 figures of Outokumpu, an important steel supplier of Valmet, production for all the steel needed for the end element would equal roughly 460 kg of slag. When the exceptionally high use rate of slag at Outokumpu is taken in to account, this still equals 47 kg of waste to landfill – 12 kg more than in the FRP end element during the whole PLC. (Sustainability review 2018, 16).

Several other LCAs were browsed through during the making of this LCI study, with its results aligning very well with them (e.g. Keskinen & Mannermaa 2019; studies referred to in Kara & Manmek 2009). Thus, even though the study was a very approximate in nature, its results give a reliable picture of the scale of impacts for each part.

4.2 Other considerations

Although the LCI study was made in mind to consider the environmental impacts, it is important to understand that it gives only a narrow sight of the total environmental load as only three metrics were factored in. Considerations in regards of other important impact categories cannot be extracted from the findings of this study.

As for other than the used quantitative environmental metrics of Valmet, some data points for water withdrawal were examined. The production of steel needed for the steel end element was calculated to take up roughly 13 times more water than production of fibres in the FRP version (1709 litres vs 136 litres), but the figure for the FRP version doesn’t account for the assumably low water consumption of the used polymers.

As glass fibres are the primary component of the FRP version with impacts of the moulding materials being minimal in contrast, it can be safely stated that the steel version would be a significantly greater consumer of water when it comes pre-production.

Social impacts of each the end element are hard to compare without any systematic data, especially given that the FRP version didn’t exist as a physical product. It seems, however, that there somewhat bigger health and safety risks associated to the FRP version, especially in terms of composite manufacturing (as discussed in chapter 6).

Economic impacts are, alike social ones, not particularly meaningful to compare as no realised data from the production of FRP element can be retrieved. As for initial estimation, the price of the FRP end element is expected to be somewhat cheaper than the comparable costs of the steel version (Korpimäki 2018), even before the possible quality expenses from remakes of the steel version are accounted for.

4.3 Conclusions for RQ1

Fibre-reinforced version of the end element has clearly a better environmental performance than its steel counterpart. Results are in line with most of the initial expectations, as steel performs best against FRP version during its disposal, is the more questionable material in energy consumption and seem to come off more expensive in production. What was surprising was that the results are so clear, even when the chosen product is virtually never moved anywhere during *operation*, the one stage of the PLC where FRPs typically perform best in. In general, **sustainability of FRPs seem significantly better than the public opinion from such materials stand for**.

5 RQ2: FRP and Valmet

5.1 Sustainability 360° agenda

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5.2 FRP at Valmet today

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5.3 FRP at competitors

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5.4 Internal studies

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5.5 Conclusions for RQ2

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6 RQ3: Improving sustainability of FRP currently

6.1 Biocomposites

Biocomposites are composites in which at least one of the components – fibres or the matrix – is bio-based (Biokomposiitti kierrätetystä materiaalista 2014). They tend to spark strong and mixed opinions, and there are two discussions revolving around them that need to be separated from each other (Jokinen 2019b)

1. **Biocomposites mixed together before composite manufacturing** by using ready-made granulates that already include the fibres on their own and can be used to injection moulding or similar applications. This typically includes reduction of the plastic polymer content of a biocomposite by adding natural fibres such as bleached sulphate pulp, mechanical pulp, wood flour or saw dust as fillers
2. **Biocomposite raw materials mixed together by the composite manufacturer** as the raw materials are bough separately. This typically includes substituting synthetic fibres by natural ones while maintaining their function as enhancement of mechanical properties.

Out of the two, the implementation of the first seem much easier than the latter, given the right applications. Industrial-scale production of biocomposite granulates like Formi (UPM), Kareline (Plasthill), Thrive (International Paper) and DuraSense (Stora Enso) have been introduced only as of late but seem a business of rapid growth in interest, which is further highlighted by parallel upscaled demand of similar consumer goods. All the products mentioned are ABS or PP-based plastic polymers combined with cellulose fibres, out of which DuraSense is being produced at Europe’s biggest biocomposite plant with its annual production volume of 15 000 tons. Typical claims of such composites include 50-80 % lower carbon footprint than in fully fossil based plastics with the biggest perceived concern being them typically missing fire-redundancy additives. This means that they need to be checked if they can be added or not and tested in aging test of considerable lengths before getting approved for heavy industrial applications like in Valmet’s case. Types of plastics that are viable are also constrained, as only PP was seen relevant for such uses. (Jokinen 2019b; Stora Enso opens Europe’s largest wood fibre-based biocomposite plant 2018.)

As for mixing the biocomposite materials together by the composite manufacturer, the use of natural fibres seem particularly appealing as they're cheap, low-density, biodegradable and conceptually easy to recycle (Saarela et al. 2003, 99). When interviewing plastics industry on the topic, though, all interviewees were surprisingly consistent and strong in their views that natural fibres are not a relevant option by any means. This was seen due to their inconsistent quality caused by seasonal variance, short fibre lengths, moisture-absorbing properties during manufacture and use, thermal sensitivity, poor availability, questionable environmental performance in previous studies and – in some cases – their incompatibility with some of the most used resins (Sippola 2019; Mannermaa & Keskinen 2019; Peltola 2019; Korpimäki 2019c). Using such forms of reinforcement would also put significant emphasis on a good protective coating to prevent moisture from reaching the fibres in use. Even with one, the coated product would be vulnerable to dents, potentially reducing chances of the such parts lasting through the paper machine life time. (Korpimäki 2018.) Natural fibres have also generally worse mechanical properties than the more traditional fibres (Saarela et al. 2003, 99) while their less homogenous quality also forces in to use of higher safety factors (Ijäs & Salonen 2018, 19-20).

The scepticism revolving around natural fibres seem understandable, as it was concluded that to use such materials efficiently, the whole value chain needs to be involved and – from the perspective of the composite manufacturer – use of biocomposites needs to be made as easy as use of any other material. This means in practice that biocomposites need to be developed and mixed together before composite manufacturing, ruling out the possibility of using thermoset resins. (Jokinen 2019b) Subsequently, this means that all relevant FRP applications need to be excluded in Valmet's case unless the products are completely redesigned, resulting in discontinuing the study of such materials. A similar stance was taken in regards of bio-polymers: as concluded in a previous internal study by Valmet (chapter 5.4), a focus should be given on recycled and well-recyclable materials instead.

6.2 Thermoplastics

Thermoplastics, due to their malleable nature, seem a solution for utilizing recyclable materials in FRPs but there are several issues in their utilization. In general, the biggest problem in using of thermoplastic composites instead of thermosets seem to be the presence of the fibres. Even if thermoplastics would be used more commonly, the very same challenges of separating them from the matrix as with thermosets still exist (Korpimäki 2019c; Blom & Dufva 2016, 16). Should reclaiming of the fibres be done from an FRP product, loss of their reinforcement properties is affected to a similar degree in both types of plastics, so recycling of fibres would not be achieved to no better degree than with thermosets. Studies also show that, contrary to the general conception, repeated recycling processes of thermoplastics do indeed degrade their mechanical properties due to mechanical shear of grinding process and high temperatures used in recycling. (Summerscales 2018; Halliwell 2006, 21, 22.) This signifies that recycling of the polymer itself isn’t as efficient either. Additionally, higher energy inputs are needed in manufacturing of thermoplastics due to considerably higher melting temperatures and viscosity that can be over 100-times as high as in thermosetting resins (Saarela et al. 2003, 53).

6.3 Thermosets

Leaving bio-composites and thermoplastics out of the table, only the option of thermoset resins and how to enhance their sustainability was left for consideration. Two principal routes for this was identified: use of recycled thermosets – that are not yet an available option but getting there may already be on a horizon as introduced in chapter 5.4 – or otherwise enhancing sustainability of the use of virgin thermoset polymers.

Thermosets are considered having an unreasonably bad reputation. Much like in plastic composites in general, the more the discussion is shifted from narrow focus areas to life cycle thinking and LCA, the more sustainable materials thermoset plastic composites become (Keskinen & Mannermaa 2019). Unsaturated polyester, vinylester and epoxy – the most used resins in thermosets – have problem areas that are very different from each other, originating from their composition and hardener-to-resin -ration among other things. Vinylesters and unsaturated polyesters are cheaper alternatives with good technical performance to price -ratio and used typically with GFRP while epoxy resins are utilized with CFRP due to compatibility reasons. (Hiltunen 2019; Korpimäki 2019d; Keskinen & Mannermaa 2019.)

Styrene is seen as the principal health and safety risk of the thermoset resin industry – at least when it comes purely for the resins – and is a clear driver in planning of occupational health and safety (Hiltunen 2019; Keskinen & Mannermaa 2019). Styrene fulfils two functions, while being widely used due to its good properties combined with an economic price. First, it keeps the polyester resin in a liquid state when dissolved to it. Without styrene – the most used monomer for fulfilling this function – polyester resin would remain solid at a room temperature. For the second, styrene produces a chemical reaction that enables the formation of a strong, three-dimensional structure. Optimal case is that all the styrene remains in the polymer matrix, but in practice some of it will always evaporate. (Keskinen & Mannermaa 2019.)

Worker exposure to such vapours are the root reason for health and safety hazards of styrene. Principal means to enhance this are utilizing resins with lower styrene content or resins with no styrene content at all. (Ibid.) While producing 0 % styrene content resins is possible and there are such products available, they're seem to be utilized only in low volumes and in less-demanding applications (Hiltunen 2019; Keskinen & Mannermaa 2019). The preferred angle the resin producer of which employees were interviewed for this thesis had been to gradually lower the styrene amount of their standard products, rather than developing 0-content ones. This has been perceived to be a more effective route in achieving grander scale of positive HSE impacts. In practice, substitutive substances for lowering styrene content were noted to be hard to come by as styrene is widely utilized for a good reason. In addition to the economic reasons, it has good chemical properties like allowing fast reactions and effective lowering of the viscosity of the used resin. The styrene content of a resin used in FRPs is typically around 40 %, but the newest products already approach values around 15-20 % while 10 % might be a target in the future. Means to lower styrene content include meddling with the polyester molecules or including more of alternative monomers into the mix. This applies also to gelcoats that are pigmented, hard resins, that are used as the surface layer of a composite laminate like paint. Styrene hazards can additionally be kept in check by utilizing paraffin coatings to reduce evaporation of styrene during the manufacture of FRPs. Since keeping the styrene inside the polymer matrix is desired, this is not only a health and safety benefit but also improves the technical performance. (Keskinen & Mannermaa 2019.)

As for thermosetting polyesters and vinylesters in general, organic peroxides used as hardeners in combination with the resin are the most hazardous substance (Hiltunen 2019; Keskinen & Mannermaa 2019) while forming typically only 1-3 % of the content in the polymer. Careful caution to the purity of the hardener, as well as allowed storage times and temperatures needs to be exercised as only small impurities or exceeding the set maximum time of storage can cause pressure explosions and fires. Peroxides are used since they enable double bonds of monomer chains of polyester and styrene to open and create interlinking connections between each other to cause the polymerization of the thermoset. Peroxides are not used in epoxy resins, as their chemistry differ substantially from unsaturated polyester resins. (Keskinen & Mannermaa 2019.)

Epoxy-based thermosets, while being an easier material in terms of solvent-based vapours, are also somewhat problematic materials on their own right as they are strongly allergenic. As epoxy resins don’t have a strong distinctive smell like other styrene-including thermosets, worker safety may not always be handled properly. With the smell of styrene being apparent already way below limits set for safe exposure, it is considered easier to remember using proper safety equipment and well-ventilated areas when using polyesters and vinylesters. (Hiltunen 2019; Korpimäki 2019d; Mannermaa & Keskinen 2019.)

6.4 Fibres

6.4.1 Glass fibres

Whereas glass fibres and GFRP are viewed as a problematic material in terms of sustainability and recycling particularly, enhancing their sustainability can make some of the biggest impacts due to the sheer volume. Glass fibres are an economic material and as their volumes are extremely high, formulation of efficient recycling routes for them is more probable than with any alternative fibres (Anhava 2019; Peltola 2019). Hence, a case on focusing on glass fibres – E-glass particularly – can be made when low-performance plastic composites are needed: using standard materials with bigger volumes instead of low-quantity ones is desirable from the waste management viewpoint, as future recycling solutions are most likely to be developed for the more common materials (Anhava 2019).

6.4.2 Carbon fibres

Carbon fibre are a somewhat contradictory material, as production of the material itself puts extreme burden on the environment, being estimated as 14 times more energy intensive while producing about 4 times more CO_2e-emissions than steel (Anane-Fenin & Akinlabi 2017, 1; Stainless Steel and CO_2: Facts and Scientific Observations 2012). On the other hand, they are widely seen as the most cost-effective type of fibre to recycle once the virgin material has been produced with energy input required at lowest being only 5-10 % of that needed for manufacturing virgin carbon fibres (Pickering, Turner, Meng, Morris, Heil, Wong & Melendi 2015, 2). Given the condition of a high recycling rate which may be a probable case in the future (as discussed in chapter 6.7), use of CFRP becomes particularly tempting from the sustainability point of view. Apart from recycling, use of CFRP seem largely an optimization problem of trade-offs between environmental and economic aspects, where sustainability of the material comes down to how much energy saves can be accumulated during the use and distribution when compared to the high energy consumption of the material production.

6.4.3 Basalt fibres

Basalt fibre is most prominently marketed as an ecological alternative to glass fibre that fares better in several environmental impact categories and has a better technical performance than the latter. The price of basalt fibres and their production vary greatly depending on the source but the newer the source, the more consistent they're with the costs being somewhat similar than E-glass. As such, the topic was subjected to particularly deep search, but reliable information turned out to be hard to retrieve with most sources being from manufacturers and distributors of basalt fibre, somewhat outdated sources and academically unproven authors.

Production of basalt fibres, made from volcanic rock, is done in a continuous process similar with production of glass fibres: the quarried basalt rock is crushed, washed, loaded to feeders, gas heated, liquified, fed through extrusion bushings to produce the filament which is sized, stretched and winded to spools (Regar & Amjad 2016).

Main advantages of basalt over glass fibres are better mechanical properties, corrosion resistance, heat resistance, thermal stability, heat and sound insulation, lesser weight losses to vibration, better abrasion resistance and electrical insulation properties (e.g. Basalttikuituvahvistetut komposiitit 2018, 2; Advanced basalt fiber 2017; Corrosion resistance 2017; Mechanical properties 2017; Sharma 2016, 1-4). In HSE aspects, their natural origin and production requiring no chemical additives are typically emphasized (e.g. Ecological properties of continuous basalt fiber 2017; Regar & Amjad 2016, 5; Recyclable resource 2010).

Disadvantages of basalt over glass fibres include the somewhat higher price point than E-glass – primarily according to older sources – and the more abrasive nature of basalt, resulting in faster wear of parts such as the extrusion bushings in production of the fibres, although this turns out as a pro in the final product in the form of better abrasion resistance. (Bhat et al. 2017, 5, 11; Sharma 2016, 1; Prince 2010) Challenges utilizing basalt fibres include the more inconsistent quality of the raw material caused by its natural origin (Peltola 2019) and lower volumes in general.

Basalt fibre is compliant material in all relevant manufacturing methods and fibre forms and is compatible with polymers used in studied FRP products of Valmet (Basalttikuituvahvistetut komposiitit 2018; Advanced basalt fiber 2018). Even though basalt fibre is most prominently viewed as a substitute for glass fibre, Sharma (2016, 3-4) points out that it is also a promising material in terms of its compatibility with carbon fibre: by mixing a low amount of carbon fibres with basalt fibre, a high-performance material with only a slightly more expensive price point but significantly better elastic properties (than with pure basalt fibre) can be created.

6.4.4 Thermoplastic fibres

Self-reinforcing polymers could be used as a substituting material for more traditional FRPs. Instead of using glass or carbon fibre on a polymer matrix, fibres could be made using high-performance polypropylene or ultra-high molecular weight polyethylene fibres, combined with matrix made from the same base material (Keskinen & Mannermaa 2019; Halliwell 2006, 33). This would result in a one material composite that could be reshaped easily as the content is 100 % thermoplastic. It would also be the most optimal type of composite for incineration as its calorific content would be equivalent to oil due the 100 % organic nature, leaving no residue or energy losses (Halliwell 2006, 25). Other benefits over traditional FRPs include the lower density of polymer fibres, potentially resulting in lighter parts. They are also more ductile in nature, so they don’t splinter like glass fibre. (Halliwell 2006, 33.) This could allow lowering the typically high safety factors needed in technical analysis of FRP (Ijäs & Salonen 2018, 20), as the malleability of the material would be closer to that of metals.

However, industrial applications of self-reinforcing polymers seem non-existent or trivial at best, so the concept seems to need further studying to become relevant (Korpimäki 2019c). One of the problems in environments such as paper and board producing ones is that such materials might not be able to withstand required high temperatures (Keskinen & Mannermaa 2019).

6.5 Design

As design is the most influential single stage in PLC with FRPs making no exception to this, a strong emphasis should be put upon choosing the right applications, ensuring that the life time of each component equals that of the product itself, optimizing material consumption and otherwise preventing generation of waste (Keskinen 2019; Anhava 2019). To achieve this, varying tools and design principles such as LCA, LCT, Life Cycle Costing, Social Life Cycle Assessment and Design for Sustainability, Recyclability, Re-use, Remanufacture, Disassembly and Environment should be considered (Getting started 2017, 3).

A major example of vital design points was the usage of excessively high safety factors suggested by some standards. This was considered to pose a clear barrier for economic and environmental design and manufacturing of FRPs, as ceasing to use too high safety factors altogether would, in some cases, constitute a significant improvement in material and energy consumption as present-day engineering methods such as FEM analysis make optimization going far beyond standard measures possible. Proving the durability of designed structures by testing can provide a way around this, but it is typically not economically viable, especially in low-quantity manufacturing. (Hiltunen 2019.)

Aspects that promote recyclability and disassembly are particularly relevant in FRPs. From the perspective of a waste management company, the ideal plastic waste constitutes only from one material and is easy to remove from its surroundings. (Anhava 2019.)

6.6 Manufacturing

The best way to ensure environmentally sustainable production seems to be minimizing the amount of waste at the location of manufacture and recycling the material in-house (Korpimäki 2019c; Peltola 2019). This can be achieved by optimization of used materials, including monitoring the amount of waste generated, proportionally and in absolute amounts. Automated methods in favour of fully manual ones on making cut out -geometries, nesting and cutting them can reduce the amount of waste generated by up to 80 % when the requirements for alignment of the layers and whether the layers need to be one piece or not are not strict. Economic use can be further promoted by using smaller trimming allowances for reduced use of fibres and polymers, subsequently resulting in smaller amounts of waste composite. (Korpimäki 2019c.)

Biggest problems in high waste-percentages concern GFRP manufacture particularly. Since the materials are so cheap, there are no economic incentives for material saving as optimizing for material consumption may come off significantly more expensive than optimizing for labour. Problems are lesser in CFRP production since the fibres are substantially more expensive, so economic aspects force in saving of the material and reusing the cut out -waste for products such as thick sheets of CFRP-laminate. Consequently, emphasizing usage of FRP primarily in high-end applications can be an efficient mechanism for promoting reduction of waste. (Ibid.)

FRPs being naturally lightweight complicate their effective recycling as they take up lots of space, resulting in ineffective transportation. Processing fibres and composite waste at the manufacturing source might be an answer for solving this issue, as grounding waste fibre and composite would ease their transportation and further processing. (Sippola 2019; Korpimäki 2019c.) Logistics of the inbound raw materials should also be considered by prioritizing nearby-produced materials to minimize their environmental stress (Sippola 2019; Hiltunen 2019).

According to the performed interviews, **the biggest occupational health and safety risks** of the production chain of FRPs **arise from composite manufacturing specifically, emphasizing the need for special focus on supplier selection**. Well-ventilated workspaces, comprehensive safety training of the personnel and the use of proper personal protection are essential, but beyond that occupational health and safety aspects can be improved primarily through selection of manufacturing methods. Most importantly, exposing the workers to the resin vapours and causing of allergic reactions should be kept in check by utilizing automated and closed methods such as vacuums and pressure bags in favour of manual ones like hand lay-up. (Keskinen & Mannermaa 2019; Korpimäki 2019c.) Other safety hazards include dust, generated from abrasive processing of plastics, particularly when working in closed spaces like FRP tanks (Sippola 2019; Hiltunen 2019).

In general, **there are huge differences between countries in terms of how safety and environmental regulations are applied**. EU has the strictest regulations in use of hazardous substances, so buying from composite manufacturers inside the area can be a substantial improvement from this perspective. Legislation and waste management infrastructure are also far ahead in EU in comparison to developing countries and Asia in particular. (Sippola 2019.)

6.7 Disposal

Recycling of FRPs has been a particularly active talking point in recent years, with aviation and automotive industries seeming to be the drivers mostly initiating these discussions. Legislation is clearly a part of this, with the demands for high recycling ratios in the automotive industry being a noteworthy example. (Hiltunen 2019.)

Landfilling, the least favourable option in waste hierarchy, has been traditionally used in end of life management but as it is becoming increasingly more expensive and less available, methods such as incineration and ones higher in the waste hierarchy need to be considered (Korpimäki 2018; Anane-Felin & Akinlabi 2017, 2). Table 8 presents the various methods above landfilling for ultimate disposal of FRP. The optimal treatment comes down to what is to be recovered and optimizing between availability, economics, legislative obligations and quality of the recovered material(s).

Incineration – with or without considerable amounts of energy recovery – is the current standard whenever landfilling is not permitted or otherwise available and is widely expected to be the preferred short-term solution for FRP waste due to its good availability. It should be noted that the incineration process is never done only to reduce the volume of the waste, as energy recovery is always exercised to some extent albeit not optimizing for it. (Anhava 2019.) Calorific content of the composite depends on the amount of organic matter in the composite waste as only the resin can be burned and utilized as energy, whereas fillers and fibres remain unburnt (Hall 2006, 10). Theoretically, recoverable energy can be as high as 30 MJ / kg if the composite waste is 100 % organic, but the amounts are considerable smaller in practice (e.g. Hall 2016, 10; Pickering 2005, acc. Blom & Dufva 2016, 15). Halliwell (2006, 25) quotes the total energy balance with typical GFRP waste of 30 % organic matter is -400 kJ/kg, concluding that incineration with energy recovery is not a sustainable long-term option.

The *cement kiln route* is seen as the most prominent method for disposal of GFRP as it is already on a commercial-scale use and has been proved to be viable technically and economically. It comprises of burning the resin in the composite waste for energy, while the remaining fibres and fillers are added to the cement as part of its raw materials (Keskinen & Mannermaa 2019; Halliwell 2006, 25). Although the method has rather strict quality requirements on the composite waste, limiting its around to only 10 % of the used fuel, the cement industry is estimated to absorb substantial volumes of waste GFRP in the future (Marsh 2013; Job 2010, 7). With the 4,05 billion tons of global consumption of cement in 2018 (Manea 2018, 1), the cement industry could theoretically reclaim hundreds of times more GFRP than has ever been produced – in a single year.

In general, implementing methods above incineration to a widespread use has been economically a hard task. Despite the strong will to find viable options, composite waste has seen to bear little to no market value with additional challenges in creating efficient waste management infrastructure and practices (Blom 2019; Korpimäki 2019c; Halliwell 2006, 37).

Table 6. Disposal methods of FRP above landfilling (multiple sources)

					Classification		
Method	**Principle**	**Pros**	**Cons**	**Maturity**	Waste hierarchy*	Recycling of composite waste**	**Recovered outputs**
Incineration (without energy recovery)	Thermal (exothermic). Decomposing polymer matrix by combustion.	Good availability	No positive outputs; side by side with landfilling in waste hierarchy	Commercial applications	Disposal	-	-
Incineration (with energy recovery)	Thermal (exothermic). Decomposing polymer matrix by combustion.	Good availability	Not a sustainable long term solution	Commercial applications	Other recovery	Quaternary	Energy from the resin (negative total energy gain)
Incineration (with fibre recovery)	Thermal (exothermic). Decomposing polymer matrix by combustion.		Fibre properties are compromised due to reduction of lenght and orientation	Commercial applications	Recycle	Secondary	Fibres
Pyrolysis	Thermal (endothermic). Decomposition or carbonization of the organic matter in absence of / limited amount of oxygen (~400-600 °C)		Not viewed as recycling by the European Commission	Commercial applications	Recycle & Other recovery	Secondary & Tertiary	Fibres and fillers Oil/gas from resin
Catalytic pyrolysis	Thermal (endothermic). Similar to pyrolysis but with significantly lower temperature (~200 °C)	Low losses of mechanical properties (<10% in tensile strenght), high purity of the recovered fibre	N/A	Commercial applications?	Recycle & Other recovery	Primary & Tertiary	Fibres and fillers Oil/gas from resin
Fluidised bed	Thermal. Feeding scrap composite into a bed of silica sand, fluidised with stream of hot air (~450-550 °C); polymer vaporizes where as fillers and fibres are carried out in the gas stream.	Particularly suitable of mixed and contaminated materials, including fittings such as rivets and bolts	High loss of mechanical properties (in glass fibre)	Piloting, commercial scale	Recycle	Primary/secondary	Fibres and fillers
Cement kiln route	Thermal. Resin is burnt in a cement kiln while its fibres and fillers are added to the cement.	Considered the most prominent option as of now	Strict quality requirements	Commercial applications	Recycle & Other recovery	Primary & Quaternary	Fibres and fillers Energy from the resin
Shredding and grounding	Mechanical. Processing of waste composites to smaller bits.		Lack of market: alternative virgin materials are cheap to produce; heavy wear of the grinding machinery	Commercial applications	Recycle	Secondary	Composite granulates to be used as thermoplastic fillers
Solvolysis (supercritical methods)	Chemical. Using supercritical fluids (propanol for carbon fiber; methanol or water at ~300-500 °C for glass fiber) to dissolve the resin cleanly without charring.	No need for pre-treatment (washing and sorting)		Being researched	Recycle Other recovery	Primary/secondary Tertiary	Fibres Chemicals from resin
High concentration acid	Chemical	N/A	Excellent mechanical properties of the recovered fibres	N/A	Recycle	Primary	Fibres
High voltage fragmentation	Electrothermal. Disintegration of solid materials by repetitive, frequent electrical pulses that generate intense, high-temperature shockwaves that produce internal stresses above the tensile strength of the material.	Better properties ofthan with mechanical recycling	More energy-intensive than mechanical recycling	N/A	Recycle	Primary	Fibres

Combined from multiple sources: *Directive 2008/98/EY on waste (European Commission), **Halliwell 2006, Anane-Fenin & Akinlabi 2017, Melendi-Espina et al. 2016, Hall 2016, Differences Between Pyrolysis and Incineration As Well As Advantages 2016, Pickering et al. 2015, Job 2010, Befesa Plásticos 2009, Allred et al. 1999

As for Finland, a major indicator of the challenges in raising in the waste hierarchy is that there are no explicit classifications for composite waste, so each waste processing plant has their own practices, resulting in that the amount of composite waste cannot be tracked even theoretically (Blom & Dufva 2016, 16, 24-25). Recovery problems such as removing adhesive and mechanical fixings, cleaning, sorting and storing the mixed composite waste in a manner that matches the requirements of the recyclate while not constituting any hazards and generally current small volumes of FRP reaching their end-of-life are slowing down the development (Blom 2019; Korpimäki 2019c; Blom & Dufva 2016, 25; Halliwell 2006, 17, 21). Other economic aspects in GFRP include the cheap virgin materials the recycled material could replace and the long transportation distances to the few existing facilities. The latter is also an environmental challenge as transport to a distant recycling plant instead of a local landfill will increase traffic pollution and road congestion. (Korpimäki 2019c; Halliwell 2006.)

While values like optimal time and temperature of each method – and which methods should be utilized in the first place – differ depending on the source, all authors whose research was studied were consistent in that mechanical properties of the reclaimed fibres are always compromised (e.g. Anane-Fenin & Akinlabi 2017; Bhat et al. 2017; Hall 2016; Melendi-Espina et al. 2016; Pickering et al. 2015; Job 2010; Halliwell 2006). This is true regardless of the principle of the method or whether the recyclate is ground waste composite or only the fibres from it. Especially in thermal and chemical methods the degradation of mechanical properties is directly linked to the process temperature: the higher the temperature, the higher the losses of properties are reported to be. This leads to a conclusion that utilizing polymers with lower melting temperatures can not only save energy but also promote primary recycling due to mechanical properties being affected less when the fibres are reclaimed from the virgin product. An exception to the preceding, consistently confirmed by all the studied authors, is that the original stiffness of fibres is not significantly affected by heat or mechanical processing. Pickering et al. (2015, 8) even conclude that carbon fibres recycled with *fluidised bed* method had slightly higher elastic modulus than the virgin material.

Another clear consistency is that **recycling of carbon fibres is seen significantly more viable compared to other fibres** due to combination of good intrinsic value, relatively high volume and loss of physical properties only at higher temperatures (e.g. Sippola

2019; Hiltunen 2019; Keskinen & Mannermaa 2019; Korpimäki 2019c; Anane-Fenin & Akinlabi 2017; Bhat et al. 2017; Pickering et al. 2015). Properties of carbon fibres start dropping only after around 450 °C which is roughly 200 - 300 °C higher than with basalt or glass fibres (Bhat et al. 2017, 5). This means the loss of mechanical properties like tensile and impact strength in recycled carbon fibres are significantly lower. The reduction in tensile strength – the most cited property – remains typically at around 20 % in carbon fibres whereas with glass fibres its reported constantly to be at around 50 - 65 %. Although the development of various recycling techniques has promoted use of lower process temperatures, the conclusion remains that primary recycling can be done more effectively with carbon fibres. This is emphasized by the notion that the scale of carbon fibre recycling processes is already transitioning from lab scale to commercial one with annual volume of at least 5 000 tons currently (Melendi-Espina et al. 2016, 2-3; Pickering et. al. 2015, 1).

The intrinsic value of the material comes of a high importance in the recycling business. Recycling of *Low-end, low cost* -materials like glass fibres is problematic as there are no economic incentives included. (Anhava 2019.) As a result, reported examples of commercial scale reclaiming of glass fibres without melting the material altogether or using the ground composite as mere fillers are notably absent. There are mixed messages in this regard. On the other hand, recovery of glass fibres is seen as “good business for nobody” (Hiltunen 2019) but as energy consumption in their recovery is still lesser than in producing virgin glass fibres, it is estimated to eventually bring new business opportunities despite the economic challenges (Marsh 2013; Halliwell 2006, 20).

6.8 Other means and remarks

Promoting circular economy, as suggested by Saario (2017, 2,4), should be done through procurement in how producers of FRP items for Valmet handle their waste, especially waste fibres some producers are able to use in-house already today or actively taking steps towards it (Peltola 2019; Korpimäki 2019c).

It should be noted that there are considerable differences between countries in how the waste is managed. Places such as the Nordics and Germany have come a long way forward, but in developing countries mixed waste is used almost exclusively outside metals. (Anhava 2019.) Technicalities of recycling processes aside, design and production of well-recyclable FRPs with efficient disassembly hold no value if their recycling at the end-of-life cannot be assured. *Take-back -schemes*, as suggested by Saario (2017, 2, 4) would be advisable to consider when industrial machinery reach their end-of-life. Importance of this is highlighted when this is done in high sustainability risk -countries, where infrastructure and law enforcement for sustainable recycling are absent.

Importance of contracts in the end-of-life treatment should not be underestimated, as recycling is seen as “chicken-or-egg-first” -type of business. To overtake a process of recycling, waste management companies needs collaborative operators in both ends: Companies like Valmet and its associates that can pre-sort the waste effectively while keeping it clean are needed in one end. On the other end are the companies that willing and able to use the recycled material effectively. (Anhava 2019.)

As for the waste hierarchy, *Prepare for reuse* cannot be utilized to any relevant extent in heavy industrial environments such as Valmet’s due to the bespoke nature of FRP products in its machinery. This can practically be generalized to any other industrial use, since the components are being designed to a very particular use. Additional problems in reuse of FRPs could be caused by difficulties of re-calculating their load-carrying capacities as recovered items, should any of them serve new purpose as structural items (Halliwell 2006, 16).

6.9 Conclusions for RQ3

As expected, means for enhancing sustainability of FRP were discovered but contrary to initial expectations, their amount was also substantial. All levels of waste hierarchy apart from *Prepare for reuse* can be considered to a relevant extent but sustainability trade-offs of some sort are included in virtually every mean discovered, making the problem area a lot more complex than was originally expected.

The most prominent existing means for increasing sustainability of FRPs are compiled as figure 16 with a more complete presentation of all brought up considerations, including possibly upcoming future applications included as appendix 7. All the presented means include their primary benefit(s) in terms of triple bottom line and are arranged per each stage of the PLC with *Selection of applications* added as a preceding one. Several relevant means of enhancing the sustainability was discovered in all stages of the PLC, excluding *Distribution* as there were no important conclusions to be made apart from the fact that choosing FRP as the material is an environmental and economic benefit on its own. Other than that, general rules on good logistics and packaging apply.

No quantitative economic assessments of costs between each of the points were made. It seems, though, that lots of good sustainability practices can be followed without crippling the economic efficiency of using FRPs. Yet, the preliminary expectation of the study that implementing these means come ultimately down to optimizing between cost-efficiency and their sustainability performance relative to what is used typically (or currently, in the case of existing products), prevails. As no meaningful rules of thumb can be made in which of the presented means suit best for any given application, this is a discussion that should be engaged on a case-by-case basis.

As a conclusion to all findings of this work, the pivot points where the enhancement of sustainability of FRPs can be best achieved by companies like Valmet that buy FRP components from their suppliers can be condensed to the following list:

1. **Sustainable selection of applications**
2. **Designing FRP components in a manner that ensures long life cycles** equalling that of the machine itself while optimizing the material consumption **and allows effective disassembly and recycling**
3. **Enforcing sustainable practices for FRP manufacturers** during supplier selection, procurement and development processes
4. **Ensuring** that **proper end-of-life -management** of FRP components included in the delivered machinery is / will be achieved

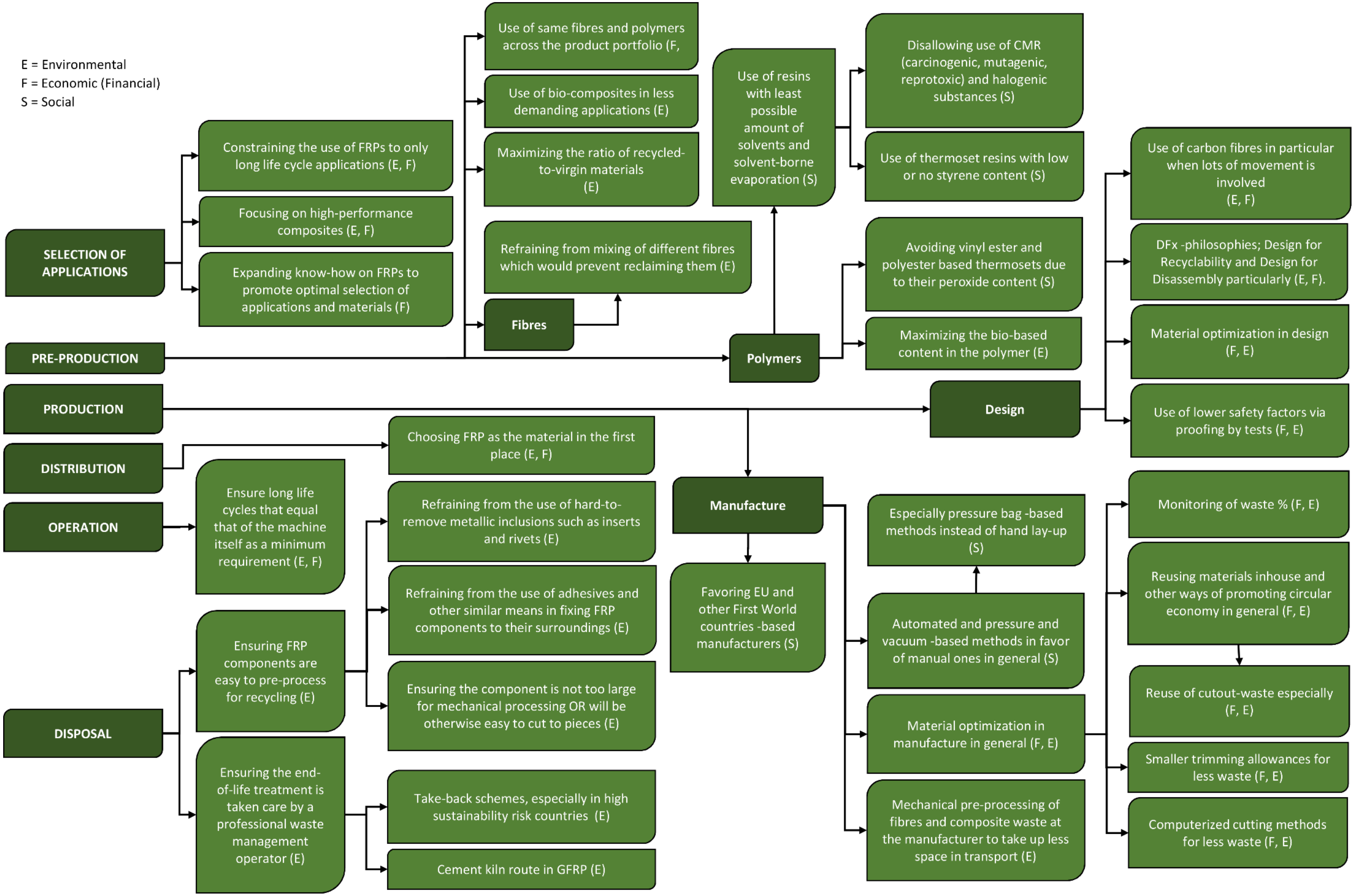


Figure 12. Means to enhance sustainability of FRPs currently

7 RQ4: Future projections

After studying all the evidence and references, prediction with the biggest certainty is that **dependence on landfilling in favor of source reduction, reuse, recycle and incineration and holistic pollution prevention will reduce**. This will create increasing number of small companies discovering business opportunities in disposal of solid waste (Theodore & Theodore 2010, 262, 271, 345). This is true also in regards of FRP, while the development will be further fortified by ever-increasing quantity of fibre-reinforced plastics reaching their end-of-life alongside with rapid growth in global consumption (Huikuri 2019; Hall 2016).

Whereas production carbon fibre is increasing at higher rates than that of glass fibre, disposal of the latter is a more current problem since a lot of GFRP products have existed substantially longer (Job 2010, 12). This probably means solving of challenges regarding it also draw nearer when compared to CFRP. This is particularly true in marine industry as about 140 000 marine vessels are expected to become due for scrapping each year in Europe alone, with most of them being glass fibre composites (Marsh 2013). Similar problem is looming with windmill blades (Korpimäki 2019a; Halliwell 2006, 35), so it is highly probable that several efficient recycling routes – for GFRP particularly – will exist by the time a paper machine being manufactured today reaches end of its life cycle.

On the other hand, the price of carbon-fibres will drop at a significantly faster rate than prices of other FRP-related materials with its prices estimated to be halved or even more in the future. This was estimated to be largely achieved with the development of less energy-intensive methods of virgin material production in combination with optimistic views in development of various recycling methods. (Keskinen & Mannermaa 2019.) Such estimations reinforce the notion of CFRP being a point of interest from the sustainability point of view.

Growing political pressure, particularly from governments and environmental agencies, are forcing changes to current practices and will continue to do so in the future (Bhat et al. 2017, 11; Hall 2016, 5). For example, Finnish acts 331/2013 28 § and 53 § valid since 1.1.2016 have forbade any material that includes more than 10 % of organic substances to be disposed into a landfill. This applies to composites due to the resins used being organic in nature (Blom & Dufva 2016, 5, 12-13). Recycling of composite waste is a major talking point within the industry in Finland currently and there are great of concerns of how to handle the issue in a sustainable manner. As of late, several waste processing sites have ceased to accept composite waste altogether. This is a direct repercussion from the landfill-prohibition of organic waste, so it seems like companies in the industry do not yet know how to circle around the problem which has resulted in tons of waste waiting for its ultimate disposal at properties of FRP manufacturers. This issue needs to and most likely will be resolved in a very near future due to its urgency. (Korpimäki 2019c.)

While Finnish FRP industry forms only a tiny fraction of global production, similar progression should be expected to happen on a major scale. Halliwell (2006) predicts most EU countries forbidding landfilling of composites in the long term, which may well be the most likely be the solution to the low recycling rate of GFRP particularly (Korpimäki 2019c). Whereas lack of disposal infrastructure is considered currently a problem, its development will inevitably accelerate due to increased composite production and reduced landfill availability, essentially forcing development of cost-effective recycling routes and associated supply chains (Job 2010, 12; Halliwell 2006, 36-37). China – where a major portion of the worlds plastic waste formerly ended up to – banning the import of plastic waste to the country couple of years ago had a significant effect on recycling of plastics. This has caused a stark realization – at least in Europe – that the problem of ever-accelerating amount of plastic waste needs to be addressed at its source. Similar imperative obligations are bound to trigger needs for more efficient recycling processes in the future. (Anhava 2019.)

Plastic composites are expected to continue replacing steel, aluminium and non-reinforced forms of plastics at an accelerating rate (Mannermaa 2015), while their broader use is considered elementary for a more environmentally-friendly development in the future as their use promotes more efficient use of renewable energy and dependence on fossil fuels (Blom & Bruun 2014, 3). At the same time, oil-based FRP polymers come out as somewhat questionable materials when it comes down to available reserves of known natural resources. According to Smith (2011, 76), British Geological Survey estimated in 2005 that known reserves of oil, the raw material for most plastics, will last only until around 2050s with the level of consumption at time. Although development of higher-performance technologies and enhanced disposal of waste have made it possible for this number to grow even without new geological findings, iron (72 years) and bauxite (148 years) – the primary components of steel and aluminum respectively – are expected to last considerably longer. This notion is underlined by the possibility of infinite recycling loops with aluminum and steel, whereas this is not the case with plastics, even when thermoplastics are considered. The most up-to-date figure for oil depletion with the current rate of consumption dates it to year 2068, with corresponding values for natural gas and coal being 2070 and 2152 in the latest published *BP Statistical Review of World Energy* (2018, 12, 26, 36).

Even though plastics industry consumes only 4 % of the oil used globally (Oil consumption 2018), depletion of resources will inevitably increase plastic recycling ratios in the long haul. Design for Recyclability and similar principles will be emphasized more in the future, as continuously growing number of companies are interested in improving recyclability of their products. The global trend of urbanization will also have a significant positive impact on recycling of plastics in general as the more concentrated living is, the easier the generated waste streams are to handle. This will promote circular economies, especially in low-volume materials like certain types of plastics that are otherwise problematic. (Anhava 2019.)

Instead of plastics industry being affected negatively by depletion of oil – which represent 99 % of plastics raw material base currently (Oil Consumption 2018) – **the exact opposite is expected**. As it becomes increasingly scarcer, oil is forecast to be reserved for high value processes such as plastics manufacturing in the future (Hammond 2012, 157). Following this prediction, FRPs as products with considerable higher refinement value compared to non-reinforced forms of plastics in general will get prioritized even more eminently. This train of thought is further reinforced by the notion that production of plastic doesn’t consume the energy content from its raw material like oil, but rather stores it for the duration of the PLC (Oil Consumption 2018). Conceptually, the fossil hydrocarbon content from oil and other raw materials of plastics can be returned afterwards to the fuel cycle via energy recovery of incineration or other means of disposal. In practice, achieving it with good efficiency might still be problematic as, for example, incineration is not typically optimized for energy efficiency but for lowest possible emissions instead (Anhava 2019).

On a grand scale, volume and toxicity of waste being generated today has exceeded the ability to properly manage it in virtually every industrialized and developing nation. By 2060, world's population could potentially increase by 50 % while economic activity is expected to increase by 500 %. This emphasizes further the need to catch up in sustainability technologies and practices. Effective prevention of pollution will require enforcement of government regulations and controls, development of more sustainable manufacturing, products and behavior across all societies (Theodore & Theodore 2010, 68, 117), as **avoiding a "major planetary catastrophe" requires investments in green technologies worth 60 – 80 trillion dollars during the next four decades** (United Nations Department of Economic and Social Affairs 2016, acc. Thiele 2016, 91). Whereas estimations like this are not a proof of future actions, it is beyond a reasonable doubt that space and market for environmentally friendly technologies will be created. As plastics typically perform extremely well on environmental LCAs, it seems highly probable that – as life cycle thinking and tools for such assessments become commonplace – higher dependency of them will be part of the solution instead of the problem (Keskinen 2019; Blom & Bruun 2014, 4). However, this calls for intensive efforts on providing solutions for micro- and nanoplastic contamination and higher use of bio- and/or recycled plastics in the future.

In general, findings of this work support the initial assumption that sustainability of plastics will be enhanced in the future, although no systematic analysis or quantitative figures cannot be given based on the study. Concrete means in enhancing individual aspects of FRPs that may become viable in the future are presented as appendix 7 in a chart that also compiles all the current options discovered.

8 Conclusions

8.1 Recommendation

As a synthesis from conclusions of all four research questions, **broader usage of fibre-reinforced plastics in heavy industrial environments seems not only justifiable, but also highly recommendable** given that the selection of application and the composite manufacturer is done in a sustainable manner and the longest possible life cycle and proper end-of-life management are ensured. Figure 17 wraps up the discussion on broader usage of FRP in the form of a SWOT-analysis (analysis of strenghts, weaknesses, opportunities and threats).

Only few findings contradict with this recommendation, with the most important aspect of all being the risk for contributing to micro- and nanoplastic contamination. That is something that should be taken extremely seriously, but as long as FRPs are not used in wearing parts and are taken care by a professional waste management operator, their contribution to the problem is nonexistent.

Strenghts

- Resource efficiency (in distribution and operation particularly)
- Quality control
- Good visual quality and design possibilities
- Lower life time costs
- Thermal and electrical insulation
- Cheaper moulding costs
- Chemical and corrosion resistance
- Lightweight
- Ease of handling
- Space-saving
- Aligning of mechanical properties
- Helps mitigating global warming
- Commendable even with ambitious sustainability goals (Valmet)

Weaknesses

- Forced use of higher safety factors
- Micro- and nanoplastics contamination in wearing parts
- Current low recycling rates and infrastructure
- Use of hazardous chemicals substances
- Constructional restrictions that prevent efficient recycling (metallic inclusions, mixing of several fibres, adhesive connections)

Opportunities

- All-around better recycling possibilities of plastics in the future
- Better recycling possibilities for fibres, especially for carbon fibres, in the future
- Expanding global demand and consumption, especially in higher-performance composites
- Cheaper raw materials in the future

Threats

- Customer perceptions towards plastics
- Disposal, especially in developing countries
- Use in unsustainable applications
- Public image

Figure 13. SWOT-analysis on usage of FRP

8.2 Future applications

Based on the findings of the study, **a list of guiding questions** was designed to help determining whether use of FRP is commendable from a sustainability point of view, including all the triple bottom line aspects of business sustainability. The short version of the list, designed for a fast check that can be made in few minutes, came out as follows

1. Does the component move or is it moved (mechanically or by hand) frequently during use?
2. Have steel and similar materials been proven insufficient for the intended application?
3. Is it likely that making the product from FRP reduces its total life cycle costs significantly?
4. Does the intended component require particularly good weight-to-stiffness -ratio?
5. Is the component moved (mechanically or by hand) frequently during maintenance, whether because of maintenance of the FRP component itself or any adjacent part, or does it otherwise aid in lowering maintenance or other production down times significantly?
6. Is good chemical or corrosion resistance required for the application?
7. Would the product, if made from FRP, be typically manufactured in a First World country? If not, is it highly probable that internal audits or similar measures will be taken to ensure its safe and environmentally friendly production?
8. Does the intended component include or would greatly benefit from complex surface forms like double curvature?
9. Is the reserved space for the component critically restricted?
10. Can a significantly longer life cycle be achieved with the use of FRP, compared to steel or similar materials?

The upper the question in this list is, the more important getting a *yes*-answer to it is for solid justification of using FRP in the application. The reasoning for selecting each of the question, determining the respective priorities between each of the questions and the complete list for a more comprehensive evaluation are presented as appendix 8.

Careful judgment of scoring an application via this list should be exercised, as getting low points from this list by a few aspects that truly stand out alone might justify use of FRP in the application and vice versa: a high score might not be enough if most of the answers are only borderline-yes. Subsequently, no certain limit for “passing” the evaluation can be given. For reference, the walkway end element scored 6/10 points in the shortlist and 13/22 points in the longer assessment. Evaluation of other Valmet-products – including their performance on the longer assessment – is introduced in detail in appendix 9.

It is important to note that whereas this list of questions with their respective priorities are formulated in a manner that would be as widely applicable as possible, they still somewhat reflect Valmet's environment and authors ultimately narrow understanding on the topic. Additionally, determining the priorities required comparison of different aspects of sustainability between each other – something extremely hard if not impossible to quantify. Therefore, the list of questions and their relative importance should be evaluated and iterated critically according to the use.

8.3 Relevance of results to FRP and aluminum

Steel is the most used material in Valmet's environment, while also being the material FRPs are most prominently considered to replace. Right after it comes aluminum – both in general and in Valmet's environment, where aluminum is the primary material when it comes to walkways of paper and board machines. Due similarity of steel and aluminum in many aspects, conclusions of this report are largely applicable with the some of the more important notions retrieved being the following

- Aluminum is the more energy-intensive material to produce (Toiviainen 2008, 27)
- Aluminum provides less efficient use of solid natural resources: aluminum consumes around 9 times more as much as steel does with respective numbers being 61 kg to 7 kg (Wuppental-institute, according to Rissa 2001, 63).
- CO_2e emissions of aluminum was noted to be 2,7-times higher than steel in a study by Roos & Szpieg (2012, 43)
- Known reserves for bauxite will last almost twice longer than those of iron (British Geological Survey 2005, acc. Smith 2011, 76)

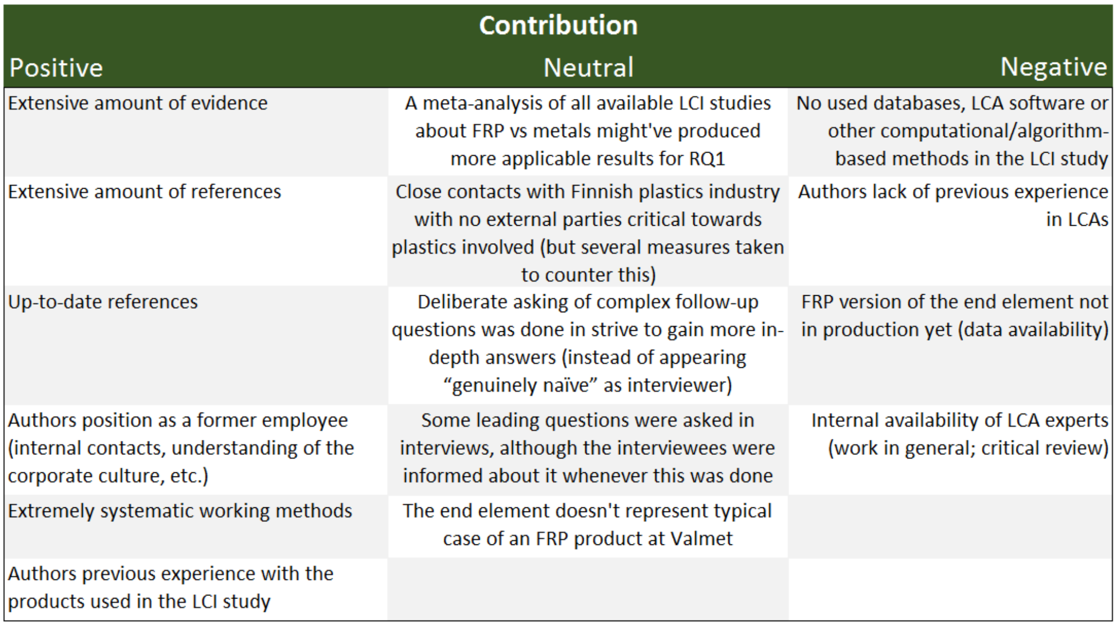
In relation to FRP, use of aluminum in powerboats were concluded to contribute 3,7 – 9,2 times more to greenhouse effect through CO_2e emissions than using GFRP when only the production is considered (Kara & Manmek 2009, 9). Should the whole PLC accounted, such figures would be substantially higher (Keskinen 2019): another LCA on boats noted that the use stage of the studied boats with outboard motors contributed 85 % of their carbon footprint (Tonteri, Auvinen, Helin & Johansson 2010, 37). With such a ratio, lifetime carbon footprint of such aluminum products might easily be 10 - 20 times higher than those being made from GFRP.

FRPs seem even more favorable choice of material when compared against aluminum with the known natural resources being an exception to this. Another benefit of aluminum comes from its recycling, as it saves up to 95 % of energy when comparing against production of virgin material (West 2018).

8.4 Critical review

No exclusive critical view session for the of the LCI study (as suggested in ISO 14040/44) was performed due unavailability of LCA experts. Instead, a critical review session of the thesis results was held, during which some alterations to its conclusions and suggestions for follow-up actions were produced. As for its prominence, the work was deemed thorough, systematically produced, well-argued and as relevant as it realistically could be in terms of its references and evidence. Table 9 provides a summary of considered factors that contributed to the reliability of the work, starting from more important ones on the top to the least important towards the bottom.

Table 7. Evaluation of the reliability of the work



Contribution		
Positive	Neutral	Negative
Extensive amount of evidence	A meta-analysis of all available LCI studies about FRP vs metals might've produced more applicable results for RQ1	No used databases, LCA software or other computational/algorithm-based methods in the LCI study
Extensive amount of references	Close contacts with Finnish plastics industry with no external parties critical towards plastics involved (but several measures taken to counter this)	Authors lack of previous experience in LCAs
Up-to-date references	Deliberate asking of complex follow-up questions was done in strive to gain more in-depth answers (instead of appearing "genuinely naïve" as interviewer)	FRP version of the end element not in production yet (data availability)
Authors position as a former employee (internal contacts, understanding of the corporate culture, etc.)	Some leading questions were asked in interviews, although the interviewees were informed about it whenever this was done	Internal availability of LCA experts (work in general; critical review)
Extremely systematic working methods	The end element doesn't represent typical case of an FRP product at Valmet	
Authors previous experience with the products used in the LCI study		

In general, a good level of reliability of the work was deemed to have been achieved although the LCI study involves significant uncertainties. Should this have been identified early in the thesis process, more satisfactory – and most likely universally more applicable results – would've been probably achieved via a meta-analysis of all available LCAs that cover the theme of FRP versus metals. Another important notion is that all the non-internal interviews were conducted with representatives of the Finnish plastics industry with no parties critical towards plastics being involved. This may or may not have affected the objectivity of the work. However, all means possible were taken to reduce a possible bias towards plastics that included

- Having a working life instructor from Valmet that was skeptical towards plastics
- Starting the thesis process by familiarizing oneself on some of the most concerning studies on climate change and depletion of resources
- Using predominantly pro-steel data points in the LCI study
- Being especially critical towards information gained from the interviews
- Employing most comprehensive triangulation of evidence in interviews particularly
- Constant and critical self-evaluation of the works' objectivity
- Striving to get interviewees that were critical towards plastics (but being unsuccessful in this regard)

8.5 Follow-up and suggestions for further research

In general, the topic of sustainability is one of high importance and addressing it properly can be translated into significant competitive advantage as concluded in the critical review session. Yet, the harsh reality is that is it still almost never brought up by the customers of Valmet and these topics are something the typical engineer doesn't have the know-how to take concrete steps in promoting them, nor would it be reasonable to expect them to be able to. The discussion revolving sustainability is also a notably complex one. Sustainability trade-offs of some sort are almost always present, so it might be next to impossible to know if an action taken towards improving sustainability contributes to making net positive impacts or not unless concrete tools, metrics and principles are being established – and even then, it might come down to value choices. To improve such aspects, the attendees of the critical review session concluded that some very basic actions like providing possibilities for **internal LCA audits and services for quick LCA-modelling and/or LCT workshops and trainings would be extremely beneficial**. As an alternative to internal LCA modelling (that would require a dedicated specialist with a license to LCA software and a database), **simple tools like an Excel-based LCA-calculator for obtaining a rough approximation of the most important impacts during PLC** could be developed.

As for the LCI study in this thesis, a second study that would be based on a proper LCA software and a comprehensive database would be commendable, especially if the FRP end element goes into production meaning more precise data from it could be obtained in the future. Benefits of this would be a more reliable model, in addition to being able to take also other important environmental aspects into account. The same applies for factoring in economic and social aspects via Life Cycle Costing and Social Impact Assessment (Social LCA) or similar tools.

The list of guiding questions for future applications was generated as a by-product of the thesis process. Such tool could well be developed a lot further and alone could form a thesis topic on its own, with considering all the important aspects more analytically, including boundary conditions for which kind of applications the tool works best for. The questions and their respective answers could also be quantified for understanding significance of each answer and their relations better.

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Appendices

Appendix 1. Collected evidence

Table 10 provides a breakdown of collected evidence with their classifications, dates and retrieval information. Names of some of the item concerning FRP products at Valmet have been censored due to confidentiality reasons. Items are labeled as either "primary" or "secondary" according to their originality (Research 101: Primary and Secondary Sources 2018). Primary classification was given to firsthand material such as personally conducted communication, interviews and fieldwork, whereas are all the material referencing on firsthand sources were titled secondary. In addition to the ones listed, a lot of other sources of evidence were planned out but not utilized in the end due to not reaching the intended persons, finding relevant information on the topics or obtaining the information needed via other passages. Some of the classifications, like items in *Participatory observation* or distinction between each item under *Documentation* or *Archival records* are debatable but still serve as a general overview on what kind of data was utilized.

Documentation included e-mails, personal documentation, internal memos and other more informal sources in nature. Items labeled as **archival records** were 3D-models, official company instructions, presentations and digital trainings. Studying internal documentation and records at Valmet was fundamental part answering RQ1 and RQ2 particularly. "Biased selectivity", listed as a weakness of documentation and archival records as sources of evidence by Yin (2014, 106) was minimized in internal documentation by studying every item accessed instead of having to make value choices in which ones seem the most relevant.

Table 8. Collected evidence, detailed breakdown

Documentation						
No.	**Label**	**For**	**Class**	**Published**	**Retrieved in**	**Retrieval from**
1	Formulation of the research problem in this thesis (plastics at Valmet)	RQ2	Primary	2018	20/08/2018	Personal discussion with Laura Puustjärvi
2	Formulation of the research problem in this thesis (plastics at Valmet)	RQ2	Primary	2018	24/08/2018	Personal discussion with Ari Saario
3	Meeting in Vilppula, production of FRP end element	RQ1 (RQ2)	Primary	2018	29/08/2018	Personal notes from the meeting
4	Presentation at the Composite sauna -session	RQ4	Secondary	2019	30/01/2019	Personal notes from the presentation by Tapani Huikuri
5	Presentation at the Composite sauna -session	RQ2	Primary	2019	30/01/2019	Personal notes from the presentation by Jani Korpimäki
6	Global paper and board market and Valmet's machinery	RQ4	Primary	2019	31/01/2019	Personal e-mail from Sampo Immonen
7	E-mails about Valmet's FRP products	RQ2	Primary	2019	31/01/2019 17/04/2019	Personal e-mails from Tommi Luosma
8	Plastic composites at Valmet	RQ2	Primary	2019	31/01/2019	Personal e-mail from Samppa Salminen
9	E-mails about Valmet's FRP products	RQ2	Primary	2019	01/02/2019 18/03/2019	Personal e-mails from Jyrki Savela
10	E-mail bundle (text and pictures) about production issues in steel end element	RQ1	Primary	2017	04/02/2019	Personal e-mail from Jussi Salojärvi
11	Information bundle about Valmet's FRP products	RQ2	Primary	2019	13/02/2019	Personal e-mail from Janne Lappi
12	Production of FRP end element and other FRP products of Valmet	RQ1, RQ2	Primary	2019	13/02/2019 18/03/2019 21/03/2019	Personal e-mails from Jani Korpimäki
13	Recycling of GFRP in Finland	RQ3	Primary	2019	13/03/2019	Phone discussion with Dick Blom (author of some of the references used)
14	Thermoset resins in Valmet's products	RQ3	Primary	2019	18/03/2019	Personal e-mail from Jani Korpimäki
15	Logistics of FRP end element and Valmet	RQ1	Primary	2019	18/03/2019	Personal discussion with Jukka Huumarkangas
16	Questions about bio- and renewable materials in Valmet's products -study	RQ3 (RQ4)	Primary	2019	01/04/2019	Personal discussion with Jaakko Jokinen (author of the study)
17	Renewable and recycled materials in paper and board mills	RQ2	Primary	2019	01/04/2019	Personal discussion with Jussi Salojärvi
18	FRP products at Valmet	RQ2	Primary	2019	03/04/2019	Personal notes from a discussion with Teemu Autio
19	Data from FRP products at Valmet	RQ2	Secondary	2019	03/04/2019	Personal e-mail from Teemu Autio
20	FRP products at Valmet	RQ2	Primary	2019	03/04/2019	Personal e-mail from Pasi Viitasalo
21	Enhancing sustainability of FRP polymers	RQ3	Primary	2019	04/04/2019	Personal e-mail from Lasse Keskinen
22	Steel consumption at Valmet	RQ2	Primary	2019	15/04/2019	Personal e-mail from Markku Vanhala
23	Comments about thesis conclusions and FRP products at Valmet	RQ2	Primary	2019	18/04/2019	Personal e-mail from Jukka Heikkinen
24	FRP products at Valmet	RQ2	Primary	2019	23/04/2019	Personal e-mail from Mika Komulainen
25	FRP products at Valmet	RQ2	Primary	2019	23/04/2019	Personal discussion with Jukka Heikkinen
26	FRP products at Valmet	RQ2	Primary	2019	23/04/2019	Personal e-mail from Timo Rantanen
27	FRP products at Valmet	RQ2	Primary	2019	23/04/2019	Personal e-mail from Juha Taari

Archival records

No.	Label	For	Class	Published	Retrieved in	Location
28	Noora Liski's Master's thesis	RQ2	Primary	2009	15/08/2018	Personal e-mail from Jussi Salojärvi
29	Sustainability @ Valmet e-learning courses	RQ2	Secondary	2018	Spring 2018	MyAcademy (Valmet)
30	Guidelines for sustainable and responsible research, development and design in Valmet	RQ2	Primary	2017	19/09/2018	Instructions database (Valmet)
31	Sustainability-related presentations (8 sub-items)	RQ2	Secondary	2017	23/01/2019	Flow (Valmet)
32	3D -model of the steel end element	RQ1	Primary	2019	31/01/2019	Catia V6 (Valmet)
33	3D -model of the FRP end element	RQ1	Primary	2018	31/01/2019	Catia V6 (Valmet)
34	Technical documentation of steel end element	RQ1	Primary	2017	04/02/2019	Personal e-mail from Jussi Salojärvi
35	Dow Jones sustainability indices (Europe and World)	RQ2	Primary	2018	11/02/2019	Website (RobecoSAM)
36	Valmet's Sustainability 360° agenda	RQ2	Primary	2018	21/02/2019	Flow (Valmet)
37	Valmet sets targets for health and safety 2025 (news article)	RQ2	Secondary	2019	21/02/2019	Website (Valmet)
38	Consumables, spare parts or products from renewables or recyclables, mid-review materials (2 sub-items)	RQ2 (RQ4)	Primary	2019	27/02/2019	Personal e-mail from Ari Saario
39	Valmet benchmarking scorecard by RobecomSAM for Dow Jones Sustainability Indices	RQ2	Primary	2018	06/03/2019	Personal e-mail from Saara Hämäläinen
40	A List scoring of CDP climate program 2018	RQ2	Primary	2019	20/03/2019	Website (CDP Worldwide)
41	Technical documentation of Valmet's FRP product	RQ2	Primary	2018	21/03/2019	Personal e-mail from Jyrki Savela
42	Consumables, spare parts or products from renewables or recyclables, summary and conclusions materials (2 sub-items)	RQ2 (RQ4)	Primary	2019	02/04/2019	Personal e-mail from Ari Saario

Themed interviews

No.	Label	For	Class	Date	Person	Title	Company
43	Enhancing sustainability of low-quantity CFRP manufacturing (32 min)	RQ3 (RQ4)	Primary	14/02/2019	Jani Korpimäki	Vice President	CSI
44	Compatibility of FRP and sustainability at Valmet (65 min)	RQ2	Primary	04/03/2019	Saara Hämäläinen	Sustainability Specialist	Valmet
45	Enhancing sustainability of FRP polymers (45/81 min)	RQ3 (RQ4)	Primary	06/03/2019	Tuula Mannermaa Lassi Keskinen	Technology Manager Application Engineer	Ashland
46	Enhancing sustainability of FRP fibres (51 min)	RQ3	Primary	07/03/2019	Minna Peltola	Quality and Lean Manager	Ahlstrom-Munksjö
47	FRP projects at Valmet (50 min)	RQ2	Primary	14/03/2019	Samppa Salminen	Senior Manager, Development	Valmet
48	Waste management of FRP (61 min)	RQ3 (RQ4)	Primary	18/03/2019	Antti Anhava	Sales Manager, Recycling and Waste Solutions	Fortum Waste Solutions
49	Enhancing sustainability of low-quantity GFRP manufacturing (56 min)	RQ3	Primary	18/03/2019	Esa Hiltunen	CEO	Muovityö Hiltunen
50	Enhancing sustainability of high-quantity FRP manufacturing (55 min)	RQ3	Primary	25/03/2019	Jani Sippola	Research Manager	Exel Composites

Participatory observation

No.	Label	For	Class	Date	Location	What
51	Composite sauna -session	RQ2	Primary	30/01/2019	Jyväskylä	Ideation session regarding wider usage of plastic composites in paper and board machines
52	Consumables, spare parts or products from renewables or recyclables in Valmet's products	RQ2	Primary	28/03/2019	Jyväskylä	Summary and conclusions -workshop of the study.

Sources of evidence not utilized Direct observation, Physical artefacts

Planning of the **interviews** and choosing of the topics and interviewees were done in such a way that they would cover each major aspect related to FRPs. This included production of the used materials (fibres and polymers), manufacturing of FRP items (carbon- and glass fibre particularly with low- and high-quantity manufacturing being both considered), disposal (waste management operator) and views of an industrial company building machinery that require FRP components (sustainability specialist and R&D manager). Several guidelines for planning and conducting the interviews, as suggested by Yin (2014, 106, 110-111), were followed

- Keeping the interviews as “guided conversations”
- Asking how *(miten)* instead of why *(miksi)*
- Asking open questions instead of closed ones
- Target length of 60 minutes at maximum
- Creating a friendly and nonthreatening atmosphere
- Assuming a conversational manner while following the case study protocol (order of questions and sticking with them) rather strictly
- Accounting for each of the weaknesses of themed interviews individually
    - Appearing genuinely naïve towards the topic so that the interviewee can provide a fresh commentary without assuming anything about the interviewers’ knowledge
    - No leading questions to reduce *Response bias*
    - Written notes during the interviews (and sending summaries afterwards) to eliminate inaccuracies due to poor recall
    - Careful planning and wordings for the interview questions (and sending them beforehand) to fight poorly articulated questions

As the interviews were all conducted in Finnish, resulting in the interview questions being in Finnish as well. The lists of questions (appendix 3), tailored for each interview according to the title and company of the participant, were sent beforehand for every interview so the participants could familiarize themselves with the topics better. Summary from each of the interviews was written directly in English (appendix 4) and sent afterwards to the participants for approval in case of misinterpretations, errors in translation and ensuring no confidential information would end up in the public version of this thesis. While this allowed for the interviewees to withdraw some of their given statements, this contributed significantly to better data quality in general.

Quick (digital) notes were written during each of the interview. In terms of reliability, a more optimal way in documenting the interviews might have been to record them but this option was disregarded as it was considered suboptimal use of time: not listening to the recordings and littering their content freed up time for a more comprehensive triangulation of evidence for other sources.

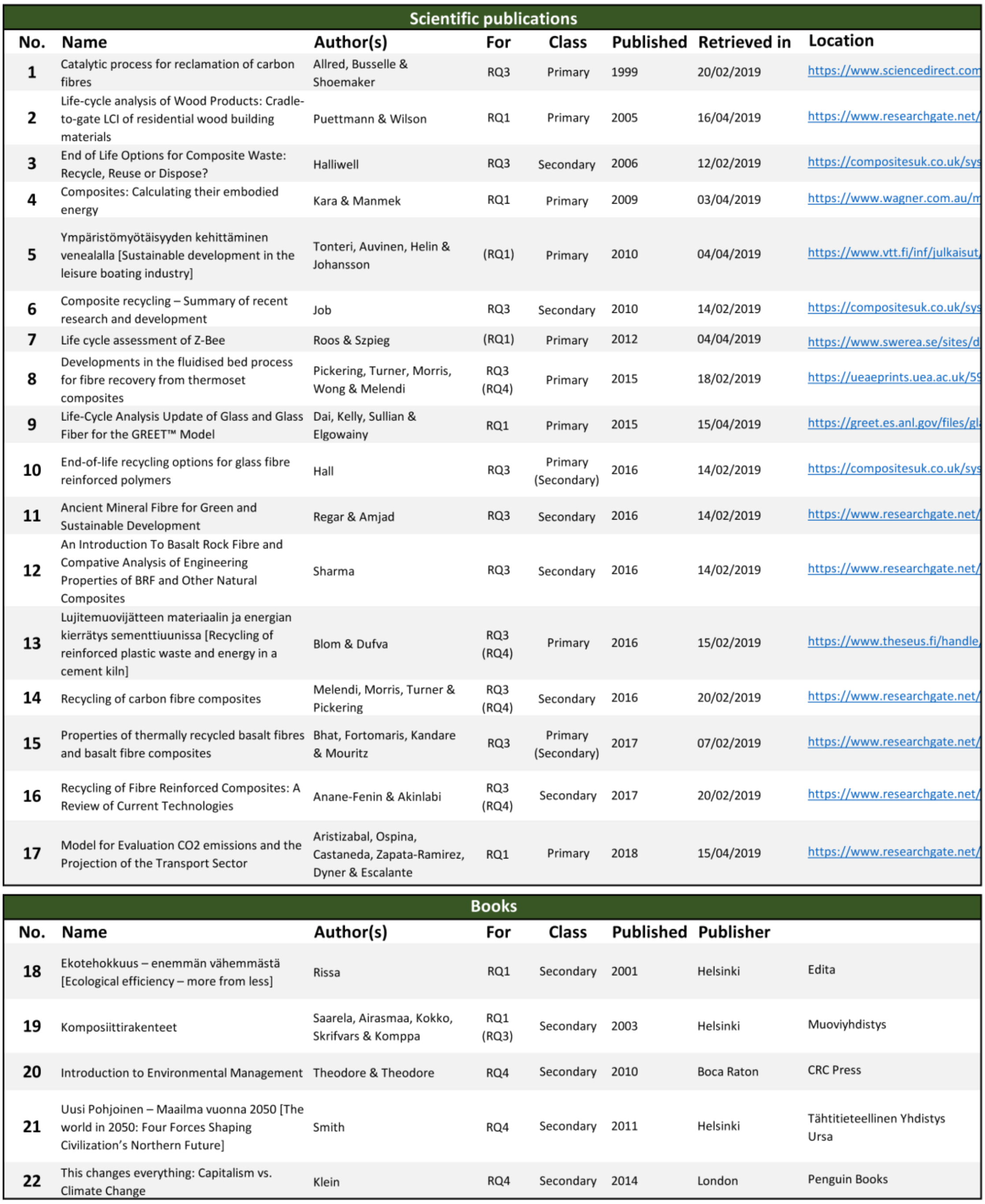
Targets of “appearing genuinely naïve” towards each topic at hand and articulating “no leading questions” were partly not achieved particularly in some of the later interviews. This was a conscious decision in favour of being able to ask more informed follow-up questions and verifying the validity of certain claims and though-processes. Additionally, the interviewees were noted about the nature of the more leading questions for better transparency. As a conclusion, this may have somewhat affected some of the received answers (or interpretations extracted from them) but with the trade-off of much more in-depth content.

Forms of **observation**, especially participatory, were considered for cross-verification and broadening the data collection regarding manufacturing of the steel end element. Ultimately, they weren’t utilized in that regard due to more optimal allocation of time, since the possibly more accurate data from such sources wouldn’t have affected any overall conclusions of this study. This same applied for **physical artefacts** as the only relevant option would’ve been a ready-made steel end-element but technical documentation alone from the item was deemed satisfactory.

Appendix 2. Used references

Table 11 breaks down each used reference arranged by source and item. Items were labeled as Primary or Secondary according to their originality alike with the collected evidence in appendix 1.

Table 9. Used references, detailed breakdown



Scientific publications

No.	Name	Author(s)	For	Class	Published	Retrieved in	Location
1	Catalytic process for reclamation of carbon fibres	Allred, Busselle & Shoemaker	RQ3	Primary	1999	20/02/2019	https://www.sciencedirect.com
2	Life-cycle analysis of Wood Products: Cradle-to-gate LCI of residential wood building materials	Puettmann & Wilson	RQ1	Primary	2005	16/04/2019	https://www.researchgate.net/
3	End of Life Options for Composite Waste: Recycle, Reuse or Dispose?	Halliwell	RQ3	Secondary	2006	12/02/2019	https://compositesuk.co.uk/sys
4	Composites: Calculating their embodied energy	Kara & Manmek	RQ1	Primary	2009	03/04/2019	https://www.wagner.com.au/m
5	Ympäristömyötäisyyden kehittäminen venealalla [Sustainable development in the leisure boating industry]	Tonteri, Auvinen, Helin & Johansson	(RQ1)	Primary	2010	04/04/2019	https://www.vtt.fi/inf/julkaisut
6	Composite recycling – Summary of recent research and development	Job	RQ3	Secondary	2010	14/02/2019	https://compositesuk.co.uk/sys
7	Life cycle assessment of Z-Bee	Roos & Szpieg	(RQ1)	Primary	2012	04/04/2019	https://www.swerea.se/sites/d
8	Developments in the fluidised bed process for fibre recovery from thermoset composites	Pickering, Turner, Morris, Wong & Melendi	RQ3 (RQ4)	Primary	2015	18/02/2019	https://ueaeprints.uea.ac.uk/5
9	Life-Cycle Analysis Update of Glass and Glass Fiber for the GREET™ Model	Dai, Kelly, Sullian & Elgowainy	RQ1	Primary	2015	15/04/2019	https://greet.es.anl.gov/files/g
10	End-of-life recycling options for glass fibre reinforced polymers	Hall	RQ3	Primary (Secondary)	2016	14/02/2019	https://compositesuk.co.uk/sys
11	Ancient Mineral Fibre for Green and Sustainable Development	Regar & Amjad	RQ3	Secondary	2016	14/02/2019	https://www.researchgate.net/
12	An Introduction To Basalt Rock Fibre and Compative Analysis of Engineering Properties of BRF and Other Natural Composites	Sharma	RQ3	Secondary	2016	14/02/2019	https://www.researchgate.net/
13	Lujitemuovijätteen materiaalin ja energian kierrätys sementtiuunissa [Recycling of reinforced plastic waste and energy in a cement kiln]	Blom & Dufva	RQ3 (RQ4)	Primary	2016	15/02/2019	https://www.theseus.fi/handle
14	Recycling of carbon fibre composites	Melendi, Morris, Turner & Pickering	RQ3 (RQ4)	Secondary	2016	20/02/2019	https://www.researchgate.net/
15	Properties of thermally recycled basalt fibres and basalt fibre composites	Bhat, Fortomaris, Kandare & Mouritz	RQ3	Primary (Secondary)	2017	07/02/2019	https://www.researchgate.net/
16	Recycling of Fibre Reinforced Composites: A Review of Current Technologies	Anane-Fenin & Akinlabi	RQ3 (RQ4)	Secondary	2017	20/02/2019	https://www.researchgate.net/
17	Model for Evaluation CO2 emissions and the Projection of the Transport Sector	Aristizabal, Ospina, Castaneda, Zapata-Ramirez, Dyner & Escalante	RQ1	Primary	2018	15/04/2019	https://www.researchgate.net/

Books

No.	Name	Author(s)	For	Class	Published	Publisher	
18	Ekotehokkuus – enemmän vähemmästä [Ecological efficiency – more from less]	Rissa	RQ1	Secondary	2001	Helsinki	Edita
19	Komposiittirakenteet	Saarela, Airasmaa, Kokko, Skrifvars & Komppa	RQ1 (RQ3)	Secondary	2003	Helsinki	Muoviyhdistys
20	Introduction to Environmental Management	Theodore & Theodore	RQ4	Secondary	2010	Boca Raton	CRC Press
21	Uusi Pohjoinen – Maailma vuonna 2050 [The world in 2050: Four Forces Shaping Civilization's Northern Future]	Smith	RQ4	Secondary	2011	Helsinki	Tähtitieteellinen Yhdistys Ursa
22	This changes everything: Capitalism vs. Climate Change	Klein	RQ4	Secondary	2014	London	Penguin Books

Other digital publications (fact sheets, leaflets, brochures, whitepapers and similar)

No.	Name	Author(s)	For	Class	Published	Retrieved in	Location
23	Demonstration of a process to recycle glass fibre waste, placed on rubbish dump, producing Polypropylene composites.	Befesa Plásticos	RQ1, RQ3	Primary	2009	15/04/2019	http://ec.europa.eu/environme
24	Stainless Steel and CO2: Facts and Scientific Observations	International Stainless Steel Forum	RQ1	Secondary	2012	11/02/2019	http://www.worldstainless.org/
25	The World in 2030, 2012 edition	Hammond	RQ4	Primary	2012	04/04/2019	https://www.rayhammond.com
26	Environmental Impacts of Using Welding Gas	Nakhla, Shen & Bethea	RQ1	Primary	2012	23.42019	https://cdn.ymaws.com/www.a
27	Lujitemuovijätteen kierrätyskäsikirja [Recycling handbook of fibre-reinforced plastic waste]	Blom & Bruun	RQ3	Primary	2014	06/03/2019	Personal e-mail from Tuula Mannermaa, recipient Juhani Salonen
28	The future development of composites	Mannermaa	RQ4	Secondary	2015	26/02/2019	Personal e-mail from Tuula Mannermaa, recipient Juhani Salonen
29	FRP vs. Traditional Materials	Bedford Reinforced Plastics	RQ1	Secondary	2017	20/03/2019	https://bedfordreinforced.com/
30	Annual Review 2017	Valmet	RQ2	Primary	2018	21/02/2019	https://www.valmet.com/globa
31	BP Statistical Review of World Energy. 67th edition.	BP p.l.c	RQ4	Primary	2018	15/03/2019	https://www.bp.com/content/
32	The Global Plastic Calamity	Bluewater group, Mirpuri foundation	RQ4	Secondary	2019	26/02/2019	https://www.bluewatergroup.c
33	Sustainability review 2018	Outokumpu	RQ1	Primary	2019	11/04/2019	https://otk-sitecore-prod-v2-cd

Articles

No.	Name	Author / company	For	Class	Date	Retrieved	Location
34	Basalt Fibers: Alternative to Glass?	Ross	RQ3	Secondary	2006	05/02/2019	https://www.compositesworld.
35	How much CO2 does an incinerator emit?	United Kingdom Without Incineration Network	RQ1	Secondary	2009	23/04/2019	http://ukwin.org.uk/resources/
36	End-of-life boat disposal – a looming issue for the composites industry	Marsh	RQ4 (RQ3)	Secondary	2013	12/02/2019	https://www.materialstoday.co
37	Differences Between Pyrolysis and Incineration As Well As Advantages	Beston Pyrolysis plant	RQ3	Secondary	2016	12/02/2019	https://bestonpyrolysisplant.co
38	Differences Between Diesel and Petrol	European Automobile Manufacturers Association	RQ1	Secondary	2016	15/04/2019	https://www.acea.be/news/art
39	Fuel Efficiency Benchmarking in Canada's Trucking Industry	Government of Canada	RQ1	Secondary	2016	16/04/2019	https://www.nrcan.gc.ca/energ
40	How to calculate the CO2 emissions from the fuel consumption?	Ecoscore-database	RQ1	Secondary	2019	16/04/2019	http://ecoscore.be/en/info/eco

Websites

No.	Page / website	Company (author)	For	Class	Date	Retrieved	Location
41	Resin Formula	Netcomposites.com	RQ1	Secondary	2004	24/04/2019	https://netcomposites.com/gui
42	Basalt Fiber Properties	Prince Engineering	RQ3	Secondary	2010	05/02/2019	https://www.build-on-prince.co
43	Recyclable resource	Basalt Fiber Tech	RQ3	Secondary	2010	06/02/2019	http://www.basaltft.com/prop/
44	Advanced Basalt Fibre	Kamenny Vek	RQ3	Primary	2017	04/02/2019	https://basfiber.com/
45	Ecological properties of continuous basalt fibre	Kamenny Vek	RQ3	Primary	2017	04/02/2019	https://basfiber.com/propertie
46	Mechanical properties	Kamenny Vek	RQ3	Primary	2017	04/02/2019	https://basfiber.com/propertie
47	Average freight energy intensity and activity in 2015	International Energy Agency	RQ1	Secondary	2017	18/04/2019	https://www.iea.org/newsroom
48	Composites Design and Manufacture: Thermoplastic Polymers	(Summerscales)	RQ3	Secondary	2018	11/02/2019	https://www.fose1.plymouth.a
49	Stora Enso opens Europe's largest wood fibre-based biocomposite plant	Stora Enso	RQ3	Primary	2018	15/03/2019	https://www.storaenso.com/ne
50	Oil Consumption	British Plastics Federation	RQ3	Secondary	2018	04/04/2019	https://www.bpf.co.uk/press/C
51	Carbon dioxide emissions intensity	Outokumpu	RQ1	Primary	2019	23/04/2019	https://www.outokumpu.com/
52	Styrofoam density	Aqua-Calc database	RQ1	Secondary	N.d	16/04/2019	https://www.aqua-calc.com/m
53	CO2 emissions for shipping of goods	Time for change	RQ1	Secondary	N.d	18/04/2019	https://timeforchange.org/co2-
54	Welding Calculator	Böhler Welding	RQ1	Secondary	N.d	23/04/2019	http://boehler-welding-service.
55	What is the proper way to calculate a welder's travel speed?	American Welding Society	RQ1	Secondary	N.d	24/04/2019	https://app.aws.org/itrends/an

Appendix 3. Interview questions (in Finnish)

Compatibility of FRP and Valmet's sustainability agenda (kuitulujitettujen muovituotteiden yhteensopivuus Valmetin kestävän kehityksen ohjelman kanssa)

- Onko Valmetilla erityistä määritelmää *sustainabilitylle* tai kestävälle kehitykselle *(sustainable development)*?
- Onko sustainabilityn eri puolia *(economical, social, environmental)* koskaan asetettu tärkeysjärjestykseen tai onko sellainen ylipäätään mielekästä?
- Yhdessä Valmetin kestävän kehityksen presentaatioista on mainittu pääasialliset määrälliset tavoitteet *(main quantitative metrics)*. Minkälaisia mittareita näiden lisäksi on? Voidaanko yksittäisille mittareille asettaa painokertoimia?
- Onko näitä tavoitteita sittemmin päivitetty?
- Minkälaisia laadullisia tavoitteita Valmetilla on määrällisten lisäksi?
- Minkälaisia ympäristökuormituksen mittareita [tässä opinnäytetyössä tehtävässä] elinkaarianalyysissä tulisi mielestäsi käyttää (esim. CO_2, veden ja energian kulutus ja kaatopaikkajätteen määrä)?
- Miten maailmanlaajuinen trendi muovikomposiittien (erityisesti hiilikuitukomposiitit) käytön raju lisääntyminen ja paine korvata metalliosia lujitemuovisilla Valmetilla sopivat yhteen yrityksen strategisen tason linjausten kanssa?
- Miten Valmetin kestävän kehityksen näkökulmaa voitaisiin mielestäsi parhaiten huomioida muovikomposiittien osalta?
- Millä tasolla Valmetin avainasiakkaiden kestävän kehityksen näkemyksiä ja toiveita hyödynnetään strategisessa päätöksenteossa tai kestävän kehityksen ohjelman linjauksissa?
- Miten tärkeässä osassa hyvä kestävän kehityksen imago on Valmetille?
- Minkälaisia näkökulmia haluaisit painotettavan työn johtopäätöksiä koskevassa osiossa?

FRP products at Valmet (lujitemuovituotteet Valmetilla)

- Mitkä ovat nähdäksesi tärkeimmät lujitemuoveilla saavutettavat edut Valmetin ympäristössä?
- Minkälaisilla prosesseilla aiempia lujitemuoviprojekteja on kartoitettu ja aloitettu?
- Ovatko tavat tai painopisteet, jolla uusia lujitemuoviprojekteja on kartoitettu, muuttuneet vuosien varrella (ja jos kyllä, miten)?
- Minkälaiset perusteet päätösten (materiaalin käytön oikeutus) taustalla ovat nähdäksesi painaneet eniten? Missä määrin kestävän kehityksen näkökulmaa on huomioitu päätöksenteossa?
- Miten näet lujitemuovia sisältävien komponenttien kehittymisen Valmetilla tulevaisuudessa? Miten kartoitettavat tuotteet, halutut ominaisuudet tai kokonainäkemys tulevat kehittymään?
- Miten tiukentuvat asiakasvaatimukset, ympäristösäädökset, poliittinen paine ja Valmetin sisäiset kestävän kehityksen tavoitteet vaikuttavat lujitemuovien käyttöön ja miten näitä asioita voitaisiin huomioida tulevaisuudessa entistä paremmin?
- Miten näet operatiivisen (paineet lisätä lujitemuovien käyttöä) ja strategisen (muovin käytön vähentäminen pitkällä aikavälillä) tasojen välisen ristiriidan? Mitä ristiriidan vähentämiseksi voisi tehdä?
- Resurssi- ja energiatehokkuuden on väitetty kulkevan Valmetin tuotteissa pitkälti käsi kädessä hyvän teknologisen tehokkuuden kanssa (haastattelu Saara Hämäläinen /

Valmet). Miten tämän väitteen toteutumista voisi parhaiten edistää lujitemuovien käytön osalta, eli miten varmistetaan että teknologinen suorituskyky vastaa pärjäämistä kestävän kehityksen mittareilla?

- Mitkä ovat mielestäsi tärkeimpiä lujitemuoveihin liittyviä toimenpiteitä, mitä Valmetin tuotekehityksessä voidaan tehdä kestävän kehityksen näkökulman parhaan mahdollisen toteutumisen mahdollistamiseksi?
- Entä minkälaisiin asioihin puuttuminen on nähdäksesi merkityksetöntä?

Enhancing sustainability of FRP polymers (kestävän kehityksen näkökulman parantaminen lujitemuoveissa käytettävien polymeerien valmistuksessa)

- Mitkä ovat merkittävimpiä hartsien valmistukseen ja käyttöön liittyviä ympäristö- ja työturvallisuusriskejä?
- Miten teillä minimoidaan edellä mainittuja riskejä? Mitä käytössä olevien toimenpiteiden lisäksi voisi tehdä?
- Minkälaisia näkemyksiä teillä on muovikomposiittien kierrättämisestä ja kierrätettävyydestä?
- Minkälaisia prosessijätteitä teillä tulee ja miten ne käsitellään? Käytetäänkö niitä / ovatko ne uudelleen käytettävissä talon sisällä?
- Sovelletaanko teillä / millä tavalla teillä sovelletaan kiertotalouteen *(circular economy)* liittyvää ajattelua?
- Minkälaisin argumentein perustelisit (kestävän kehityksen näkökulmasta) muovikomposiittien käytön laajentamista?
- Missä määrin / oletko osallistunut hartsiteollisuuden edustajana tällä hetkellä Suomessa käytävään keskusteluun orgaanisen jätteen kaatopaikkakiellosta ja miten se koskettaa komposiittivalmistajia? Onko nähdäksesi vastaavaa kehitystä ennakoitavissa laajemmassa mittakaavassa (esim. EU-tasolla tai Globaalisti)?
- Lähettämässäsi presentaatiossa mainitaan hartsien matalampi styreenipitoisuus sekä biopohjaiset ja kierrätetyt raakamateriaalit. Minkälaisia projektioita styreenipitoisuuden madaltumiseen hartseissa liittyy? Mitkä ovat olennaisimpia biopohjaisten ja kierrätettävien raakamateriaalien / hartsien yleistymiseen liittyviä huomioita? Minkälaiset materiaalit yleistyvät tulevaisuudessa? Minkälaisia muita näkökulmia muovikomposiittien ja ennen kaikkea niissä käytettävien hartsien tulevaisuuteen liittyy?
- Tuoreimmassa näkemässäni arviossa (BP Statistical Review of World Energy 2018) öljyvarojen ehtyminen ajoitetaan nykytahdilla vuoteen 2068. Mihin raaka-aineisiin teillä valmistettavat hartsit pohjautuvat ja minkälaisilla suhteilla, vai ovatko kaikki öljypohjaisia? Vaikuttaako / millä tavalla luonnonvarojen rajallisuus vaikuttaa hartsiteollisuuteen?
- Minkälaisiin hartseihin ja pinnoitteisiin muovikomposiittivalmistajien olisi mielestäsi hyvä panostaa, jos tavoitteena kestävän kehityksen näkökulman kehittäminen? (Lähetetty jälkikäteen sähköpostitse.)

Enhancing sustainability of FRP fibres (kestävän kehityksen näkökulman parantaminen lujitemuovikuitujen osalta)

- Miten teillä huomioidaan kestävään kehitykseen liittyviä tekijöitä (ympäristö-, työturvallisuus- ja taloudelliset näkökulmat omina kokonaisuuksinaan)?
- Minkälaisia ympäristöriskejä lasikuidun valmistukseen liittyy?
- Minkälaisia työturvallisuusriskejä lasikuidun valmistukseen liittyy?
- Miten näitä riskejä minimoidaan teillä? Mitä teillä käytössä olevien toimenpiteiden lisäksi voisi tehdä?
- Minkälaisia prosessijätteitä teillä tulee ja miten ne käsitellään? Käytetäänkö niitä / ovatko ne uudelleen käytettävissä talon sisällä?
- Minkälaisia näkemyksiä teillä on lasikuitujen ja lasikuidulla lujitettujen tuotteiden kierrättämisestä ja kierrätettävyydestä?
- Lujitemuovituotteissa erityisesti lasikuidun edullisuus tuntuu nousevan usein esille puhuttaessa sen kierrätyksen haastavuudesta ja esimerkiksi hiilikuidun kierrättäminen nähdään usein mielekkäämpänä. Miten näet hiilikuitujen ja lasikuitujen kierrätettävyyden ja niiden välisiä eroja? Miten lasikuitujen kierrätettävyyttä (ja kierrätyssuhdetta) voitaisiin mielestäsi parhaiten parantaa?
- Basalttikuitua mainostetaan usein kestävämpänä vaihtoehtona lasikuidulle. Miten koet tähän liittyvän keskustelun ja missä määrin olet törmännyt siihen?
- Missä määrin / oletko osallistunut lasikuituteollisuuden edustajana tällä hetkellä Suomessa käytävään keskusteluun orgaanisen jätteen kaatopaikkakiellosta ja siitä miten se koskettaa komposiittivalmistajia?
- Missä määrin teillä on kokemuksia muista muovikomposiiteissa käytettävistä lujitekuiduista ja miltä osin edellä keskustellut näkemykset ovat mielestäsi sovellettavissa niihin?

Lisäksi käsiteltiin seuraavia kysymyksiä, joita ei oltu lähetetty etukäteen

- Minkälaisia odotuksia teillä on lasikuidun käytön tulevaisuudesta? Mihin suuntaan lasikuituteollisuus on menossa?
- Minkälaisiin kuituihin ja näkökulmiin muovikomposiittivalmistajien (ja muovikomposiitteja ostavien yritysten kuten Valmet) olisi mielestäsi hyvä panostaa, jos tavoitteena kestävän kehityksen näkökulman kehittäminen?
- Missä määrin (jos ollenkaan) luonnonkuidut ovat mielestäsi sovellettavissa paperitehtaiden kaltaisissa kosteissa, kuumissa ja syövyttävissä ympäristöissä?

Enhancing sustainability of low-quantity CFRP manufacturing (kestävän kehityksen näkökulman parantaminen matalan volyymin hiilikuitulujitettujen muovien valmistuksessa)

- Miten kertamuovin ja kuidun yhdistelmästä tehtyjen komposiittien ympäristöystävällisyyttä voisi parantaa?
- Entä kestomuovikomposiitit? Onko teillä kestomuoveihin liittyvää valmistusta?
- Ovatko kestomuovikomposiitit ylipäätään järkevä materiaalivalinta päätyelementin kaltaisissa tuotteissa (tai kestomuovikomposiitteja ylipäätään onko niitä harkittu ylipäätään Valmetille tehtävissä projekteissa)? Jos kyllä, minkälaisia tuotannollisesti ja taloudellisesti järkeviä yhdistelmiä voisi harkita?
- Onko teillä kokemuksia luonnonkuitujen hyödyntämisestä? Ovatko ne nähdäksesi poissuljettuja paperi- ja kartonkikoneympäristöissä?

- Onko teillä kokemusta itseään vahvistavista polymeereistä *(self-reinforcing polymers)*, esimerkiksi polypropeenimatriisiin yhdistetyt polypropeenikuidut?
- Minkälaisia materiaalihukkaprosentteja teillä on ja minkälaisia keinoja materiaalihukan pienentämiseen hyödynnätte?
- Mihin hukkamateriaalit (kuidut, hartsit ja komposiittijäte omina kokonaisuuksinaan) teillä viedään?
- Onko 1.1.2016 voimaan tullut orgaanisen jätteen kaatopaikkakielto vaikuttanut toimintaanne? Onko mahdollisilla poikkeusluvilla ollut vaikutusta tähän?
- Minkälaisia työturvallisuusriskejä muovikomposiittien valmistukseen liittyy?
- Miten näihin riskeihin voidaan vaikuttaa valmistusmenetelmän valinnalla?
- Minkälaisin keinoin teillä pyritään minimoimaan työturvallisuusriskejä (esim. hartsihöyryt)? Onko muita toimenpiteitä lisäksi harkittu? Mitä muita toimenpiteitä voitaisiin toteuttaa?

Enhancing sustainability of low-quantity GFRP manufacturing (kestävän kehityksen näkökulman parantaminen matalan volyymin lasikuitulujitettujen muovien valmistuksessa)

- Minkälaisena koet lujitemuoviteollisuuden (Suomessa tai laajemmin) nykytilanteen tällä hetkellä? Esim. eri tuoteryhmien tai teollisuudenalojen korostuminen, ympäristökeskustelut, mikro- ja nanomuovit, lainsäädäntö ja työturvallisuusnäkökulmat.
- Missä määrin / oletko törmännyt muovikomposiittiteollisuudessa tällä hetkellä Suomessa ajankohtaiseen keskusteluun orgaanisen jätteen kaatopaikkakiellosta ja siitä, miten se koskettaa komposiittivalmistajia tai teitä erityisesti? Esim. venevalmistajien tuotantojätteiden kerääntyminen omalle tontille.
- Onko vastaavaa kehitystä mielestäsi tapahtunut tai ennakoitavissa laajemmassa mittakaavassa?
- Miten (lujite)muoviteollisuus on kehittynyt viimeisen 45 vuoden aikana ja minkälaiseen suuntaan lujitemuoviteollisuus tulee nähdäksesi jatkossa kehittymään Suomessa tai laajemmin tarkasteltuna?
- Missä määrin / ovatko asiakkaidenne asenteet tai vaatimukset ovat ympäristönäkökulmia kohtaan muuttuneet olennaisesti yrityshistorianne aikana? Minkälaiset kysymykset ja/tai asiakasvaatimukset ovat tällä hetkellä pinnalla?
- Mitkä ovat mielestäsi tärkeimpiä toimenpiteitä, joita lujitemuovituotteita ostava yritys voi tehdä varmistaakseen kestävän kehityksen näkökulman parhaan mahdollisen toteutumisen?
- Mitkä seikat, joihin tuotteita suunnittelevan ja valmistavan yrityksen ja valmistajan yrityksen näkökulmasta voitte vaikuttaa, ovat mielestäsi olennaisimpia? Entä minkälaiset näkökulmat ovat nähdäksesi kokonaisuuden kannalta merkityksettömiä?
- Missä määrin joudutte miettimään tuotteidenne loppusijoitusta esim. suunnittelun tai valmistuksen aikana?
- Miten kertamuovin ja kuidun yhdistelmästä tehtyjen komposiittien ympäristöystävällisyyttä voisi parantaa? Entä kestomuovikomposiittien osalta? (Onko teillä molempiin liittyvää valmistusta ja jos kyllä, miten kerta- ja kestomuovikomposiittien käyttökohteet teillä eroavat toisistaan?)
- Onko teillä kokemusta itseään vahvistavista polymeereistä *(self-reinforcing polymers)*, esimerkiksi polypropeenimatriisiin yhdistetyistä polypropeenikuidusta? Entä

luonnonkuitujen hyödyntämisestä tai bio-/ekokomposiiteista laajemminkin? Näetkö tämänkaltaisilla materiaaleilla tulevaisuutta teollisuusympäristöissä?
- Minkälaisia materiaalihukkaprosentteja teillä on ja minkälaisia keinoja materiaalihukan pienentämiseen voisi hyödyntää / hyödynnätte? Miten jätemateriaalit (kuidut, hartsit ja komposiittijäte) teillä käsitellään tällä hetkellä?
- Minkälaisia työturvallisuusriskejä muovikomposiittien valmistukseen liittyy? Minkälaisin keinoin näitä voidaan minimoida ja/tai minimoidaan teillä?
- Missä määrin kertamuovihartsit (epoksit, vinyyliesterit, polyesterit) eroavat toisistaan työturvallisuusmielessä? Mitkä ovat merkittävimmät hartsikohtaiset riskit?
- Lasikuituteollisuus on väitetysti hiilikuituteollisuutta ekologisesti haastavampaa ainakin hukkamateriaalin ja kierrätettävyyden näkökulmasta. Missä määrin olet samaa mieltä väitteen kanssa? Näkyykö väitetty haastavuus jotenkin yrityksenne toiminnassa?
- Missä määrin lujitemuoveihin ja muovikomposiitteihin liittyvää keskustelua ja johtopäätöksiä voidaan soveltaa muihin teollisuuskäytössä oleviin muoveihin? (Missä määrin koet lujitemuoveja käsittelevän opinnäytetyön johtopäätösten olevan yleistettävissä muoveihin?)

Enhancing sustainability of high-quantity FRP manufacturing (kestävän kehityksen näkökulman parantaminen suuren volyymin kuitulujitettujen muovien valmistuksessa)

- Miten valmistuksenne jakautuu a) valmistustekniikkojen b) hartsien c) kuitujen ja d) käyttökohteiden välillä? Esim. mitä kaikkea käytössä, karkeasti osuuksia tuotannosta.
- Mitkä ovat tärkeimmät tekijät, mitä lujitemuoveja teettävä yritys Valmetin kaltainen yritys voi tehdä varmistaakseen kestävään kehitykseen liittyvien näkökulmien (taloudelliset, sosiaaliset ja ekologiset) toteutumisen?
- Entä mitkä asiat ovat merkityksettömimpiä?
- Missä määrin muovikomposiittivalmistaja voi vaikuttaa oman tuotantonsa ekologiseen kestävyyteen? Minkälaisia toimenpiteitä teette itse ja mitä näiden lisäksi voisi tehdä?
- Minkälaisia keinoja materiaalihukan pienentämiseen käytätte?
- Miten hukkamateriaalit (kuidut, hartsit, komposiittijäte) käsitellään teillä? Missä määrin olette pyrkineet kierrättämään materiaaleja sisäisesti?
- Minkälaisia työturvallisuusriskejä muovikomposiittien valmistukseen liittyy? Miten työturvallisuusriskejä minimoidaan teillä?
- Missä määrin eri kertamuovihartsien työturvallisuusriskit eroavat toisistaan? Minkälaiset materiaalit ovat kaikkein ongelmallisimpia?
- Missä määrin eri kuitujen kierrätys kesto- ja/tai kertamuovikomposiiteista on teille tuttua? Minkälaisia näkökulmia niihin liittyy tällä hetkellä tai miten näette niiden kehittyvän tulevaisuudessa?
- Missä määrin ekokomposiitit (luonnonkuidut, biomuovit ja ekokomposiittituotteet) ovat teille tuttuja ja missä määrin niiden käyttö on nähdäksesi relevanttia raskaan teollisuuden sovelluksissa nyt ja tulevaisuudessa?
- Minkälaisena koet lujitemuoviteollisuuden (Suomessa tai laajemmin) nykytilanteen tällä hetkellä? Minkälaiset näkökohdat lujitemuoveissa ovat pinnalla tällä hetkellä? Entä vastaisuudessa? Esim. eri tuoteryhmien tai teollisuudenalojen korostuminen, ympäristökeskustelut, mikro- ja nanomuovit, lainsäädäntö, työturvallisuusnäkökulmat.
- Missä määrin joudutte miettimään tuotteidenne loppusijoitusta esim. suunnittelu- tai valmistusvaiheessa?

Waste management of FRP (lujitemuovien jätteenkäsittely)

- Minkälaisella prosessilla lujitemuovijätettä kerätään/lajitellaan/esikäsitellään/kierrätetään/loppusijoitetaan teillä?
- Miten teillä mitataan polttoprosessin tehokkuutta (esim. hiilidioksidipäästöt, energiankulutus, energian talteenotto) ja miten sitä voisi kehittää? Minkälaisia keinoja on käytössä jo nyt?
- Minkälaista jäännöksiä polttoprosessista jää ja mitä jäännöksille tehdään (mikäli sellaista syntyy)?
- Missä määrin orgaanisen jätteen kaatopaikkakielto on vaikuttanut toimintaanne lujitemuovien osalta? Onko teillä ollut erityisiä keskusteluja lujitemuoviteollisuuden kanssa, esim. venevalmistajien komposiittijätteen kerääntyminen omalle tontille? Missä määrin poikkeuslupajärjestelyt vaikuttavat edelleen kokonaisuuteen? Onko vastaavaa kehitystä mielestäsi tapahtunut tai ennakoitavissa laajemmassa mittakaavassa?
- Miten näet muovikomposiittien kierrätyksen kehittymisen tulevaisuudessa Suomen mittakaavassa tai toisaalta EU-tasolla / maailmalla?
- Missä määrin olet perehtynyt lujitemuovien kierrätykseen (kuitujen tai energian talteenotto) ja erilaisiin siihen liittyviin menetelmiin?
- Liittyykö lujitemuovien keräämiseen, lajitteluun ja kierrättämiseen erityisiä työturvallisuusriskejä? Onko näissä/minkälaisia eroja näet alueellisesti ja eri mittakaavassa tarkasteltuna (Suomi-EU-maailma)?
- Mitkä ovat jätteenkäsittely-yhtiön näkökulmasta tärkeimpiä toimenpiteitä, joita lujitemuoviosia tuotteissaan hyödyntävä Valmetin kaltainen yritys voi tehdä varmistaakseen kestävän kehityksen parhaan mahdollisen toteutumisen?
- Entä minkälaiset seikat ovat jätteenkäsittely-yhtiön näkökulmasta kokonaisuuden kannalta merkityksettömiä?

Appendix 4. Key takeaways from the interviews in thematical order

Compatibility of FRP and Valmet's sustainability agenda

Saara Hämäläinen | Sustainability Specialist | Valmet | 65 min

- Saara is part of Valmet's sustainability team, working on a corporate-level supporting Business Lines/Areas with solid backup from other functions such as like product development, HSE, sales and legal. Bits of information has been excluded from this public summary and mentioned only in chapter 5.1 for confidentiality reasons.
- Valmet doesn't have a context-specific definition for sustainability or sustainable development, but sustainability is largely viewed through Valmet's sustainability 360° agenda and it's five focus areas (sustainable supply chain; HSE; people and performance; sustainable solutions; corporate citizenship). The triple bottom line of business sustainability should also be considered.
- Neither aspects of business sustainability, focus areas in the 360° agenda or individual key performance indicators cannot be put in an order of priority or weighted. Each of them has their own, set goals that have responsible individuals or teams addressing, monitoring and updating them regularly. The sustainability team and relevant support functions and business line/area representatives work out in close cooperation to carry out predetermined action plans.
- In addition to the main quantitative metric of Valmet, there are also qualitative metrics but their details could not be disclosed for this work as the internal communication on the action plans and relevant metrics were still under work.
- CO_2, consumption of water and energy and amount of waste to landfill seem a reasonable set of impact metrics and are well-aligned with Valmet's sustainability agenda.
- The question of whether FRPs (from a sustainability point of view) should be utilized or not is a complex one and hard to answer without a deep knowledge Valmet's product portfolio and reasoning behind choosing FRP as the material in each of the cases. It comes mainly down to considering the total sustainability impacts of the product life cycle: does the material choice contribute to net positive impacts or not. A good balance in the bigger picture should be pursued after instead of making decisions based on a narrow set of criteria. Trade-offs like achieving higher product safety or saves in energy consumption during the use can and should be considered in the use of FRPs.
- Key customers' perceptions are surveyed frequently and accounted for with a great care. Some of them have a strong emphasis on reduction of use of plastics in their value chain. This has a direct impact to Valmet's own stance towards the use of such materials and underlines the importance of having discussions and informed decision-making around it.
- Sustainability-driven decision-making is heavily emphasized by Valmet's mission (Converting (converting renewable resources into sustainable results): particularly enabling its customers in producing sustainable solutions.
- RobecoSAMs methodology in their sustainability evaluations for Dow Jones Sustainability Indices has changed since 2017. This affects Valmet's scoring of 2018, as the ratio of companies Valmet outperforms has stayed virtually the same between these years.
- As a rule of thumb, resource- and energy efficiency have been noted to have a strong correlation with good technological performance. This has been observed explicitly in previous studies of Valmet's products and has been identified as one of the spearheads in development of the product portfolio. Thus, sustainability performance and technical performance should be looked upon as complementary aspects, not mutually exclusive ones.

FRP products at Valmet

Samppa Salminen | Senior Manager, Development | Valmet | 50 min

- Samppa is a Senior Manager in R&D, having a vast knowledge about FRP projects at Valmet in general while having been active in Composite Sauna sessions since its first instalment. Bits of information has been excluded from this public summary and mentioned only in chapter 5.2 for confidentiality reasons.
- Most important justifications for utilizing FRP include better ease of handling and usability gained through lightweight structures in addition to cost-efficiency.
- Other considerations are good corrosion resistance of certain plastics, space saving, easy optimization of shape and constraining the weight below 25 kg and 50 kg thresholds. These are the weights that one (25 kg) and two (50kg) persons are allowed carrying without special lifting equipment. In certain application like fabric change poles this is essential, as reaching a weight below 25 kg has not been possible in machines with web width above 7 meters.
- In some cases, steel is simply not enough for example because of its weight, shapes needed or quality aspects. In the case of the latter, quality issues on the steel version of the walkway end element have simply been too frequent, resulting in remaking some of the elements 2-3 times (including their shipping to the other side of the world). This is not only extremely costly, but also puts serious burden on the environment. With FRP version of the end element, it is possible to make a high-quality piece every time, outweighing possible concerns such as recyclability of the material. The FRP version can be also seen as a last-ditch effort to provide an all-around sufficient solution with good visual impression and reasonable costs.
- There has not been systematic work, agenda or targets involved in finding new FRP applications. New ideas come mostly from a very specific need when new products are being developed The emphasis is clearly in how to develop the most efficient product possible and as a result, the best technologies and materials how to achieve it come in to discussion organically; higher usage of plastics is not also something actively strived towards but use of FRP sometimes simply turns out to be the most potent solution technologically. Composite Sauna sessions have obviously promoted finding the most efficient applications for FRPs, but they don’t have a special role in how new projects are being planned.
- Essentially, (environmental) sustainability hasn’t had a role in discussions regarding FRP usage. In practice, only a single individual at R&D has been vocal on the topic by constantly reminding about its importance and bringing up viewpoints from that angle. For example, the development of the end element has been postponed due to suspicions on how they fit into Valmet’s sustainability practices.
- The biggest proposed push towards higher usage of FRPs in memory was in early 2010. The proposition was declined back then and has not been studied ever since but has probably remained to most pivotal point to date in discussions whether FRPs should be utilized more or not.
- Ensuring good recyclability seems one of the more important aspects in more sustainable development of new FRP applications.

Enhancing sustainability of FRP polymers

Tuula Mannermaa | Technology Manager| Ashland Performance Materials | 45 min

Lassi Keskinen | Application Engineer | Ashland Performance Materials | 81 min

Resins in general

- Ashland is a producer of thermoset resins and gelcoats that are used mainly in GFRP. Total length of the interview was 81 minutes, of which Tuula was present for the first 45 minutes.
- Thermosets (especially their Finnish term *kertamuovit*, "one-time use plastics") have an unreasonably bad reputation. The more the discussion is shifted from narrow focus areas to life cycle thinking and LCA, the more sustainable materials thermoset plastic composites become.
- Ashland produces almost exclusively unsaturated polyester resins that are thermosets, that are formed from crosslinked polymer chains of styrene and polyester which cannot be separated without chemical means. They form a 3-dimensional "mesh" which keeps it form, even if some of the links would break. In 99 % of cases by volume, their products are oil based. When it comes to finite planetary resources, Ashland is only a minor consumer of styrene and glycols, meaning they (or plastics composite industry to an extent) are not a driving force in consumption of non-renewable resources.
- Ashland produces resins, but not hardeners or fibres used in manufacturing FRPs; their distributors handle selling all the three components to FRP manufacturers. Thermosetting polyester resin and its' hardener are always a predetermined combination, tailored according to the desired properties.
- Polyesters can be used also in saturated form, in which case they are thermoplastics that consist of high amounts of non-crosslinked polymer chains that are able to move relative to each other. Individual chains are easy to remove from their surroundings by heat. Thermoplastics are not included in field of expertise of Ashland.
- Epoxy resins (not produced by Ashland) have problem areas very different from polyester resins, originating from their composition and hardener-to-resin -ration, among other things. The amount of hardener in epoxy resin is typically around 30-50%, where as in polyester resins stays between 1-3%. Out of the two thermosets (polyester and epoxy), polyester is more widely used.
- Ashland has only limited experiences of biomaterials with a 20% bio-based product being introduced in 2011. No breakthrough was achieved with it, with the market being seemingly not ready for such a product. Interest towards biomaterials has been on a constant rise, but the customers are not ready to pay extra for them (the situation might change though, as environmental consciousness has been on a rapid rise lately). Additional problems in biomaterials are caused by their restricted availability and their seasonal variation, which is hard to eliminate or adapt to in product design and development particularly. An LCA regarding carbon footprint of the biomaterial discussed was made with similar results as with non-biomaterials, meaning it didn't hold an advantage over them in terms of its environmental performance. However, it had to be brought from a long distance for the production due to availability reasons; an aspect that has probably got better since.
- Natural fibres like wood aren't compatible with resins of Ashland due to their moisture-absorbing properties.
- Materials most typically being replaced by FRPs are metals. Previous LCAs [made, commissioned and/or studied] are consistent that plastic composites produce less environmental stress than similar products made from metal. This is true even in cases where the plastic products have no bio content but are 100% fossil based instead.

- The primary source of micro- and nanoplastics is the thermoplastic industry (polyethylene and polypropylene particularly). Thermosets were seen to be, by definition, not a problem in this regard, which is further fortified by the notion that Ashland (and thermoset plastic composite industry to an extent) serves its customers on a B2B basis, whereas lots of thermoplastics end up at the hands of individual consumers; industrial waste is being handled and monitored more effectively than municipal, resulting into more effective proper disposal of it.
- The process of producing thermosetting resins is a very typical one for chemical industry. It is a well-controlled, closed-loop process with no environmentally hazardous by-products (only distilled water and glycols) or risks related to occupational health and safety. A high worker safety is achieved by good level of automation, virtually eliminating all exposure to chemicals. Recorded accidents are slips, trips and similar accidents that are not directly related to the chemicals.
- The biggest perceived risks regarding environmental or social aspects emerge during the manufacture of the plastic composites. Some of the most effective means for enhancing worker safety include proper training, selection of manufacturing methods, utilizing well-ventilated booths and including good personal protection when needed.
- Organic peroxides used as hardeners in unsaturated polyester resins is by far the biggest safety hazard of the polyester industry. Careful caution to its purity and allowed storage times and temperatures needs to be exercised, as just small impurities (collecting dust particularly) or exceeding the set maximum time of storage can cause pressure explosions and/or fires. This is, though, somewhat outside the scope of Ashland since they don’t produce hardeners (but offer safety trainings and technical services on the topic instead).
- There are lots of different types of peroxides and typically they form 1-3% of the content in the polymer, depending on the desired curing properties like the time required. The reasons peroxides are used is that the resin contain accelerators that break the peroxides to free radicals. The free radicals subsequently enable the double bonds of polyester and styrene chains to open and form interlinking connections between each other. If the resin doesn’t contain accelerators, adding peroxide to the resin doesn’t harden it unless heat is used. In such cases, merely heating up the mix of peroxide and resin cause the polymer to harden. Peroxides are not used in epoxy resins, as their chemistry differ substantially from unsaturated polyester resins.
- As purely for resins, styrene (considered volatile organic content, VOC) is the principal HSE risk of the industry. It is used widely due to its good properties/price and it fulfills two functions. First, it keeps the polyester resin in a liquid state when dissolved to it. Without the styrene – the most used monomer for fulfilling this function – the polyester resin would remain solid at a room temperature. For the second, styrene produces a chemical reaction that makes the polymer form a “3D structure”. The optimal case is that all the styrene remains in the polymer matrix without evaporating (the root reason of its HSE problems) from it.
- Reducing styrene content of the products is an ongoing endeavor at Ashland. In practice, substitutive substances are hard to come by as styrene is widely utilized for a good reason. In addition to the economic reasons, it has good chemical properties like allowing fast reactions and effective lowering of the viscosity of the used resin. The styrene content of a resin used in FRPs is typically around 40%, but the newest products of Ashland already approach values around 15-20%, whereas 10% might be a target in the future.
- Producing 0 % styrene content resins is possible, which is the case in some of the products the competitors of Ashland are providing. Yet, they seem niche products with high price points and low volumes as for now. The preferred angle of approach at Ashland has been to gradually lower the styrene amount of their standard products, rather

than developing 0-content ones. This has been perceived to be a more effective route in achieving grander scale of positive HSE impacts.

- Styrene is a major talking point also due to its long-time use and extensive studying of the associated health and safety risks. Should a broadly applicable substitute for styrene be found and scrutinized to a similar extent, it may well be that it would accumulate parallel amounts of restrictions.
- Means to lower styrene content include meddling with the polyester molecules or including more of alternative monomers into the mix. This applies also to gelcoats (pigmented, hard polyester resins) that are used as the surface layer of a composite laminate alike paint, only with around 10 times thicker layers.
- Means to lower styrene hazards include utilizing paraffin coatings to reduce evaporation of styrene during the manufacture of FRPs – as keeping the styrene inside the polymer matrix is desired, this is not only a health and safety -benefit but improves the technical performance in addition.
- Legislative restrictions (e.g. on allowed amounts of styrene vapors) are getting stricter all the time, resulting into higher use of certain manufacturing methods like the ones utilizing vacuum technologies, where there is no significant amount of styrene evaporation (in contrast to wet lay-up and pultrusion in some cases where high amounts of styrene vapor are present).

Disposal

- From the Ashland point of view, the volume and steadiness of the waste stream is so low that there are no relevant possibilities for collecting composite waste for recycle/recovery from the end users. Incineration with energy recovery was seen the most prominent method for recovery and disposal as for now.
- As for recycling methods, the cement kiln route (using the matrix to produce heat energy and returning the glass fibres to their mineral form to be used as additives in the cement) was seen the most prominent one for GFRP. Recycling of glass fibres while maintaining their fibrous form wasn’t seen viable, as it is simply not economic enough. The same logic was perceived to apply in chemical recycling of thermosets: it is possible, but too energy intensive.
- The price of carbon fibres is estimated drop considerably faster than with other materials of plastic composites with its prices estimated to be halved or even more in the future. Lots of this projection was addressed due to less energy-intensive methods being developed: Production of carbon fibres has been expensive in the past due to high energy inputs required, whereas its’ raw material is cheap. With new methods with significantly lower energy inputs being researched and introduced, the price of carbon fibres can be expected to come down alongside them. Another big factor perceived was current optimistic views on various recycling processes of carbon fibres.
- The good progress in recycling of carbon fibres was traced back to their intrinsic value and well-maintainable properties as recyclate. The combination of high-enough volumes and economic incentives for recycling might create positive, self-reinforcing loop at best: higher amounts of waste CFRP leads into better economic incentives for its recycling (including higher recycling ratios); which leads into cheaper recycling costs; which leads into cheaper (recycled) raw materials costs; which leads into broader usage of carbon fibres; which leads to higher amounts of CFRP being used; which leads to higher amounts of waste CFRP, completing the cycle.
- Keskinen was familiar with the idea of all-plastic composites, especially ones made from polyethylene fibres (UHMWPE). The volumes are insignificant to his understanding. Polyethylene is hard material to utilize as reinforcing fibres due to its low surface energy causing it hard to wet. The “1+1=3” nature of composites is due to the matrix material wetting the fibres well and passing the external forces for the fibres to carry.

If the matrix doesn’t wet the fibres, mechanical properties will stay modest. When UHMWPE fibres are combined with polyethylene matrix, good wetting and recyclability is achieved, but the composite doesn’t withstand heat well, with a melting point of not much above 100 °C. Nevertheless, it should have good applications.

Enhancing sustainability of FRP fibres

Minna Peltola | Lean and Quality Manager | Ahlstrom-Munksjö Glassfibre | 51 min

- Ahlstrom-Munksjö is a leading manufacturer of glassfibre products used in flooring, building and transportation. Minna works as a Lean and Quality Manager in their Karhula unit (2019-), with previous working experience as development engineer in Mikkeli plant (2007-2011) and as QHSE Manager (Quality, Health, Safety and Environment; 2011-2019) in Karhula plant.
- The company uses mostly E-glass fibres, but also E-CR (Electrical/Chemical Resistance) and high modulus glass fibres are utilized. There has been production of glass fibres in the past, but it has been outsourced since 2011.
- Before 2011, LCA studies and monitoring and lowering emissions were a current topic amongst producers of glass fibre across the board. HSE aspects have a firm focus in the Karhula factory, with the corporation level target of zero injuries, minimizing of the water consumption and considerable investments being made for heat recovery processes being some examples. Risk assessments are being made regularly, including audits and internal benchmarking between different sites of the company.
- Karhula produces glass fibre nonwovens that are used mostly within construction industry like in flooring or wall liners. A portion of the product is utilized in composite laminates.
- The process of producing nonwovens is a very similar one to paper-making. It is a wet process where discontinuous fibres are spread across the web width, after which an organic matrix is applied. The organic content in them is typically 20-25% with the rest being fibres.
- There aren’t particularly severe HSE risks associated with the glassfibre industry. Air filters aren’t generally needed, but they’re being used in particularly dusty tasks like working with micro-glass (with fibre diameter being typically 3-6 µm) that is small enough to enter human respiratory system. Most glass fibres are typically 15-18 µm in diameter, well over the safe limit in this regard. When Minna was associated with raw material production in Mikkeli where there was lots of mechanical handling of glass fibres that cause the material to snap easily, lots of dust was present. This was minimized by increasing the air humidity in production. In general, HSE risks associated with production of fibres and fibrous products in FRP seem orders of magnitude smaller than the ones regarding FRP polymers.
- Recycling of glass fibres and nonwovens being produced in Karhula is a tricky and technically challenging task and only a few companies can handle glass fibre -based waste, even on a global scale. One of the bigger problems is the relatively low organic content of the product, disallowing it to be used effectively as a fuel since there is not more of it. This leaves out the cement kiln route and similar enterprises. On the other hand, it cannot be landfilled either [in Finland] since the amount of organic content is too high.
- Ahlstrom-Munksjö has an ongoing project that aims for efficient recycling of the Karhula-produced nonwovens inhouse by removing the organic content from its fibres. Information regarding this is disclosed as of now, as the development process is still ongoing.
- Basalt fibre was considered as a new material in the company in the early 2000s but its tryouts were ceased early, because quality of the raw material (caused by its natural origin) was too inconsistent to go on with the development.

- Natural fibres weren't seen as a sustainable option. Their seasonal variance, physical properties and even carbon footprint seem just not to be up to par with the more traditional fibres. It is hard to imagine natural fibres where stable quality, good availability and better environmental performance would all actualize. A better solution in reducing environmental stress of the fibre industry was perceived to be development of recycling methods and infrastructure and decreasing impacts of manufacturing processes of fibres.

Enhancing sustainability of low-quantity CFRP manufacturing

Jani Korpimäki | Vice President | Composite Solutions & Innovations | 32 min

- Jani works as head of design at CSI.
- Enhancing sustainability of FRP production is a complex topic, as seemingly unsustainable products such as glass fibre thermosets may put less stress on the environment than biocomposites, due to better properties resulting into longer life cycles.
- Categorizing is important when estimating total loads. Means to enhance sustainability should be studied within each product/application category instead of comparing them over different categories. Even though thermosets are conceptually harder to recycle, they're are typically products of longer life cycles. This is particularly true in industrial and marine applications, but also products of shorter life cycles such as ski poles exist in thermosets.
- Biggest problems seem to be in GFRP, where the materials are cheap; there are no economic incentives for material optimization which may be more expensive than not optimizing for material but for working time instead. This is easier in CFRP production, since the fibres are substantially more expensive, so economic aspects force in saving of the material and reusing the cut out -waste for products such as thick sheets of CFRP-laminate.
- CSI uses mainly carbon fibres, so economic use of them comes naturally due to the high price. This means fibre waste in their production is almost non-existent. Resins are collected by Lassila & Tikanoja. Composite waste is taken care of through normal waste management routes without special sorting at the site of manufacture.
- Sparing use of material is at the core of the recycling of FRP. Using computer-aided methods in making of the cut out -geometry, nesting and cutting them can reduce the waste of fibre fabrics all the way down to 10 – 20 % when the requirements for alignment of the layers are not strict and each of the layers don't have to be one piece. When the requirements are stricter and/or only manual methods are used, the amount of waste can go as high as 50 %.
- Promising research of composite waste recycling is done, but the economic reality is harsh. At least in Finland, the stream of waste is still too low and uneven for a dedicated processing plant to be established (or seen profitable enough for start planning one). For example, study of establishing a cement kiln route in Finland (Blom & Dufva 2016) was discontinued, evidently due to economic reasons.
- Another problem in dedicated processing plants is caused by the counterproductivity of long-distance transportation for energy recovery; should a dedicated plant in Finland exist, how much longer transportation distances are still justified instead of taking them to a nearby landfill (or processing plant for incineration)?
- Problems in recycling are further caused by the lightweight nature of plastic composites: they're lightweight and take up a lot of space, so their transportation is not efficient.

- The best way to ensure sustainable production seems to be minimizing the amount of waste fibres and composites, along with processing the generated waste at the location of manufacture. The latter would solve a lot of the issues regarding the recycling: when they're being processed to take up less space (like grounding composite waste or waste fibre fabrics), their transportation and further processing becomes a lot easier.
- Recycling of composite waste is a major talking point currently within the industry in Finland and – even though the volumes in Finland aren't still relatively low – there are great of concerns of how to handle the issue in a sustainable manner.
- During the past 6 – 12 months, several waste processing sites have ceased to accept composite waste altogether. This is very likely due to the 1.1.2016 landfill-prohibition of organic waste, so it seems like companies in the industry do not yet know how to solve the problem.
- Some sites not accepting composite waste has resulted to tons of waste sitting currently at properties of FRP manufacturers, marine manufacturers particularly. This issue needs to and will most likely be resolved in a very near future due to its urgency.
- It seems very likely that problems with low recycle rates, especially with GFRP waste, will be solved by employing more strict regulations and waste fees that will force the companies to act on a more sustainable manner (contrary of the industry regulating itself).
- Jani has no personal experience from industrial applications of self-reinforcing polymers but had heard about the concept of thermoplastic fibres.
- Challenges in health and safety of the workers in CSI are addressed mainly by chosen methods of manufacturing. For example, using pressure bag -based methods instead of wet lay-up exposes the workers considerably less.
- CSI produces thermosets almost exclusively, so questions regarding thermoplastics were mostly dismissed. In general, the problem in using of thermoplastic composites instead of thermosets seems to be the presence of the fibres. Even if thermoplastics (of which production is harder and more energy-consuming due to higher temperatures) would be used more commonly, the very same challenges of separating them from the matrix as with thermosets still exist. In practice, it doesn't seem viable.

Enhancing sustainability of low-quantity GFRP manufacturing

Esa Hiltunen | CEO | Muovityö Hiltunen | 56 min

Specific to Muovityö Hiltunen

- Esa has a long history in the plastics industry, with formal education as an automation technician. A 2nd generation entrepreneur, Esa has been working at Muovityö Hiltunen since his studies and as a CEO since 2001. Bits of information has been excluded from this public summary and mentioned only in chapter 5.2 for confidentiality reasons.
- Muovityö Hiltunen makes mostly single unit and low-quantity batches out of fibre-reinforced thermosets that constitute roughly 70 % of the production while the rest 30 % comes from non-reinforced thermoplastic products that are also smaller in size. Glass fibres are used virtually exclusively ("99 %"), while small portions of carbon fibre are sometimes added to enhance electrical conductivity. A similar ratio of used thermoset resins apply: almost everything is done with vinylester while a marginal amount of epoxy is used as adhesives and in CFRP production.

- Thermoplastics are utilized in smaller products since their welding is possible and they are more malleable than thermosets. This enables cost competitive single unit -production as they can be constructed much like sheet metals. If thermosets would be used instead, costs would be much higher as everything would need to be moulded. When going to a bigger scale, fibre-reinforced thermosets are used instead to ensure good enough load-carrying capacities. Sandwich-structured combinations of the two are also produced occasionally, with the skins being made from FRP laminates whereas the core is thermoplastic. A very rough approximation of annual production is around 100 tons.
- Production of Muovityö Hiltunen is done exclusively on demand with no stock products being made. Most of the orders are made to corrosive industrial environments with good chemical resistance being the primary justification for choosing plastics. This is typically done after stainless steel has proven to be simply just not enough. Smaller segments of their customers come from the energy sector (due to electrical insulation properties of plastics) and for laboratory and smaller process equipment. Typical products include various tanks (e.g. for caustic soda and acids, hydrochloric acid particularly) and pressure vessels, chimneys, pipework and flue gas scrubber parts. Sometimes the company is contacted because a product made from a corrosive resistant grade of stainless steel has been made, corroded useless and needs to be replaced.
- Whereas sustainability is a major talking point at the plastic composite industry, these topics are much more absent when only the relatively narrow sector of FRPs where Muovityö Hiltunen operates in is accounted. The products being made have long life cycles while being one-time bespoke orders, so customers are typically not coming forth with specific demands for sustainability.
- The plastic composites industry has evolved a lot during the past 45 years the company has been on the business. Environmental aspects have come in to discussions while they weren’t talked about at all in the past. Material losses are considered much more carefully, especially in products that need good chemical resistance as raw materials for them are more valuable. Designing and manufacturing – including more careful selection of manufacturing methods – have also a lot more emphasis to further reduce material waste being produced. Customer expectations have changed the most in the field of logistics, where more focus has been put on end-of-life treatment; when considering a typical client of heavy industries, sustainability isn’t brought up at all even nowadays. End-of-life treatment of their products hasn’t been a major talking point either.
- All of production waste at Muovityö Hiltunen is handled by L&T and go to incineration. Energy waste and mixed waste is collected separately.
- Prohibition of landfilling of organic waste has not had effect on operations at Muovityö Hiltunen. It was noted that there are problems in certain municipalities in this regard.

Occupational health and safety

- Styrene in vinylester resins is the biggest perceived safety risk in the manufacture and is a driving aspect in the occupational health and safety planning. Employees that do laminating are bio-monitored regularly by the occupational health care workers to identify possible exposures as early as possible. This has been on the check for a very long time already with no known exposures being found.
- Thermoset hardeners [peroxides], while being more hazardous substances than thermoset resins, were not considered nearly as big of a worker safety risk as styrene included in vinylester and polyester resins. The fact that hardeners are mixed in to the resins before applying them in to the product, instead of spraying them separately like in some applications, plays a part in this.

- Styrene free resins as a safer alternative seem relevant, especially in the close future and in less-demanding applications.
- Styrene fumes are being monitored particularly carefully when using pigmented resins [gelcoats]. Evaporating of styrene is prevented by utilizing special coatings (*kalvo*).
- Epoxy resins, while being styrene-free, are somewhat problematic as being strongly allergenic. As epoxy resins don't have a strong distinctive smell like other styrene-including thermosets, worker safety is not handled properly a lot of times. As the smell of styrene is already evident way below limits set for safe exposure, it is easy to remember using proper safety equipment and well-ventilated areas.
- Other safety hazards include dust generated by mechanical processing of plastics (cutting and sanding of bevels particularly). When the production is based on low quantities, dust is bound to be generated as majority of used manufacturing methods are labour heavy and put emphasis on hand-held tools and manual grinding. Catching all the dust at its source would be optimal and is strived after but is not always possible. Use of personal protection is advocated, particularly when working inside tanks.

Recycling

- Sustainability of FRPs has clearly surfaced as a theme in the recent years. Recycling, both in Finland and over Europe, has been a particularly active talking point with aviation and automotive industries seeming to be the drivers mostly initiating these discussions. Legislation is clearly a part of this, with the demands for high recycling ratios in the automotive industry being a noteworthy example.
- Recycling of glass fibres and GFRP waste is a tricky topic, as it seems good business for nobody. Recycling of carbon fibres is clearly a more prominent topic due to their much higher price point than that of glass fibres. Esa noted that he has followed how recycling of FRPs has progressed but is no expert on the topic.
- Recycling of thermoplastics as industrial waste as rather straightforward (compared to, for example, domestic thermoplastic waste): the waste being generated is pure and fully comparable to virgin material with the waste constituting mostly from heavy blocks that have lots of material by weight. Therefore, unlike in, for example, domestic waste, it is easy to collect larger quantities of it.

General

- There was a clear hype surrounding FRPs in the past a – particularly in the consumer business – all sorts of things were in the talks of getting replaced by FRPs. In practice, the hype was short-lived as FRPs turned out to be too expensive for most applications as they stuck around mostly as materials for more expensive applications with longer life cycles.
- Some of the more important means a manufacturer FRP products can do to improve sustainability of their products include ensuring long life cycles, understanding emissions and calculating product carbon footprints and favouring raw materials that are produced nearby to fight environmental stress in the logistics.
- Usage of (too) high safety factors in conservative standards pose a clear barrier for economic and environmental design and manufacturing. As they are not something enforced by law, just ceasing to use too high safety factors altogether would constitute a significant improvement in material and energy consumption. Safety standards also come out somewhat absurd at times: where as a stationary [pressure]container in a fully stabile, unchallenging industrial environment is done with a safety factor of 8, transport container of a heavy truck travelling 80 km/h all year-round, winter or summer, needs only a safety factor of 4. Present-day engineering methods such as FEM analysis make it possible for optimization going far beyond standard safety factors.

- A way around this would be to prove the durability of the structures built with lower safety factors by testing but this would come out a lot more expensive in low-quantity manufacturing than just coping with the standard requirements.
- Non-reinforced thermoplastics are ultimately very similar materials to fibre-reinforced thermosets [apart from their recycling], so conclusions made by studying sustainability of the latter should be largely applicable with the former.
- [Life cycle thinking is clearly an important topic in transport due to most energy being consumed at the use stage – maybe this is an indicator that it is an industry where other stages of PLC are considered more carefully in addition?]

Enhancing sustainability of high-quantity FRP manufacturing (kestävän kehityksen näkökulman parantaminen suuren volyymin kuitulujitettujen muovien valmistuksessa)

Jani Sippola | Research manager | Exel Composites | 55 min

- Jani works as Research Manager / Senior Chemist at Exel Composites. Jani's department does research and trials on new materials and chemical safety and provides support for production, sales and customer services. On the latest Exel Composites Annual Financial Report (2018), Exel had a 96,6 M€ revenue, out of which 40 % came from industrial applications and 37 % from construction. This is a clear shift from industrial to construction applications when compared to the previous year.
- Almost all production at Exel is made by pultrusion (~97 %) with the rest being done by continuous lamination. Used resins include unsaturated polyester (~80 %), vinylester (~10 %) and epoxy (~10 %) with minor amounts of polyurethane used in addition. Whereas most of the products are made from glass fibres, it is very typical for clients to be initially interested in carbon fibres due to their good public image as high-performance materials. Minor amounts of aramid and special types of glass fibre are also used.
- Exel has 7 production plants in total, with the Joensuu-site being one of the biggest manufacturers of pultrusion-based FRP in the world. There are no significant differences in carbon and glass fibres when material waste from the production at Exel is considered. In terms of recycling, carbon fibres are a somewhat more relevant topic than that of glass fibres, with the most notable example of the latter being the use of GFRP waste in the cement industry.
- Principal reasons why FRPs are being considered include good lightweight of structures, chemical resistance, fatigue strength, long life cycles in general and – in Valmet's context – tolerance towards heat and moisture. Sometimes FRPs simply need to be considered when their metallic counterparts don't perform well or are not even viable in the intended applications. A good example of this is wind energy, where nowhere near as good efficiency could be reached if the turbine blades would not be GFRP. Other benefits of light weight structures include economic savings through ease of handling, shorter maintenance times and – in some cases – energy efficiency through good insulation properties.
- Ecological aspects of FRP, including end-of-life treatment, are not considered during product design or manufacturing and customers of Exel are not asking sustainability-related questions either. They are, however, factored in indirectly, as FRPs promote energy and material savings in production and use. This is particularly true in carbon fibres, as they're very energy intensive to produce and not very sustainable in that regard, but this is compensated effectively during the use stage. A lot of the times eco-

logical aspects go hand in hand with economic aspects, as, for example, constant monitoring of material waste ratios at Exel promote saves in both regards. In this sense, a case can be made that the ecological aspect of FRPs comes from their practical benefits (good chemical resistance, long life cycles, energy efficiency, etc.)

- Biggest occupational health and safety risks were perceived to come from the used thermoset resins. Ceasing the use of CMR (Carcinogenic, Mutagenic or toxic to Reproduction) substances altogether and way ahead of compelling legislation has been the single most important step taken towards safer working environment. Resins that contain halogens are also restricted heavily proactively, as they are a safety and an environmental hazard and hinder incineration of products containing them.
- Styrene wasn't considered a particularly relevant talking point as they have been studied extensively with the most up-to-date conception being that they're not a carcinogenic substance.
- Peroxides – while being extremely inflammatory, some of them to the degree they cannot be extinguished after catching fire – weren't seen particularly problematic materials. Their use puts emphasis on proper storing like keeping them separate from other chemicals and bringing in only the amount of peroxides being consumed during the day, but not much else.
- Additional health and safety risks included fibre-based dust from cutting of composites, but it is comparable to any other dust in a production environment and handled by using vacuums and personal protection.
- There are huge differences between countries in terms of how safety regulations are applied. Right now, EU has the strictest regulations in use of hazardous substances (REACH), so buying from composite manufacturers inside the area can be a significant improvement from environmental and occupational health and safety perspectives. Additional benefits from buying inside EU [from the perspective of another EU-based company] include shorter transport distances, as resins are typically produced rather locally as they can react harmfully during the transport. Legislation and waste management infrastructure are also far ahead in comparison to other areas, developing countries and Asia in particular.
- Natural fibres, bio-based plastics and bio-composites seem completely irrelevant in the use of heavy industries like in paper and board machines. This is mostly due to moisture-absorbing properties and low tolerance towards heat. Sensitivity towards moisture hinders also manufacturing, since lots of energy needs to be used in keeping them dry enough. The short nature of natural fibres causes additional problems, as they may perform well on a lab scale tests on short fibres but their inconsistency and discontinuous nature make it impossible to translate the good lab-scale performance to actual products that utilize them. While there have been few individual projects that utilize natural fibres at Exel in the past, use of plain wood without considering plastic composites at all would seem a much more relevant option. If good recyclability, competitive pricing and good thermal resistance could all be combined in a bio-composite, such material might get relevant.
- Expanding know-how in the field of FRPs – most importantly, on what kind of applications they best strive at – would increase their sustainability in the bigger picture, as the best possible applications would be easier to find. This also includes selection of the right materials for each application.
- Recycling and FRPs are a challenging combination in terms of transport to the recycling plant, since to do it efficiently would require them to be processed into a more compact form before dispatching.

Waste management of FRP

Antti Anhava | Sales Manager | Fortum Waste Solutions | 61 min

General

- Antti, currently working at Fortum's Jämsänkoski site, has over 20 years of experience in waste and recycling businesses. He has considerable amount of experience as a production manager and SRFs (Solid Recovered Fuel), fuels made from recycled waste of significant calorific value.
- Recycling is sort of a chicken-or-egg-first -type of business. It must be ensured that there is a market for the recycled material before producing it in the first place; on the other hand, producing recycled materials creates such markets. That is also the reason why recycling of plastics is so concentrated on the easy-to-recycle types of plastics currently. Importance of contracts should not be underestimated either. To overtake the process of mechanical processing and pre- and post-sorting of certain waste, a collaborative company that is able to effectively use the recycled material is needed.
- The ideal plastic waste consists of only one type of plastic, underlining good product design. For example, plastic bottles have two kinds of plastics: the bottle itself is typically PET, whereas the cap is typically PE, making the bottle somewhat problematic product to recycle.
- There are considerable differences between countries in how the waste is managed. Places such as Nordics and Germany (and Europe in general) have come a long way forward, but the reality is that developing countries use mixed waste almost exclusively. Metals constitute a clear exception to this due to their intrinsic value and easy recyclability, which are also the root reasons for their good recycling ratios in general.
- Regardless of the type of incineration (what is burned and what kind of process is utilized), the process is never done only to reduce the volume of the waste. Energy recovery is always exercised to some extent.
- There are three primary outputs on incineration plants: residue (slag and ash) and fumes. Residue is almost a lava-like substance – especially in incineration of hazardous waste – that cannot be processed further.
- In terms of occupational health and safety risks, preventing the generation of dust in the mechanical processing of the waste is important. Utilizing vertical electrical rails produce less dust than horizontal ones. In addition, the standard means of personal protection need to be used.
- Ensuring the cleanliness of the products that reach their end-of-life, alongside with ease of disassembly are among the most important actions to take from the perspective of a waste management operator. An emphasis should be laid on appropriate sorting and keeping the waste clean, instead of focusing too much on the recycling itself.
- Keeping products as simple as possible in terms of amount of materials or components like additives inside each material should be strived for. For example, mixing carbon fibres with basalt fibres [as referred to Sharma (2016, 3-4) in this report] would not be advisable from this perspective. Still, one should avoid paying too much attention on the end-of-life treatment but consider the whole PLC instead. Making too hasty conclusions on narrow aspects like recycling of the product are to be avoided.
- The Waste hierarchy should also be kept sternly in mind, as laying too much stress in the management of the accumulated waste is not desirable. The higher levels of the waste hierarchy should be considered instead, with the most important being how to prevent generating waste in the first place. Improving product quality and ensuring

long life cycles should also be considered. Antti, as a representative of a waste management company, was very unambiguous in underlining the importance of continuity through long-term collaboration and development, instead of settling for the easy way of maximizing the amount of collected waste in a short time frame.

- Effectivity and the sheer scale of each action should also be considered. For example, instead of focusing too much on differences in emissions how much combustion engines of each car model produce, it is more relevant to talk about the used propulsion principle. Or even more importantly, whether transportation is needed at all or not.
- Using standard materials with bigger volumes instead of low-quantity ones is desirable. When talking about using fibres like basalt instead of E-glass, Antti emphasized that recycling solutions are mostly made for materials that are used more consistently. Thus, using of glass fibres over less known ones seem a better overall solution.
- The intrinsic value of the material comes of a high importance in the recycling business. Recycling of *Low-end, low cost* -materials is problematic as there are no economic incentives included.

Specific to Finland

- There is currently a dramatic oversaturation of market for energy waste in Finland. This is largely due to fire destroying a production plant (that was a considerable consumer of such waste) in Pori a few years back. This caused around 40 000 tons of free capacity and there are no plans for rebuilding the plant. Lots of SRF is currently used as a fuel in the cement industry.
- Disposal of fibre-reinforced plastics in Finland is currently done exclusively via incineration with energy recovery. There has been talks at Fortum on how to improve the situation, but no actions have been taken so far. FRPs are problematic materials on their end-of-life treatment, particularly when large items need to be handled, laying emphasis on their pre-processing.
- In practice, the prohibition of landfilling of organic waste in Finland has resulted in almost everything that cannot be recycled going through incineration process (with one clear to this being asbestos that goes directly to landfills), so it has changed the industry sector comprehensively. Permits of exception are still taking effect on some landfilling that would else be prohibited.
- There are approximately 10 incineration plants that handle energy waste. In the bigger picture, energy waste is just a one fuel amongst others. In general, there are too few incineration plants in Finland with one being built in Salo currently.
- There was an important change in the waste law in Finland in early 2019. It declares that local waste management sites should concentrate on domestic waste, while corporate waste is to be handled via more open competition and lesser amount of binding obligations. Since existing contracts are something companies want to understandably hold on to, there will still be a transitional period, but ultimately it will have a significant impact on the waste sector. There will inevitably be agents that are interested in FRP waste, but the real discussion is in finding the right price level for it and how much handing of the composite waste will cost to its producer.
- Import and export are relevant points in waste discussions. Finland is a net exporter of waste, meaning more waste is exported from the country than imported to it. Statistics are somewhat skewed by proximity of borders in some plants. For example, lots of board is being exported to Sweden in the North of Finland due to closer distance to relevant board mills.
- Fortum has three plants for processing of hazardous waste. Beside the Riihimäki-plant, there are plants in Sweden and Denmark. Waste transfer is actively done between the three: for example, acids are transferred from Riihimäki to Sweden, while some of the

waste Sweden is brought up to Riihimäki; most of mercury by any company in Finland is exported to Germany. It is no different than any other inhouse transfers between sites of any given company.

Specific to Riihimäki-site (former Ekokem)

- The waste incineration plant at Riihimäki treats substantial amounts of the hazardous waste produced in Finland. The process itself is a very typical one and doesn't substantially differ from generic incineration with energy recovery. Incoming waste is rather heterogenous with big differences in its' calorific value. This forces to make "mixes" out of them in their pre-treatment to ensure high-enough burn temperatures. Otherwise auxiliary fuels (too low calorific content in the waste) or cooling off the process (too high calorific content) would be needed.
- The waste stream of Riihimäki plastics refinery consists mostly from domestic thermoplastic waste and virtually processes all such waste collected in Finland. The volume of waste being treated there has increased rapidly in the latest years with numbers for 2017, 2018 and 2019 (forecast) being 6 000, 13 000 and 17 000 – 18 000 respectively. There is a clear "hype" around recycling of plastics that keeps accelerating the amount of waste collected. Currently, plastics are not collected separately at Valmet's Rautpohja-site, so they go directly to mixed waste.
- (Thermo)plastics in Riihimäki are received usually in the form of bales which are subsequently shred open, separated by near-infrared (NIR) spectrometers and jets of high-pressure water, cleaned, baled and stored. Later they're fed one type of plastic at time into the granulating production line in which they're washed two times (including de-colouring them), heated, extruded as granulates and cooled off.
- The incineration process is not optimized for energy-efficiency but instead for resulting fumes and their treatment, with the aim of maximizing the amount of waste being processed. A telling comparison is that whereas the incineration furnace is only 12 meters long, the post-processing of fumes (flue gas scrubber, electrostatic precipitators, etc.) reserve 80-meter long space. Sensors that monitor the emissions going out from the chimney in real-time are used in addition.

Future projections

- China – where a major portion of the worlds' plastic waste formerly ended up to – banning the import of plastic waste to the country couple of years ago had a significant effect on the sector. This caused a stark realization – at least in Europe – that the problem of ever-accelerating amount of plastic waste needs to be addressed at its source. Similar imperative obligations are bound to trigger needs for more efficient recycling processes in the future.
- Depletion of resources will inevitably increase plastic recycling ratios in the long haul. Design for Recyclability and such principles will for sure be emphasized more in the future, as a continuously growing number of companies are interested in improving the recyclability of their products. The impact of this is already felt heavily in the package design and how well they can be recycled as frequent inquiries about such topics are being made currently. Addressing such themes may well explode in a near future.
- The global trend of urbanization will have a significant positive impact on recycling. The more concentrated living is, the easier the generated waste streams are to handle as they are steadier. Bigger volumes also enable recycling of plastics and similar materials that are economically problematic otherwise.

Appendix 5. Source data from FRP end element

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Appendix 6. Source data from steel end element

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Appendix 7. Enhancing sustainability of FRP now and in the future

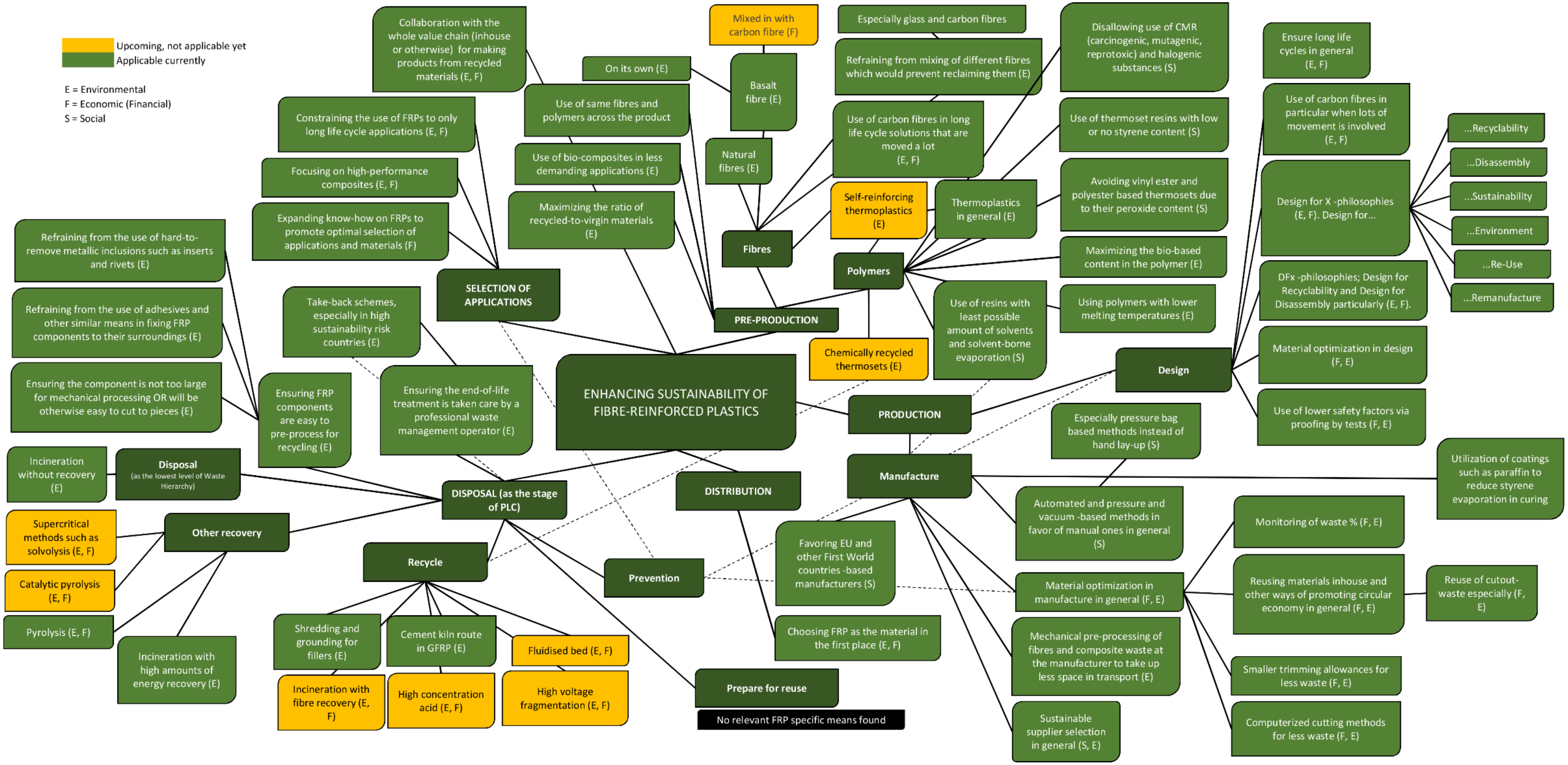

Figure 14. Means to enhance sustainability of FRP now and in the future (complete)

Appendix 8. List of guiding questions for new FRP applications

After formulating the list of questions needed (all given letters from A to X), the order of priority between them was determined thru paired comparison of questions. Results from the comparisons are presented as table 12, where the frequency of each question (letter) determined its relative importance.

As the long list of questions turned out to be rather laborious to go through, two versions of the list were made: First comes the shortlist, where only the top 10 questions need to be considered for a quick check that should take only about 5-10 minutes. The second one is longer, as it includes all the questions for a more comprehensive assessment. The two main exception to this was the exclusion of question S that was planned because total sustainability impacts through the product life cycle as whole should be considered instead of paying attention only to singular aspects (most of the other questions). Sustainability trade-offs can and need to be made to ensure lowest possible total impacts, even if it means slightly impairing the performance of individual aspects like recycling, carbon footprint or total costs. This was, however, deemed hard to answer reliably – even for a sustainability specialist – and was dropped out in combination with the fact that this very list of questions strives to answer it anyway. Combining of questions V and W was also made due to their similar nature.

The complete list of questions considered for this list are presented after table 12. While there are no determined weighs for each question, it needs to be pointed out that some of the pros of FRPs like being able to produce lightweight constructions are being approached from several angles through several similar questions. This ensures that – even when questions are not weighed numerically relative to each other – products that utilize primary benefits of FRPs score better in the list.

Table 10. Paired comparison of questions

Question																									Instances	Priority
Does the intended component include or would optimally have or be have a large, one-piece surface?	A	B	A	D	E	A	A	H	A	A	K	L	A	N	O	P	Q	A	S	T	A	A	W	X	9	15
Does the intended component include or would greatly benefit from complex surface geometries like double curvatures?		B	B	D	B	B	B	H	B	B	K	L	B	N	B	P	Q	B	S	T	B	B	B	B	14	9
Does the intended component require or considerably benefit from aligning its stiffness according to measurement direction?			C	D	C	F	C	H	C	C	K	L	M	N	O	P	Q	C	S	T	C	C	C	C	9	17
Is good chemical or corrosion resistance required for the application?				D	D	D	D	H	D	D	K	L	D	N	D	D	D	D	S	T	D	D	W	D	16	7
Are good thermal or electrical insulation properties or minimizing of thermal expan-sion mandatory for the application?					E	F	G	H	E	E	K	L	M	N	O	P	Q	R	S	T	E	V	W	X	4	19
Does the intended component require particularly good visual quality and/or surface finish?						F	F	H	F	F	K	L	F	N	O	P	F	F	S	T	F	V	W	X	9	16
Does the intended component require serial production (regardless of volume)?							G	H	I	J	K	L	M	N	O	P	Q	G	S	T	G	V	W	X	3	22
Does the intended component require particularly good weight-to-stiffness -ratio?								H	H	H	K	H	H	N	O	H	H	H	S	T	H	H	H	H	18	5
Can the application be made from typical reinforcing fibres such as (E-)glass OR carbon fibres without mixing them or using alternative, less used fibres?									I	I	K	L	M	N	O	P	Q	R	S	T	I	V	W	X	3	20
Does the intended component require use of carbon fibre reinforcement in particular? (Is achieving similar performance with glass fibre reinforced plastics, steel, aluminium or other alternative materials not possible?)										J	K	L	M	N	O	P	Q	J	S	T	J	V	W	X	3	21
Does the component move or is it moved (mechanically or by hand) frequently during use?											K	K	K	K	K	K	K	K	K	K	K	K	K	K	23	1
Is the component moved (mechanically or by hand) frequently during maintenance, whether because of maintenance of the FRP component itself or any adjacent part, or does it otherwise aid in lowering maintenance or other production down times significantly?												L	L	N	L	L	L	L	S	T	L	L	L	L	18	6
Is it otherwise significantly beneficial for the component to be lightweight?													M	N	O	P	M	M	S	T	M	V	W	X	8	18
Have steel and similar materials been proven insufficient for the intended application?														N	N	N	N	N	N	N	N	N	N	N	22	2
Is the reserved space for the component critically restricted?															O	P	Q	O	S	T	O	O	O	O	14	10
Would the product, if made from FRP, be typically manufactured in a First World country? If not, is it highly probable that internal audits or similar measures will be taken to ensure its safe and environmentally friendly production?																P	P	P	S	T	P	P	P	P	16	8
Would the product typically reach its end-of-life in a First World country? If not, is it highly probable that take-back schemes or similar means would be taken to ensure its proper disposal?																	Q	Q	S	T	Q	V	W	Q	11	12
If made from FRP, is it likely that the component will be designed and manufactured in a manner that allows its easy and fast disassembly from its surroundings and removal of metallic parts included in it?																		R	S	T	R	V	W	X	3	23
Is it likely that significant environmental, social and/or economic benefits can be achieved via the use of FRP?																			S	S	S	S	S	S	21	3
Is it likely that making the product from FRP reduces its total life cycle costs significantly?																				T	T	T	T	T	20	4
Would the product typically be shipped over long distances in distribution?																					U	V	W	X	0	24
Is the application one of a particularly long life?																						V	W	V	10	13
Can a significantly longer life cycle be achieved with the use of FRP, compared to steel or similar materials?																							W	W	13	11
Can considerable saves in material consumption be achieved with the use of FRP, compared to steel or similar materials? (Large parts or small parts with large volumes.)																								X	9	14
																								TOTAL	276	

1. **Does the component move or is it moved (mechanically or by hand) frequently during use?**
   Energy-efficiency achieved through lightweight parts is the single most important benefit of FRPs in comparison to metals.

2. **Have steel and similar materials been proven insufficient for the intended application?**
   Sometimes FRPs can be the last-ditch effort on making a product work or just be the only economically or otherwise viable options, after the more traditional materials have already been considered and rejected.

3. **Is it likely that making the product from FRP reduces its total life cycle costs significantly?**
   In addition to sustainability trade-offs in general, their economic aspect needs to be promoted, as using of FRPs can reduce production, investment and/or life cycle costs particularly.

4. **Does the intended component require particularly good weight-to-stiffness -ratio?**
   Good weight-to-stiffness ratio is one of the primary benefits of FRP.

5. **Is the component moved (mechanically or by hand) frequently during maintenance, whether because of maintenance of the FRP component itself or any adjacent part, or does it otherwise aid in lowering maintenance or other production down times significantly?**
   The same reasoning as for the question regarding frequent moving of the component in use should be considered also in terms of maintenance: If the FRP part needs to be removed and reinstalled because changing and/or maintenance of adjacent parts (like in the case of casings, protective covers and similar elements) the ease of handling may have a significant impact on maintenance times. This is particularly true in process industries like in paper and board making, where downtime of the process has immense economic setbacks.

6. **Is good chemical or corrosion resistance required for the application?**
   FRPs can provide chemical resistance far superior to metals, resulting in longer life cycles and usage in applications in which even stainless grades of steel wouldn’t be viable.

7. **Would the product, if made from FRP, be typically manufactured in a First World country? If not, is it highly probable that internal audits or similar measures will be taken to ensure its safe and environmentally friendly production?**
   First World countries, especially EU area, generally have some of the strictest regulations for harmful substances like the typical thermoset resins being used, so buying inside its borders will significantly increase the proper treatment and manufacturing from environmental and social aspects of sustainability.

8. **Does the intended component include or would greatly benefit from complex surface geometries like double curvatures?**
   Making complex double-curved features is natural to FRPs, especially when moulds are involved.

9. **Is the reserved space for the component critically restricted?**
   Since FRPs are naturally lightweight, they allow packing certain functionalities to such restricted spaces that wouldn’t be possible with other materials.

10. **Is the application one of a particularly long life OR can a significantly longer life cycle be achieved with the use of FRP (compared to steel or similar materials)?**
    Long life cycles are part of waste prevention – the highest level of the waste hierarchy – and should be emphasized in any sustainability-related evaluation. FRPs, due to the combination of challenges in recycling, good corrosion resistance and strong life cycle performance (compared to when only the initial investment is considered), should typically not be advocated in short life cycle applications. On the other hand, the longer component life cycle is, the less relevant its recycling is in the bigger picture.

11. **Would the product typically reach its end-of-life in a First World country? If not, is it highly probable that take-back schemes or similar means would be taken to ensure its proper disposal?**
    As disposal of FRPs is typically problematic, it is important that either a proper waste management infrastructure exists in the country of disposal or proactive means are taken to ensure that the highest level possible in the waste hierarchy is achieved.

12. **Can considerable saves in material consumption be achieved with the use of FRP, compared to steel or similar materials?** (Large parts with large material savings or small parts with large volumes.)
    Material saves are part of waste prevention – the highest level of the waste hierarchy – and should be emphasized in any sustainability-related evaluation.

13. **Does the intended component include or would optimally have or be a large, one-piece surface?**
    Being able to make large, one-piece constructions is one of the primary benefits of FRPs.

14. **Does the intended component require particularly good visual quality and/or surface finish?**
    FRPs enable easy quality control, even surface finishes and visual quality.

15. **Does the intended component require or considerably benefit from aligning its stiffness according to measurement direction?**
    Non-isotropic nature of some FRP products such as laminates and pultrusion-based pieces make aligning of mechanical properties, stiffness most importantly, possible without changing the geometry.

16. **Is it otherwise significantly beneficial for the component to be lightweight?**
    Possible other benefits of lightweight structures (than merely energy savings) should also be considered. An example of other benefit would include restricting components weight below certain thresholds, like below 25 kg to allow manual handling without special lifting equipment.

17. **Are good thermal or electrical insulation properties or minimizing of thermal expansion mandatory for the application?**
    FRPs in general have good thermal and electrical insulation properties. Producing near--zero thermal expansion FRPs are also possible due to carbon fibres having negative thermal expansion along their fibre axis.

18. **Can the application be made from typical reinforcing fibres such as (E-)glass OR carbon fibres without mixing them or using alternative, less used fibres?**
    Using standard solutions in materials increases the probability of materials in the component being recycled after its useful life time: efficient recycling solutions are and will

be most available for the solutions with biggest volumes. In terms of fibres, these include E-glass fibres and carbon fibres particularly.

19. **Does the intended component require use of carbon fibre reinforcement in particular?** (Is achieving similar performance with glass fibre reinforced plastics, steel, aluminium or other alternative materials not possible?)
    As carbon fibres are a special point of interest in FRPs from the recycling perspective, use of carbon fibres promote primary recycling and gives best chances for fibres of an FRP product being manufactured today will be recycled when it reaches its end of life. Carbon fibres are very energy intensive to produce, so careful consideration should be made in terms of this question but if the use of carbon fibres can be justified from economic perspective, it is highly likely that the energy used for the fibre production will be compensated by better energy efficiency during the use. Use of carbon fibres can be also promoted from the sustainability point of view because there are much higher economic incentives (when compared to most other fibres, glass fibres most importantly) in using them effectively without generating waste.

20. **Does the intended component require serial production (regardless of volume)?**
    Economic serial production, even in low quantities, typically require moulding. As moulds for FRP are cheaper than in metals, starting serial production of a new component requires smaller investments.

21. **If made from FRP, is it likely that the component will be designed and manufactured in a manner that allows its easy and fast disassembly from its surroundings and removal of metallic parts included in it?**
    Problems in the disposal of FRPs should not be underestimated. As such, it is important to produce such parts in a manner that makes their removal from the surrounding structures easy. This includes but is not limited to using least amount of mechanical fixings possible and constraining the use of adhesives. The use of metallic inserts and similar parts should also be considered, as parts containing them cannot be mechanically pre-processed if they are not removed.

22. **Would the product typically be shipped over long distances in distribution?**
    Whether this question is relevant or not is very application-specific, but as FRPs are typically more lightweight than constructions made from alternative materials (metals and cast products especially), they can promote significant saves in the logistics via lesser fuel consumption and environmental impacts.

Appendix 9. Evaluation of Valmet’s FRP projects

Removed from the public version.