Opportunity Analysis for Re-cycling Household Plastic Wastes in Denmark – Exploratory Case Study and Future Outlook

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ABSTRACT

Exploratory case studies have been conducted within three best-case companies in the plastic value chain in Denmark to illuminate technical capabilities of sorting and further processing of plastic wastes, and to identify current re-cycling strategies and market opportunities for re-cycled plastics. Departing from circular economy principles this paper concludes that few re-cycling values chains have been established in Denmark, which origin from plastic packaging waste from households, and none for food packaging re-use. Unfavorable waste management practices mostly lead to a downcycling of the plastic quality within the current value chain. The study reveals that companies support the re-cycling of plastic, but until the quality of sorted plastic is assured for larger adaptation, they focus on e.g., buyback programs and cooperation with selected actors in a small segment of the value chain to valorize their flows of plastic. This paper further concludes that re-use strategies must be prioritized alongside the re-cycling of high quality plastics. As future outlook, biological methods like bacteria and enzymes treatment are discussed, as well as the watermark technology for tracing the origin and type of plastic. Besides re-use and re-cycling strategies reducing the pressure on virgin feedstock, we outline potentials for producing bio-based and PtX (electro-fuel) plastics.

1. INTRODUCTION

In the production of plastic polymers, the industry utilizes substances that are produced in the processing of natural gas and crude oil, which require high energy inputs. Besides this, manufacturing of the final plastic products also needs supply of energy, just as waste treatment - when plastics are discarded - needs energy. On an annual basis, 260 million tons of plastic waste is being generated from a virgin feedstock extraction of 300 million tons of plastics, of which merely 40 million tons (or 16 %) are collected for re-use/re-cycling [1]. The remaining plastics are either incinerated, landfilled, or simply not managed [2], [31], [32]. It is therefore outmost important to sustain the energy usage accumulated in the plastic products, by emphasizing on re-use and re-cycle strategies.

Both re-use and re-cycling of plastics provides usage of the accumulated energy embedded in the plastics and reduce the need for harvesting new virgin feedstock [3], [33]. High priority must therefore be channeled to strategies that enables the deployment of circular economy principles, where re-use and re-cycling of plastic wastes are adopted. This includes for example appropriate waste collection and sorting systems, as well as processing facilities that enables the plastic wastes being re-cycled again as for example granules. Also, companies within the plastic value chain must be capable of re-cycling the plastic in their manufacturing processes. Around 27 million tons of plastic wastes are generated within the EU on an annual basis, where 30 % of this is collected for re-cycling purposes. The exact number being re-cycled is however estimated to be much lower [4]. 41 % of the plastic packaging wastes within EU is being re-cycled, separated as e.g., 37 % from households and 47 % from the industry. Only around 32 % of all plastic packaging waste in Denmark are currently being re-cycled, which entails 17,2 % being plastic waste from households [4]. This is only a minor share of the 350.000 tons of plastic waste being generated on an annual basis, hereof 215.000 tons being plastic packaging wastes specifically [5].

In this paper, we will assess how companies within the plastic value chain can adapt to the re-cycling of plastics to reduce the pressure on virgin feedstock, and hence lower the energy usage and CO_2 emissions, associated with the production and management of plastic packaging wastes. We apply the lens of circular economy looking into opportunities for re-use and re-cycling of plastic packaging waste from households to enhance the circularity of production systems within companies in the plastic value chain.

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1.1. Outline of the research

In the *first part* of this paper, we thus conduct exploratory case studies investigating how to increase the volume of plastic appropriate for re-cycling, and how plastics can be integrated into manufacturing processes of companies within the plastic value chain. Emphasis will be on the following issues: What are the current limitations of the Danish waste sorting plants, and are re-cycling facilities established producing easy re-cyclable plastics for manufacturing companies? Which strategies do plastic packaging companies already apply, and plan to apply, to adapt to future re-cycling requirements? We will further investigate how companies can integrate re-cycled plastics in their product portfolio, and whether a market for re-cycled plastic exists.

In the *second part* of the paper, we elaborate on future perspectives for producing, sorting, and managing plastics. It is investigated how the re-use of plastics could be introduced for plastic packaging wastes, as opposed to re-cycling, and look at the potentials for producing plastics from new materials, like PtX, biomass, as well as re-cycling opportunities by bacteria and enzymatic treatment. Besides this, we discuss the watermark technology, which could enable high quality plastics to be separated at the sorting plants and provide new opportunities in tracing the origin (producer) of plastic wastes.

2. MATERIALS AND METHODS

In the following section, we proceed to describe the methodologies adopted in this paper.

2.1. Theoretical platform and data retrieval

Circular economy principles

Circular economy is an approach, in which materials and energy flow are designed and shaped with the purpose of facilitating re-use and re-cycling. Circular economy can be applied to re-think our existing production and consumption patterns to develop sustainable environmental and commercial circles, and cascades within the resource utilization of industry and agriculture [6]. The inspiration derives mainly from the Industrial Ecology theory [7], in which natural eco-systems are applied on industrial activities. In these natural systems nothing is wasted, and resources go through eco-systems from plants to animals and eventually predators, who then die and decompose in which nutrients are provided to plants, animals, and micro-organisms, etc. [8]; [9]; [10]; [11].

The circular economy principles can be understood as a termination with the concept of linear-economic thinking, where products are utilized in a classical use-dispose matter. The linear economy puts pressure on natural ecosystems through an over consumption of non-renewable resources etc. and creates large quantities of waste, which should be avoided [12]. Ellen MacArthur Foundation provides the following definition of circular economy [12]: *"A Circular Economy is an industrial system that is restorative or regenerative by intension and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models".* In this paper, the principle of circular economy is applied as a concept to access in which part of the plastic value chain opportunities for re-use/re-cycle plastics can be deployed. The purpose is to sustain a high quality of the plastics as long as possible, to avoid a downcycling to lower quality levels, and hence to limit the extraction of virgin feedstock supplied into the cycle of materials use.

Case study approach

We utilize an *exploratory case study* approach [13]; [14] to the cases investigated, as we did not have any pre-determined expectations of outcomes when entering the empirical research field. The interview situations were approached - applying a *semi-structured* interview method [15] - without exact knowledge of the stakeholder's position to the topic investigated, the technology level adopted as far as re-cycling plastics, their reluctance/welcoming of more plastics to be re-cycled in the future, nor of the companies' capabilities to address future requirements. According to [13] and [16], exploratory case studies are also appropriate when you need to gain very detailed descriptions of a social phenomenon. The exploratory case study is used to explore and investigate presumed causal links that are too complex for a survey or experiment. According to [14], case studies are appropriate when asking "how," "why," "what," and "who" questions.

Case company selection

To assess the plastic industry's view on opportunities for re-cycle larger quantities of plastics, we have collected empirical data from three 'best-cases' companies [17], who each have their own position in the plastic value chain. Three case studies have thus been conducted with company managers, the *first* from 'Damifo' in Vojens, who recently won a tender for sorting plastics from source separated household waste, which previously was transported to Krefeld in Germany to be sorted and processed further for re-cycling purposes. Collaboration between Damifo, a processing facility and supermarket chains in Denmark, has now led to the re-cycling of plastics for non-food purposes.

The *second* company selected within the plastic value chain is 'Færch' in Holstebro, who produce plastic packaging mainly for the food industry, and where future ambitions is to become a larger part of the entire value chain for food packaging plastic to secure their supply of re-cyclable plastics. *Third*, the manager from 'Gibo' in Skjern, being an example of a traditional Danish company in the plastic value chain, who welcome the re-cycling of plastics, but where logistic, structural, and quality issues currently hamper this. Experiments with the re-cycling of plastic wastes from households were previous applied at Gibo, but the low sorting quality resulted in plastics being inappropriate for this and hence terminated.

3. RESULTS AND DISCUSSION

In the following two sections, we proceed to elaborate on the results from our empirical data collection within companies in the plastic value chain in Denmark, followed by findings and discussion of future outlook for sorting, producing, and managing plastic wastes.

3.1. Findings from exploratory case study

Sorting quality and re-cycle facilities

It is evident from the empirical data that improvements on sorting plants and further re-cycling facilities to produce e.g., granulates, are needed. Damifo (sorting plant) and Aage Vestergaard Larsen (re-cycling facility producing granules) are examples of the few companies in Denmark in this part of the value chain (besides companies re-cycling PET bottles as a part of the Danish Return System not included in this study). According to Damifo, it is however possible to expand the sorting and processing of plastic for further re-cycling, if the supply of clean source separated household plastics increase. New value chains for re-cycled PE plastics (polyethylene) from household waste are slowly being developed but should be upscaled in quantity and include other types of plastic like PP (polypropylen) and PET (poly-ethylene terephthalate) in the future [18].

As pointed out by the interviewee, source separation at household level must be easy and the technology at sorting plants must be upgraded [18]; [19]; [20], e.g., with new equipment like for example watermarks that provides evidence of the type and origin of plastics. The manager from Damifo stresses that….” *we need to increase the quality of the sorted plastic, by for example leaving out PS and LDPE, and develop and apply better product design of PET, PE and PP”…* He qualifies this by continuing…” *Only focusing on a few high quality types of plastic will make it easier for household and industry to re-cycle the plastic”…* [18].

From the interviews it is clear, that lack of harmonized rules within Danish municipalizes of how to source separate household waste, is interpreted as one of the largest barriers for re-cycling plastic packaging waste in a Danish context. A consequence of this is down-cycling, as seen at Gibo, where sorted household waste undertook re-cycling, but as the manager puts it “…. *we did not know what it was, but it was not a clean material, so we could only produce fences, tables, chairs, and floors……”* [19]. This is qualified further by the manager from Færch, who said … *”1m^3 waste contain up to 80 % PET, but the sorted fractions are only around 40 %. The goal is quality in and quality out”…* [20]. Higher quality and more uniform collection and sorting systems are hence requested by the company managers, and the rules and regulations must be harmonized and enforced to secure quality and quantity. A large barrier are thus the municipalities in Denmark who have failed to deliver efficient waste collection systems [18]; [19]; [20].

More advanced sorting plants and re-cycle facilities are also needed for re-cycling plastics for food packaging usage, which currently are supplied by companies outside Denmark. A few re-cycling value chains have however been established, e.g., by Damifo, for plastic waste from households - supplying bottles for soap products to supermarkets - but not to be utilized for food packaging. These actors can however increase the re-cycling quantities depending on the available plastic for re-cycling [18]. The informants agree that it is outmost important that better source separation systems are deployed within Danish municipalities to make sorting easier for citizen and prevent contamination of plastic and secure high quality with emphasis on PE, PP, and primarily PET.

Re-cycle opportunities and barriers

In the case of Gibo, we identified that logistical barriers, size structures of the marked, and the technology applied, however hampers a re-cycling of their own plastic products. Currently, the company re-use regenerates from their own production of plastic components mainly to the industry (see Figure 1). But, if clean PE from source separated household waste can be supplied to Gibo, they would however welcome the use of this material in their extrusion processes based on granulates. Hence, a part of the production relies on high quality PE granulates used in extrusion processes, but the raw materials are in general supplied from outside Denmark, due to the size of the plastic plates needed. As the manager mention…”*no Danish suppliers have the size of machinery needed for this and the market is too small in Denmark. Therefore, we must get it transported over long distances from very large industries with many costumer’s”* [19]. For Gibo long distances makes re-cycling unsustainable, just as the lack of Danish re-cycling facilities providing quality products ready to be re-cycled. As the manager state: “…*we need to re-cycle more locally or regionally otherwise it does not make sense, and for us it is plastic for extrusion processes, where we can re-cycle…”* [19].

Færch already utilizes 70 % re-cycled plastic in their PET products and have adopted a plan for further re-cycling activities to assure the quality of the returned plastics. A buyback program has for example made it possible for Færch to get their own plastic trays back, and hence to re-cycle a material that they already know the quality of, and such programs could very likely expand in Denmark [20]. The watermark system is welcomed by the companies to identify plastic types and hence facilitate re-cycling, as well as the original producer, and is referred to as the Holy Grail (research project) [18]; [20]. The issue of contamination is very important for producers of food packaging and today a coating with virgin plastics is applied on some food packaging products (sandwich coating with re-cycled plastic in the middle). It is therefore a challenge to obtain 100 % re-cycling, hence a down-cycling is evident and the drawing on virgin feedstock are inedible. But, as the manager from Færch states….*"In the future, if we are limited in the amount of virgin plastic that we can utilize, new resources can be acquired from PtX technology, which is capable of producing plastics…"* [20].

Currently, there is no re-cycling facilities in Denmark that processes plastic used for food packaging to granulates, which can be re-cycled within the food industry again. At Færch plastic for re-cycling is delivered to their company Cirrec in Holland who have the capacity to clean and upgrade the plastics to be re-cycled for food packaging again with coating [20]. If plastic packaging from households is sorted properly - and being of high quality - this waste can, according to the company, also be processes in Holland, and used for food packaging again [20]. Thus, it is clear, that improving the Danish sorting and processing facilities would be beneficial, and Færch are currently investigating options for deploying a Færch-owned re-cycling facility in Denmark, or at least within Scandinavia, to tap into this unsaturated market for processing re-cycling plastic [20], as emphasized below.

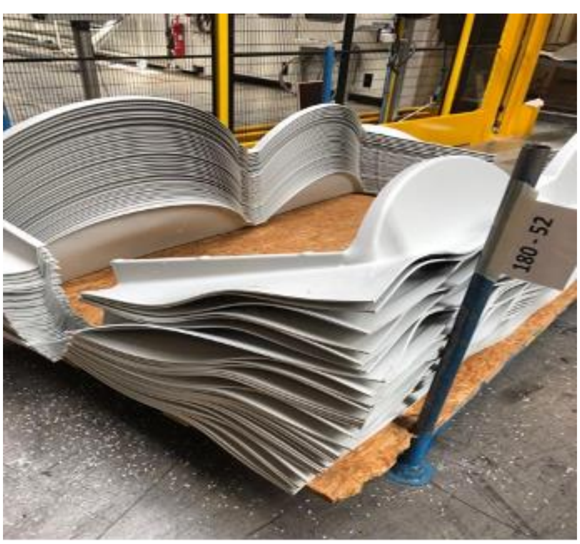

Fig. 1: Regenerate from Gibo to be utilized for the same product again, here for the Danish windmill industry (figure by authors).

Market for re-cycled plastics

From the case companies investigated we saw that a Danish market for re-cycled plastic already is established and growing. Industrial customers like windmill manufactures and supermarket chains etc., are requiring re-cycled plastic in their products [18]; [19]. The production of re-cycled plastic in Denmark is however too small to saturate the Danish marked, where Danish Return System for example only can deliver 20-25 % of the re-cycled plastic that Færch utilizes, and the remaining is hence supplied from outside Denmark [20]. From the empirical data we also saw that Danish companies in the plastic value chain are keen on utilizing re-cycled plastic in their products due to environmental considerations etc., but also because of requirements from their customers [18]; [19]; [20]. The empirical data show a tendency towards companies consolidating themselves, by becoming a part of a larger value chain for plastics; hence possessing both sorting plants and re-cycle facilities, as well as being plastic product manufactures, as in the case of Færch.

We now proceed to elaborate further on how plastics could be manufactured and utilized by means of a more circular approach in the future outlook section below.

3.2 Findings from future outlook

Expanding the Danish Return System

Re-use and not only re-cycling strategies are also important to lower the pressure on virgin feedstock and hence fossil fuel usage. Plastic packaging are only to a minor extend re-used, especially not within the food sector, except from drinking bottles and milk crates etc. We suggest manufacturing more rigid and durable food trays, which could be collected by e.g., Danish Return System, rinsed and cleaned to be utilized again for food packaging. The material should be able to withstand several cycles of re-use and be re-usable without risks for the consumer. The trays could be delivered to the re-turn machines within supermarkets, like for the case of cans and bottles, and the tax on the product returned. This provides an upcycling of the plastics, before the quality decay hampers a further re-use, and the plastic can hence undertake a re-cycling for other purposes.

Besides this, knowledge from Sweden, Germany and France are valuable. Here, the ambitions for plastic packaging re-use are supported by quantitative politically targets based on re-use (refill). In e.g., Sweden, the share of re-usable packaging must increase to 20 % from 2022 to 2026, and to 30 % by 2030 [21]. In Germany, at least 70 % of drinking bottles must be re-usable by 2022, and a re-usable packaging choice at take-away restaurants will be given to costumers not adding to expenses. In France 5 % of all packaging materials must be re-usable by 2023 increasing to 10 % by 2027 [21]. Another option could be to make it mandatory for supermarkets to have a flea market section in which grocery and food products are sold without packaging, which in turn are brought as re-usable containers by costumers themselves. This is already seen in some small shops, but not widely disseminated. Besides leading to re-use of packaging - and not necessarily plastics - instead of re-cycling, it could avoid food wastes as costumers are expected only to bring back home what they need.

Watermarks to trace plastic type and origin

As seen from the case studies, companies within the plastic value chain hope for plastic sorting and producer identification systems, like the one investigated in the Holy Grail project, and e.g., commercially available from the Dutch company FiliGrade with their CurvCode watermark reading system applied on plastic packaging products [22]. The watermarks are printed or embossed on the plastic products when being produced, and hence both the origin of the plastic and the specific type of plastic can be identified by sorting machinery using lights and cameras. The color of the plastic is not important, and in this way plastic manufactures are not restricted to avoid the color black, which many customers prefer for their food packaging [20].

The Danish located project 'Holy Grail 2.0' also investigates and test the usability of watermarks on plastic wastes, initiated by the Alliance to end Plastic Waste and the AIM European Brand Association, and includes more than 160 companies who participate in the initiative. Watermark technologies, implementation barriers and investigation of cost improvements are among others assessed in the Holy Grail 2.0 project [23]. The watermark technology can provide valuable data about industries within the plastic value chain, for example which companies do, or do not, utilize re-cycled plastic in their products and to what extent. In this way consumers can require changes, and impact the manufacturing of future plastic products, and regulatory tools are easier targeted relevant stakeholders [24]. Besides this, companies are easier regulated when the origin of plastics are clear, and the companies - on the other hand - will easier be able to get back their own plastic wastes for re-cycling purposes.

Bio-plastic

Bio-plastic is often regarded as a promising future pathway in our use of plastics, and there are overall two types of categories; Bio-degradable plastic and bio-based plastics, which is qualified in the following. *Bio-degradable plastic:* This plastic is interpreted as a solution to the plastic pollution in our natural environment, but the decomposition of the plastic requires temperatures that are not found in the natural environment. Some of the bio-degradable plastics are for example mainly based on fossil fuels like oil or natural gas, like in the case for green food-waste bags in Copenhagen municipality. If the bio-degradable plastic is mixed with other sort of plastic without the same configuration, it will hamper the re-cycling options. *Bio-based plastics* are manufactures from biological materials as for example corn (maize) and sugarcane. Unless the biological feedstock is based on agricultural residues - and not only harvested with the purpose of making plastics - it will also increase the pressure on agricultural land to feed the growing global population [25].

The plastic industry prefers bio-based plastics, as it can be included and re-cycled together with the existing fossil fuel based plastic materials composed of e.g., PET, PE, and PP [20]. Bio-based plastic is regarded as a favorable product as being carbon neutral, by only releasing the amount of carbon when wasted, as it took up when growing. The bio-based plastic could hence act as a carbon sink, taking up CO_2 and hence store it in the plastic product. Thus, its function as a carbon sink in this sense, is only possible if the plastic packaging waste is re-cycled, besides off course being utilized in products with a much longer lifespan than plastic packaging, as for example construction materials [1]. Bio-based plastics can hence prevent the use of traditional virgin feedstock, potentially store carbon when re-cycled and should ideally be produced from agricultural residues only.

PtX plastic

Plastics made from the PtX technology relies on electricity from renewable energy technologies, often windmill electricity, which split water (H_2O) by electrolysis into oxygen (O) and hydrogen (H_2), where the latter can be utilized for various purposes. Hydrogen can e.g., be utilized directly as an energy carrier in the transportation sector and used as fuels for ships, aircraft, and trucks. It can be used in a synthesis process, with for example CO_2 extracted on upgrading biogas plants, which produces methane (CH_2) and supplied to the natural gas network. In smaller quantities, hydrogen can also be injected directly into the natural gas network. Besides methane, hydrogen can furthermore be used to produce other types of fuels and chemicals as kerosene, diesel, methanol, and ammonia when adding nitrogen (N). These fuels are often referred to as e-fuels (electro-fuels) since they are produced using electricity and can be utilized in the production of plastics.

The fuel from PtX is regarded as carbon neutral as it is produced from green power (e.g., from windmills) and carbon (e.g., CO_2 from upgrading biogas) being re-cycled from other usage [26]. PtX can potentially prevent the use of traditional virgin feedstock in the production of plastics. Even though plastics can be made by other resources than fossil fuels (e.g., bio-based & PtX addressed here) the ambitions are still to keep the resource at the highest quality level as long as possible, applying re-use and re-cycling strategies.

Bacterial enzymes and larva re-cycling plastic

Experiments and research are conducted within this field to harvest microbes' enzymes - proteins that speed up chemical reactions - capability to re-cycle certain types of plastics, as for example plastics made from carbon atoms joined by an oxygen atom as opposed to plastic made by bonds linking atoms directly together. Utilizing enzymes to break down e.g., PET could potentially save energy and virgin feedstock, and become a supplement to the current chemical industrial re-cycling processes. Enzymes are seen as a greener approach than current methods and will also be able to target specific types of plastics in the waste mix. The break down process happens as the organisms, by low temperature requirements, feed on the PET plastic, and produces two building blocks: ethylene glycol and terephthalic [27].

Research conducted by [28] demonstrates that biological re-cycled plastics using enzymes, can obtain the same properties as petrochemical PET, hence virgin materials.

The French company Corbios has built a demonstration plant, intended to be upscaled for commercial purposes, and they plan to market re-cycled plastic by means of such enzymatic and bacterial treatment [27]. A partnership with the Danish company Novozymes has been agreed upon for developing enzymes for PET degradation contained in various plastics and textiles. A depolymerizing of PET is conducted in the process where the monomers are purified to be able to re-polymerize the plastic, equivalent in quality to virgin materials. The PET can hereafter be utilized for manufacturing new plastic products [29]. With the increasing demand for re-cycled wastes, such solutions might be viable within near future.

A final method mentioned here, is the use of larvae (worm) for biological treatment of plastic, which currently is in its very infancy of research. The wax worms are the caterpillar larvae of wax moths, which belong to the family *pyralidae* and is a specimen. The enzymes which the caterpillar produces have proven to be able to dissolve plastic as they are reared in a controlled environment, or alternatively, extracted as a sort of concentrated gastric juice to be utilized separately [30]. Both methods described above, if fully adoptable, will maintain the plastic quality at a high utility level and even purify the monomers to be able to re-polymerize the plastic, equivalent in quality to virgin feedstock. A down-cycling and hence contamination of PET, which occur in the existing re-cycling system, can thus be avoided providing promising perspectives for infinite re-cycling in the future.

4. CONCLUSIONS

The exploratory case study has revealed that companies within the Danish plastic value chain are engaged in the transition to utilize more re-cycled plastic, and that a market for re-cycled plastic exists. The research also showed that companies are capable of utilizing re-cycled plastic within their manufacturing processes. There is, however, a need for a thorough mapping of the industry to assess how much and where re-cycled plastic can be utilized within the production processes to substitute virgin feedstock. More sorting plants and re-cycle facilities also needs to be deployed in the future. Adaptation of technology for selected types of plastics that enables re-cycling, are however in operation now for certain types of plastics and deployed by some actors within the plastic value chain. To secure a high quality of re-cyclable plastic, some companies has moreover established bay-back programs, and plan to implement re-cycling facilities in the future. This study further revealed that more emphasis on municipal sorting and collection schemes for household waste must be prioritized, to be able to apply higher circularity of plastic packaging wastes. In the current management of plastics, a down-cycling of the quality is identified, where various types of plastics are being utilized and mixed making re-cycling difficult. More focus on single polymers plastics is thus favorable, e.g., PE, PP and PET. As a future outlook, this paper emphasized *re-use* of plastics, which should be prioritized over re-cycling, and elaborated further on perspectives of the watermark technology capable of identifying both type and origin of the plastic wastes. Plastics made from PtX (electro-fuels) and biomass, if the latter utilized sustainable, could be deployed in large scale to substitute virgin feedstock. Besides this, re-cycling of plastics by means of enzymatic bacterial methods - with potentials to completely sustain the high quality of plastics - were discussed, but the methods however still on an experimental level.

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