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Substitution of trichloroethylene in metal parts cleaning in the European Union

A survey-based study on the effects of the authorisation requirements in REACH

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Responsibility for the content of the report rests with the authors alone. For questions or comments on the report, please contact Dr Daniel Slunge at daniel.slunge@gu.se.

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List of abbreviations

AoA	Analysis of alternatives
AfA	Application for authorisation
CFC	Chlorofluorocarbon
CLP	Classification, labelling and packaging
CO_2	Carbon dioxide
CoRAP	Community rolling action plan
CMR	Carcinogenic, mutagenic and toxic to reproduction
DU	Downstream user
ECSA	European Chlorinated Solvents Association
ECHA	European Chemicals Agency
EPA	Environmental Protection Agency
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HFC	Hydrofluorocarbon
HFE	Hydrofluoroether
HFO	Hydrofluorolefin
IARC	International Agency for Research on Cancer
n-PB	n-propyl bromide
PBT	Persistent, bioaccumulative and toxic
PERC	Perchloroethylene
RAC	Committee for Risk Assessment
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SEAC	Committee for Socio-Economic Analysis
SVHC	Substance of very high concern
TCA	Trichloroethane
TCE	Trichloroethylene
vPvB	Very persistent and very bioaccumulative

Summary

Trichloroethylene (TCE) has been a very common solvent used in metal parts cleaning in the European Union. While several hundreds of European companies were involved in applications for authorised use of TCE after the REACH sunset date in 2016, no applications for renewed authorisation after 2020 have been made. This implies that the legal use of TCE for metal parts cleaning in the European Union has ended. The purpose of this study is to identify what solvents and methods have replaced TCE in metal parts cleaning in the EU and to analyse the role played by the REACH authorisation requirements and other factors in the companies´ substitution decisions. Based on a literature review, interviews with stakeholders and industry experts, and an industry survey, the main findings of the study are:

A large share of the companies that have used TCE in metal parts cleaning under the previous authorisation is instead using perchloroethylene (PERC). As PERC has similar chemical characteristics as TCE, companies can continue to use the same machines after making minor modifications. Some companies have combined the shift to PERC with the introduction of other solvents or methods, mainly modified alcohols.

In some cases, companies continue to use older types of machines (open top) in metal parts cleaning with PERC. This is surprising since the REACH authorisations for the use of TCE only covered closed metal cleaning systems. Older types of machines increase exposure risks.

The costs for substituting TCE with PERC are low. The annualised investment cost to modify machines from TCE to PERC use is around 1900 EUR on average for the surveyed companies. There are no clear trends in terms of changes in overall operating costs when substituting from TCE to PERC.

The substitution from TCE to PERC may at best have created some marginal health benefits. TCE is within the European Union classified as a substance which "*may cause cancer*" and PERC is classified as "*suspected to be carcinogenic*". As the substitution process in most cases has not involved major changes in metal cleaning machines or processes, larger health and environmental benefits have not been achieved.

The main reason for substituting TCE has been to avoid the cost of having to renew the application for authorisation. The majority of the surveyed companies stated that a longer review period would not have influenced their substitution decision.

The inclusion of TCE in the REACH authorisation list incentivized substitution. As the two TCE authorisations for metal parts cleaning covered several hundreds of downstream users, but only 38 companies made actual use of the authorisation, a large share of the companies must have substituted TCE between the years of application (2014) and the years of granted authorisation (2017 and 2018).

The study focuses on those European companies that have been the slowest in substituting TCE. Companies who substituted TCE prior to the sunset date have not been surveyed. The late substitution of TCE among the companies that participated in the survey may partly be explained by industry-specific requirements in for example the aerospace industry. Based on the survey responses in combination with interviews with industry experts, we believe the findings of this study to be representative of the companies under the previous TCE authorisation.

1 Introduction

This study analyses the substitution of trichloroethylene (TCE) in metal parts cleaning in the European Union[1] and the role played by REACH authorisation in this process. TCE is a colourless, non-flammable chlorinated solvent, which has been widely used in primary metal parts cleaning by the European industry. Other uses of TCE includes manufacturing of pharmaceutical compounds and flame retardants where TCE is used as a chemical intermediate, the textile and asphalt industry where TCE is used as an extraction solvent and in paint and pesticides (Brautbar & Wu, 2019). What historically has made TCE such a popular cleaning solvent is its applicability to different kinds of materials. With its relatively low boiling point of 87°C, it can be used on parts where low temperature is critical. As TCE additionally is non-flammable, it has been considered as a safe solvent for workers (Thomas & Ellenbecker, 1996).

With increasing knowledge about the health and environmental effects of exposure to TCE, the substance has been subject to increasingly stricter regulation. Due to the early suspicions of TCE´s carcinogenic properties, the substance has since the 1980s been restricted on a national level by different Member States. For instance, Sweden imposed a law prohibiting the professional use of TCE and methylene chloride in 1991, which entered in force in 1996. The ban did however evolve into a permit system for companies that could not find a substitute (Slunge & Sterner, 2001). Germany instead imposed technical standards for equipment and emissions in 1986, targeting all surface treatments, dry cleaning, textile finishing and extraction equipment using halogenated solvents (Birkenfeld et al., 2005). Norway chose a different type of regulation, by implementing a tax on TCE, which entered in force in 2000. The Norwegian tax did not only cover TCE but also the chemically similar substance perchloroethylene (PERC) (Slunge & Sterner, 2001).

Within the European Union, TCE is classified as a carcinogenic substance and is suspected to be mutagenic, i.e. cause genetic defects[2]. Due to its carcinogenic properties, TCE was included in the candidate list of substances of very high concern (SVHC) for authorisation in 2010 (ECHA, n.d.-f). The substance was further included in the REACH Authorisation list (Annex XIV) on 21 April 2013, thus restricting its use within the European market after the sunset date to those holding an authorisation. The sunset date for TCE beyond which it is not allowed to use TCE without authorisation was set at 21 April 2016 (European Commission, 2013). Consequently, 21 applications for authorisation were submitted to ECHA, whereof two were made for the use of TCE in metal parts cleaning. The two applications from Blue Cube and Chimcomplex covered many downstream users (DUs)[3] who mainly used TCE for metal cleaning purposes. As authorised use of TCE was granted for three to four years by the European Commission, the submissions of review reports for renewed application were due in February 2019 and October 2020 for Chimcomplex and Blue Cube respectively (ECHA, 2020c). However, no review reports have been submitted to ECHA, implying that the hundreds of European companies that were included in the applications for authorised use of TCE in 2014 have substituted TCE in metal parts cleaning.

[1] During the time for this study, the United Kingdom was a member state of the European Union.
[2] Classification according to the CLP regulation https://echa.europa.eu/information-on-chemicals/cl-inventory-database
[3] Downstream user (DU) notifiers are companies that continue to use a substance included in the Authorisation List after its sunset date, based on an authorisation granted up their supply chain. DUs are required to notify ECHA of their use of the substance, according to article 66 in REACH. https://echa.europa.eu/du-66-notifications

1.1 Purpose

The fast substitution of TCE during the 2014-2020 period among hundreds of European companies raises several questions of interest to both industry and authorities. The purpose of this study is to identify what solvents and methods have replaced TCE in metal parts cleaning in the EU and to analyse the role played by the REACH authorisation requirements and other factors in the companies´ substitution decisions.

The study addresses the following research questions:

- What solvents and methods have replaced TCE in metal parts cleaning in the EU?
- What has the cost and benefits of substitution from TCE been for the companies (i.e. investment and operating costs, quality of metal parts cleaning, exposure)?
- What role has the REACH authorisation requirements and other factors played in the companies´ substitution decision?

1.2 Method and data

The study is based on a literature review, interviews with experts and stakeholders, and an industry survey. The literature review included published papers as well as governmental reports and other grey literature. A detailed review of the documents related to the REACH authorisation was conducted, including the applications made by Blue Cube and Chimcomplex for authorised use of TCE in metal parts cleaning which covered DUs.

Empirical data was gathered through a survey distributed to former users of TCE for metal parts cleaning. The survey was developed based on the literature search and the key informant interviews, see appendix A. In the course of survey formulation, questions were first drafted based on the literature search, including the review of applications. To deepen the understanding of the practical replacement of TCE in the metal cleaning industry and refine the questionnaire, several interviews were conducted with industry experts and DU notifiers.

The first part of the survey consists of company-related questions, such as applicable sector, number of employees, and country of operation. The second part targets the substitution of TCE and includes questions about the companies´ previous TCE use, what alternatives companies have replaced TCE with and factors affecting the decision to substitute TCE. The third part of the survey covers investment and operating costs related to the substitution of TCE and in the fourth part, questions relating to companies´ involvement in the authorisation process are included. The full survey is included in appendix B.

The survey was distributed to two different groups of companies. The first group consists of DU notifiers of TCE for metal parts cleaning. Contact details for this group were obtained from the notifications made to ECHA, and the survey was distributed via email to all DU notifiers. Emails with an invitation to answer the survey and a unique weblink to the survey were sent to 38 companies. Following this first invitation, four reminders via email were sent and companies who did not respond to the survey were also reminded via telephone. The second group of companies consists of former TCE users in the United Kingdom. These companies were found through contacts at one solvent distributor and three UK solvent suppliers. In this case, an invitation to participate in the survey was sent to these four contacts which forwarded the invitation and a weblink to the survey via email to their customers. The survey was in this way distributed to approximately 100 companies. The four chemical distributors received reminder emails for further distribution.

1.3 Outline

The report is structured in the following way.

Chapter 2 describes the REACH authorisation process and particularly its relevance in terms of regulating TCE.

Chapter 3 describes metal parts cleaning with different cleaning solvents and methods. The chapter first describes metal parts cleaning with chlorinated solvents, followed by an overview of alternative cleaning solvents and methods. The chapter ends with a comparison of the different cleaning solvents and methods, including technical and chemical properties, hazard classification and costs.

Chapter 4 presents the results of the industry survey.

Chapter 5 discusses and concludes the substitution of TCE within the European Union.

2 REACH authorisation of trichloroethylene (TCE)

This chapter gives a brief overview of the REACH authorisation process and how it has been applied to the authorisation of TCE in metal parts cleaning.

2.1 The REACH authorisation process

Identifying and reducing the risk posed by substances of very high concern (SVHC) is central to the European chemical regulation REACH (registration, evaluation, authorisation and restriction of chemicals) which entered into force the first of June 2007. Article 55 of REACH reads "*to ensure the good functioning of the internal market while assuring that the risks from substances of very high concern are properly controlled and that these substances are progressively replaced by suitable alternative substances or technologies where these are economically and technically viable*".

SVHCs are identified by either Member States or ECHA and are first listed in the Registry of SVHC intention until outcome (ECHA, 2019). Candidate substances can then be moved to the "*Candidate list of substances of very high concern for authorisation*" if their use poses a risk to human health or the environment. Substances may be identified as SVHC if they are either carcinogenic, mutagenic or toxic for reproduction (CMR); persistent, bioaccumulative and toxic (PBT) or very persistent and very bioaccumulative (vPvB); or equivalent level of concern as CMR or PBT/vPvB substances (ECHA, n.d.-d).

Substances on the candidate list can after examination be included in the Authorisation list, Annex XIV in the REACH regulation. The inclusion of an SVHC in the authorisation list is based on the substance intrinsic properties; wide dispersal use or high volumes (ECHA, n.d.-c). The purpose of the authorisation process is to ensure that less dangerous substances or technologies progressively replace SVHCs, where technically and economically feasible alternatives are available. Once included in the authorisation list, substances are given a sunset date beyond which the use of the substance requires authorisation. Continued use is thus only possible if granted an authorisation. Companies applying for authorisation need inter alia to provide the use applied for, a chemical safety report, an analysis of alternatives (AoA), and a socio-economic assessment (SEA) of the costs and benefits to society of continued use of the SVHC (ECHA, 2021c).

An application for authorisation can be made by either an individual company or several companies jointly. Each application for authorisation (AfA) is "use-specific", meaning that authorisation is granted for a specific use of an SVHC (ECHA, 2021c). An application can however include one use or several different uses of a substance. The AfA is after a public consultation evaluated by the Committees for Risk Assessment (RAC) and Socio-economic Analysis (SEAC). RAC and SEAC then draft an opinion on whether to grant the authorisation or not, based on the application and information received in the public consultation. The European Commission makes the final decision. An authorisation is granted either if the risk from using the SVHC is assessed to be adequately controlled, or when the socio-economic benefits of continued use of the substance outweigh risks and there are no suitable alternatives for the applicant(s) (ECHA, 2021c). If granted an authorisation, the use of the substance is subject to conditions in the application's chemical safety report, and potentially additional conditions imposed by the Commission. The Commission´s decision also includes the review period, i.e. the duration period of a granted authorised use of an SVHC. If a company needs to continue to use an SVHC after the review period, it must apply for a renewed authorisation by submitting a review report, no later than 18 months before the review period ends. DUs do not need to apply for authorisation if an actor upstream holds a granted authorisation. DUs should however notify their usage to ECHA within three months of the first supply of the substance (ECHA, n.d.-b).

The authorisation process involves certain costs. Applying for authorisation requires the preparation of several documents which is often time-consuming. Companies may therefore choose to hire consultants which prepare the application. Apart from this, there is also an application fee to be paid. The application fee varies between applications and depends on volumes applied, whether the application is submitted jointly by several companies or by an individual company and the size of companies applying. Small- and medium-sized companies and joint applications are entitled to reduced fees (European Commission, 2008).

2.2 The REACH authorisation process for TCE in metal parts cleaning

Due to its proven carcinogenic properties, TCE was included in the *Candidate List of substances of very high concern for Authorisation* in June 2010 (ECHA, n.d.-f). In 2013, ECHA further prioritised TCE from the Candidate List of SVHCs for authorisation for inclusion in Annex XIV (i.e. the authorisation list) due to the high volume used and the risk for significant exposure for industrial workers for some uses (European Commission, 2013). The sunset date for TCE was set to 21 April 2016 (ECHA, n.d.-a). Consequently, 21 applications for authorisation (AfAs) were made, covering several different uses of TCE. For the use of TCE in metal parts cleaning, the two applicants, Chimcomplex and Blue Cube, were granted authorisation in 2017 and 2018 respectively.

Table 1 summarises the applications made by Blue Cube and Chimcomplex, which covered more than 650 DUs. Only 38 companies notified ECHA that they made use of the authorisation.

Table 1 Authorisation for metal parts cleaning with TCE.

Authorisation holder	**Chimcomplex S.A. Borzesti**	**Blue Cube Germany Assets GmbH & Co. KG**
Use	Industrial use of trichloroethylene as a solvent as a degreasing agent in closed systems	Use of trichloroethylene in industrial parts cleaning by vapour degreasing in closed systems where specific requirements (system of use-parameters) exist
Application number	REACH/16/19/0	REACH/18/19/0
Date of application	17 October 2014	18 August 2014
Date of authorisation decision	8 February 2017	8 October 2018
Nr of DU notifications	22	17
Nr of notifying companies	22	16
Aggregated annual volume used by notifying DUs [tonne/year] *	13.5 – 135.0	103.0 – 1030.1
End of review period	21 February 2019	21 October 2020

Source: (Chimcomplex SA Borzesti, 2014; DOW Deutschland Anlagengesellschaft mbH, n.d.; ECHA, 2020c; European Commission, 2017, 2018)

* The annual volumes were calculated by adding annual tonnage notified by the DUs in respectively application. Note, that not all companies provided a volume range.

The authorisation sent by Blue Cube covered five uses of TCE, whereof one use was for "*its use in industrial parts cleaning by vapour degreasing in closed systems…*". The application was granted since the socio-economic benefits outweighed the risks to human health and the environment. However, as RAC concluded that the risk management measures and operational conditions described in the application's chemical safety report were not appropriate and effective in limiting the risk to workers, additional conditions were included in the decision (European Commission, 2018). According to article 2 in the Commission's decision for Blue Cube, the use of TCE in industrial parts cleaning is subject to the following condition "*ECSA Type III machines shall be replaced with Type IV or preferably Type V machines at the latest by the end of their service life and in any event by 3 February 2020, unless it is possible to substitute trichloroethylene with an alternative*" (European Commission, 2018, p. 5). Another condition was that the authorisation holder's DUs should provide a written declaration to ECHA. The declaration should include that the DU has assessed that no suitable alternatives to TCE exist for their use, as well as a confirmation that the DU has applied the risk management measures indicated in the exposure scenarios. It is additionally stated, that in the written declaration "*the authorisation holder's downstream users shall confirm the use of trichloroethylene exclusively in ECSA type IV or V machines at the latest by the end of the service life of the ECSA Type III machines and in any event by 3 February 2020*" (European Commission, 2018, p. 6). The review period for Blue Cube was set to 54 months (European Commission, 2018).

The authorisation sent by Chimcomplex only covered the single-use of TCE as "*a solvent as a degreasing agent in closed systems*". The Commission approved the application with similar motivation as for Blue Cube and provided that risk management measures and operational conditions described in the application's chemical safety report, as well as additional conditions (article 2) and monitoring arrangements (article 4) set out in the decision, were fully applied. As for Blue Cube, the Commission stated that type IV or V machines should replace type III machines by the end of their service life. There is however no latest date for this exchange stated in the decision for Chimcomplex, as there is for Blue Cube (European Commission, 2017, p. 5). Even though conditions for monitoring arrangements and occupational measurements are similar for both Blue Cube and Chimcomplex, the condition of submission of a written declaration from DUs are missing in the decision for Chimcomplex. The review period for Chimcomplex was set to 34 months, which was longer than the 26 months review period proposed by SEAC. The reason for the longer review period was that the sunset date had already passed when the Commission's decision was made. If given only 26 months, Chimcomplex would not have been able to submit a review report, which needs to be submitted at least 18 months before the expiry of the review period (European Commission, 2017).

At the end of the review periods, February 2019 for Chimcomplex and October 2020 for Blue Cube respectively, they are no longer authorised users of TCE for metal parts cleaning and no review reports for a renewed authorisation have been submitted (ECHA, 2020c).

3 Metal parts cleaning

In metal processing, metal cleaning is an essential process where contaminants, such as grease, oils, soils or particles are removed from metal parts. As metal parts are typically covered in grease or oil when cut or processed, to reduce friction or prevent corrosion between different process steps, metal cleaning is required to enable metal parts to be prepared for further assembly or surface treatments, such as electroplating or painting (Slunge & Sterner, 2001). Metal parts cleaning is carried out by metal processing companies, including many small and medium-size companies, operating in a wide range of sectors, such as aerospace, automotive, energy, defence and medical industry. Metal parts cleaning is mainly carried out either with the use of solvents or aqueous cleaning systems.

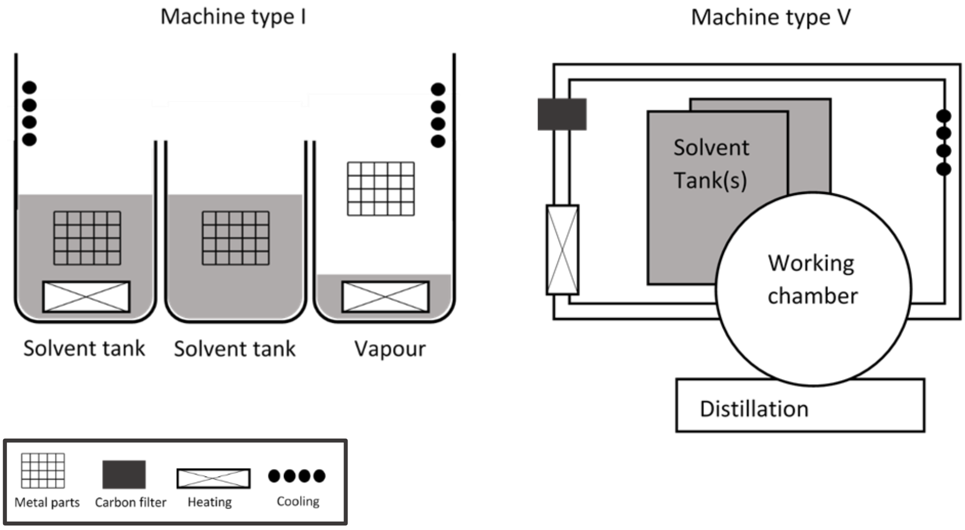
3.1 Metal parts cleaning with TCE and other chlorinated solvents

Chlorinated solvents have historically been widely used as cleaning solvents in the metal industry. Due to their chemical properties such as non-polarity, high volatility and non-flammability, chlorinated solvents are efficient cleaning agents and can be applied to a variety of materials (Harrington et al., 2004). Besides TCE, perchloroethylene (PERC) and methylene chloride (also known as dichloromethane) are examples of other chlorinated solvents used in metal parts cleaning. Historically, trichloroethane (TCA) and chlorofluorocarbons (CFCs) have also been used for similar purposes but were phased out through the Montreal Protocol due to their ozone-depleting properties (Slunge & Sterner, 2001).

Developments of metal parts cleaning machines

The cleaning process with chlorinated solvents has undergone various changes since the mid-1980s. Historically, very simple machines were used, with immersion cleaning in open-top systems, where metal parts were brought manually to the cleaning bath and dipped in solvent media, see figure 1. These machines consisted typically of one or two liquid pre-baths where the parts were dipped and then followed by a vapour bath for final cleaning (Birkenfeld et al., 2005; ECSA, 2021). Due to the open-top system, vapours of the volatile chlorinated solvents used were emitted into the surrounding air, posing a high exposure risk for workers. According to the nomenclature developed by the European chlorinated solvent association (ECSA), these early open bath systems are classified as type I machines. The type II machines operate similarly, but the whole cleaning equipment is encased with a vented air lock for loading and unloading of metal parts. The type II machines also operate with automatic transport of goods and some models are additionally equipped with a carbon filter for solvent abatement for exhaust air (ECSA, 2021).

Figure 1 Metal cleaning machine type I and V.

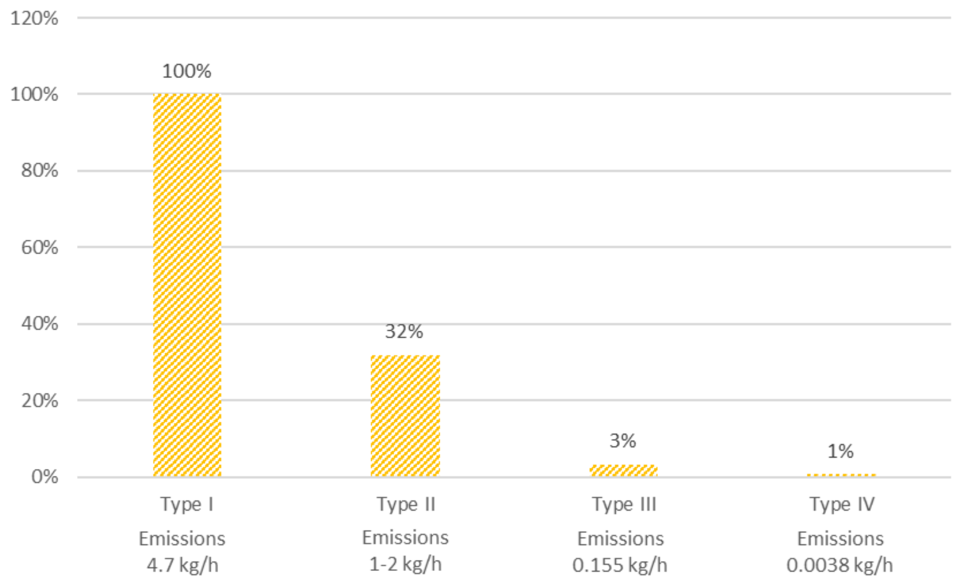


Source: Authors based on (Birkenfeld et al., 2005; ECSA, 2021; Kikuchi et al., 2010)

A more fundamental change in the cleaning equipment was first seen with the introduction of the type III machines. These machines consist of a closed single chamber and enable the reuse of the cleaning solvent (ECSA, 2021). Cleaning is for these machines achieved by vapour degreasing and the machines have a heating zone, typically in the bottom, and a cooling zone, typically near the top. The solvent is heated until nearly boiling point and thus, evaporates. The solvent vapour can then condense on the dirty metal parts and dissolve the contaminants and drain back into the tank, after distillation. In this way, the solvent can be recycled and used in several cleaning cycles (Thomas & Ellenbecker, 1996). With these closed systems, air emissions were drastically reduced. The type III machines can however not be considered as completely closed, as vapour is still vented out into surrounding air. The type IV machines are operating similarly but without a vent (ECSA, 2021). In these machines, the air is additionally directed over an activated carbon filter, before re-entering the working chamber (Birkenfeld et al., 2005). The latest cleaning technology, the type V machines, operate similarly as type IV machines but use vacuum technology for drying, see figure 1. By using vacuum technology, the working chamber and distillation is kept under reduced pressure during operation, which enables improvements such as an extended lifetime of the cleaning solvent due to lower temperature, improved drying and reduced waste (ECSA, 2021).

Figure 2 illustrates emission reductions when switching from a type I to more advanced machines. According to ECSA (2021), a 99% reduction of emissions can be achieved, when comparing a type I with a type IV machine (data for type V machine is not available).

Figure 2 Air emissions for different cleaning systems.



Source: (ECSA, 2021)

Risk management developments

Besides large developments in metal parts cleaning machines, developments have also taken place in the management of risks from transports, storage and disposal of solvents. Safechem, which distributed the solvents for the Blue Cube authorisation, has developed a leasing business model where customers are offered a cleaning solution, including transport, storage and handling of the solvent, and not only a cleaning solvent (DOW Deutschland Anlagengesellschaft mbH, n.d.). In this leasing service, Safechem also helps customers with monitoring the cleaning process and educates customers in handling the cleaning solvent safely. By managing the supply chain of solvents, emission reduction from transport and handling have been possible according to the company. The leasing model applies to all solvents supplied by Safechem (personal communication with a solvent distributor, 2021).

Trichloroethylene (TCE)

TCE is a colourless, non-flammable chlorinated solvent, with a boiling point of 87°C. It is a highly volatile[4] and stable solvent with a vapour pressure of 99hPa at 25°C (ECHA, 2021e). TCE has historically been widely used for metal parts cleaning purposes by European industries due to its great solvency properties and applicability to different kinds of materials (Thomas & Ellenbecker, 1996). TCE decomposes naturally in contact with air and forms phosgene, hydrogen chloride, and dichloroacetyl chloride[5]. In contact with water, TCE becomes corrosive and forms dichloroacetic acid and hydrochloric acid.

TCE is manufactured and/or imported to the European Union at ≥10 000 tonnes annually (ECHA, 2021e). Due to technological developments of cleaning equipment, stricter regulation and industry voluntary agreements, there has been an extensive reduction in the use of TCE.

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[4] Volatility is a measure of a liquid's tendency to evaporate at normal temperature and pressure. A substance volatility depends on its vapour pressure.

[5] https://www.euro.who.int/__data/assets/pdf_file/0003/123069/AQG2ndEd_5_15Trichloroethylene.pdf

TCE has been proven to have environmental- and health-hazardous properties and has consequently been subject to increasingly stricter regulation over the years. TCE is within the European Union classified as a substance that "*may cause cancer*" with classification code Carc. 1B and is suspected to be mutagenic, i.e. may cause genetic defects (classification code Muta. 2)[6]. TCE causes also skin and eye irritation and is hazardous to the aquatic environment.

Due to its carcinogenic properties, TCE is subject to the REACH regulation and its use requires an authorisation within the EU, see chapter 2. Legal requirements have also been accompanied by voluntary agreements within the industry, to reduce the risk posed by the substance. In 2007, the European Chlorinated Solvent Association (ECSA) issued a TCE charter, where signing parties committed to phasing out sales of TCE for open metal cleaning systems by December 31, 2010 (ECSA, 2007). This commitment meant that after 2010, TCE is only delivered by signing parties to end-users using a type III machine or higher. This voluntary agreement also included that the signing parties should inform end-users about this industry agreement as well as provide them with essential information about closed cleaning systems. The requirements were also declared to be incorporated into the signing parties´ distribution contracts. Both Chimcomplex and Blue Cube (at that time; DOW), are listed among the four signing parties.

Other organizations and governments have also recognized the carcinogenic properties of TCE. The International Agency for Research on Cancer (IARC) classified TCE as "*carcinogenic to humans*" in 2014 (IARC, 2021). TCE is also classified as "*carcinogenic to humans*" by the United States Environmental protection agency (U.S. EPA) (United States Environmental Protection Agency, 2011b). TCE has recently been re-evaluated by the U.S. EPA, where the agency released its final risk evaluation in November 2020. The evaluation found unreasonable risks to workers, occupational non-users, consumers, and bystanders for 52 out of 54 uses of TCE, including the uses "*industrial and commercial use as a solvent for open-top batch vapour degreasing*" and "*industrial and commercial use as a solvent for closed-loop batch vapour degreasing*" (United States Environmental Protection Agency, 2020e). The agency will now propose regulations to reduce these present risks.

Perchloroethylene (PERC)

PERC (also known as tetrachloroethylene) is a chemically similar substance to TCE. PERC is a volatile liquid and tends to volatilize quickly when released to surface water or surface soil. It is mobile in soil and therefore has the potential to leach below the soil surface and contaminate groundwater (Brautbar & Wu, 2019). The substance has a boiling point of 121°C, which is higher than that for TCE, and a vapour pressure of 25hPa 25°C (ECHA, 2021d). PERC can also biodegrade to TCE, TCA, vinyl chloride or ethene through reductive dechlorination (Brautbar & Wu, 2019). PERC has mainly been used as a chemical intermediate, but also in dry-cleaning and metal parts cleaning (ECSA, 2015). For dry-cleaning purposes, PERC is the number one substance used in Europe (ECSA, 2020). The global consumption of PERC, TCE and TCA in 2020 was estimated to around one million metric tons, with PERC constituting approximately 50% of the total amount (IHS Markit, 2020). PERC is manufactured and/or imported to the European Union at ≥100 000 to <1 000 000 tonnes annually (ECHA, 2021d).

PERC has similar hazardous properties as TCE but is not subject to the same legal constraints as TCE. PERC is classified as "*suspected to be carcinogenic*" within the European Union (classification code Carc. 2) and is not included in the REACH candidate list for authorization. PERC is also classified as toxic to aquatic life with long-lasting effects (having classification code Aquatic Chronic 2) (ECHA, 2021d).

[6] Annex I in https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R1272&from=EN

Due to the wide and dispersive use of the PERC and concerns about potential PBT and CMR properties, the substance was evaluated by Latvia in 2013 under the Existing Substances Regulation (EC) No. 793/93[7]. The evaluation found that PERC fulfilled criteria for persistence (P), but not for bioaccumulation (B) and toxicity (T). As PERC was not found to be a PBT nor a CMR substance, the evaluation concluded that there is "*no need of further risk management measures*" (Latvian Environment, Geology and Meteorology Centre, 2014).

The IARC classified PERC as "*probably carcinogenic to humans*" in 2014 (IARC, 2021). In the United States, PERC has a similar hazard classification: "*likely to be carcinogenic to humans*" (United States Environmental Protection Agency, 2000, 2012). The U.S. EPA has however just recently re-evaluated PERC and released a final chemical risk evaluation in December 2020, concluding that there are "*unreasonable risks to workers, occupational non-users, consumers and bystanders from 59 out of 61 uses*" of the substance (United States Environmental Protection Agency, 2020d). Included in the 59 uses are "*industrial and commercial use as solvent for open-top batch vapour degreaser*" and "*industrial and commercial use as solvent for closed-loop batch vapour degreaser*". The agency will now propose regulations to reduce these present risks.

Methylene chloride
Methylene chloride (or dichloromethane) is a colourless and volatile liquid with high vapour pressure, belonging to the family of chlorinated methanes (Dekant, Jean, & Arts, 2020). Methylene chloride is classified as a non-flammable liquid, even though it is flammable under certain conditions[8]. Compared to TCE and PERC, methylene chloride has a rather low boiling point of 39.6°C and a vapour pressure of 58.4hPa at 25°C (ECHA, 2021b). The substance is mainly used for synthesis, extraction and purification purposes, e.g. of pharmaceutically active substances such as caffeine and antibiotics. It is further used in applications such as paint strippers and as a cleaning solvent for metal parts. The substance is a high production volume chemical with a current global industrial production of 0.8-1.3 million tons per year, of which less than 10% is used within Europe (Dekant et al., 2020). Methylene chloride is produced and/or imported to the European Union at ≥100 000 tonnes annually (ECHA, 2021b). The substance is also produced naturally by processes in seawater and soils, and by biomass burning (Dekant et al., 2020).

Methylene chloride is classified as "*suspected to be carcinogenic*" (category code Carc. 2) within the European Union (ECHA, 2021b). It is not included in the REACH candidate list for authorisation, but some uses of the substance are restricted under Annex XVII of REACH. The substance is under evaluation by Italy within CoRAP[7], due to concerns of methylene chloride being carcinogenic, suspected mutagenic and reprotoxic, potential endocrine disruptor and suspected sensitiser and additionally due to high (aggregated) tonnage (ECHA, 2020b). The evaluation started in 2016 and Italy has recently submitted an intention for re-classification of the substance from a Carc. 2 – "*suspected to be carcinogenic*" to a Carc. 1B – "*may cause cancer*" (ECHA, 2020a).

The IARC has classified the substance as group 2A – "*probably carcinogenic to humans*" in 2017 (IARC, 2021). In the United States, methylene chloride is classified as "*likely to be carcinogenic to*

[7] Substances targeted for evaluation are listed in the Community rolling action plan (CoRAP), and aims to clarify whether a substance constitutes a risk to human health or the environment. CoRAP substances are evaluated by EU Member States.

[8] The flammable limit of methylene chloride in air is between 13 and 22 volume percent at 20°C, although the vapour formed is hard to ignite (Ohligschläger et al., 2019).

humans" (United States Environmental Protection Agency, 2011a). In similarity with PERC, methylene chloride is receiving attention in the US for risks related to the use of the substance. In June 2020, the U.S. EPA concluded the final risk evaluation for methylene chloride, finding that there are "*unreasonable risks to workers, occupational non-users, consumers and bystanders under 47 out of 53 conditions of use*" (United States Environmental Protection Agency, 2020a). Included in the 47 uses is "*industrial and commercial use as solvent for batch vapour degreasing*" (United States Environmental Protection Agency, 2020c). Vapour degreasing being stated to include open-top and closed-loop vapour degreasing. The agency will now propose risk management strategies.

3.2 Metal parts cleaning with non-chlorinated solvents and aqueous cleaning

Besides chlorinated solvents, several other non-chlorinated solvents and methods can be used in metal parts cleaning. The following section describes water-based cleaning and some alternative non-chlorinated solvents.

Aqueous cleaning

Aqueous cleaning has been used for a long time by the metal parts cleaning industry and generally combines a water-based cleaning solution with mechanical action like spray pressure, agitation or ultrasonic. The water-based cleaning solution can be either alkaline, acidic or neutral. Alkaline cleaners are viewed as the most viable and used cleaners as they are capable of removing nearly any type of contaminants from the metal parts (Underwood & Thomas, 1995). The cleaners often contain a mixture of different substances, adding certain properties to the cleaning solution (DOW Europe GmbH, n.d.). Components of the cleaners can be divided into three categories: surfactants, builders and additives. Surfactants are surface-active agents, and builders such as phosphates, carbonates, hydroxides and other inorganic alkaline salts often amplify their effect. Different additives act primarily as contaminant dispersants, water softening agents, detergent fillers and corrosion inhibitors (Underwood & Thomas, 1995).

A typical water-based cleaning process entails washing, rinsing, and drying. Metal parts are typically passed through the cleaning process automatically and dipped into the washing and rinsing tanks. Washing tanks are filled with the water solution of aqueous chemicals while the rinsing tanks are filled with water. The metal parts are then dried using drying machines such as hot air blowing or vacuum drying (Kikuchi et al., 2010). Different levels of cleanliness depend on the number of different tanks and the purity of water for washing and rinsing. To amplify the cleaning level achieved by the aqueous chemicals, the washing and/or rinsing steps can include mechanical action, for instance ultrasonic. Ultrasonic cleaning uses high-frequency sound to create waves in the liquid. This is normally performed at frequencies ranging from approximately 20 to 200 kHz, and the high-intensity sound waves create cavitation bubbles which will collapse and thus create impulsions, which enhance the removal of contaminants from surfaces (Fuchs, 2015).

Instead of the immersion (i.e. dipping) aqueous solution, water-based spray cleaning is a common method. These machines are often more compact and cleaning is achieved by the impact of the high-velocity stream of the aqueous solution with the surface being cleaned. In this way, the kinetic energy of the spray improves the cleaning action of the aqueous solution. Although this spray method is limited to only cleaning surfaces with direct access to the spray nozzle, a combination with for instance injection or immersion cleaning can be provided to clean hidden areas, such as inside a hollow metal part piece (personal communication with machine manufacturer, 2021).

Alcohols, modified alcohols

When cleaning with alcohols, the cleaning effect is determined by the solvency power of the alcohols used. Blends of alcohols are typically used, with one base product (personal communication with a solvent distributor, 2021). The blends allow the cleaning of both polar and non-polar contaminants[9]. Examples of alcohols used are isopropyl and butoxypropanol.

Cleaning with modified alcohols is undertaken in a similar way as with chlorinated solvents. Metal parts are immersed in the alcohols (or sprayed), where contaminants are dissolved in the cleaning solvent. To achieve a higher level of cleanliness, mechanical action such as ultrasonic can be used. After cleaning, follows vapour drying for metal parts and distillation for solvent media. Through distillation, the reuse of alcohols is possible. Cleaning with modified alcohols is thus operated within closed single chambers, as for chlorinated solvents. One distinct difference from chlorinated solvents is that alcohols cannot be used in open-top systems, due to their flammable properties. This can partly explain why the historical use of cleaning with alcohol has been limited (personal communication with a solvent distributor, 2021).

n-Propyl Bromide (nPB)

The halogenated hydrocarbon solvent n-propyl bromide (nPB) (also known as 1-bromopropane) is a highly flammable liquid with a boiling point of 71°C (ECHA, 2021a). It has a high vapour pressure, making it well suited for cleaning through vapour degreasing (TURI, 2009). The substance is within the EU classified as toxic for reproduction (classification code Repr. 1B – "*Presumed human reproductive toxicant*")[10], causes serious eye irritation, may cause damage to organs through prolonged or repeated exposure, causes skin irritation, may cause respiratory irritation and may cause drowsiness or dizziness. Due to its reproductive toxicity properties, nPB was included in the REACH candidate list for authorization in 2012 (ECHA, n.d.-e) and was further included in the authorisation list where the sunset date was set to July 4th, 2020 (ECHA, n.d.-a). As no applications for authorisation have been submitted to ECHA, n-PB is not used within the EU for any purposes. nPB was earlier used as a substitute for TCE in metal parts cleaning in the UK (personal communication with a solvent distributor, 2021).

In the United States, nPB has increasingly been used as a substitute for ozone-depleting substances and chlorinated solvents. This trend has not been without concern and the use of nPB has recently caught attention (United States Environmental Protection Agency, 2020b). The U.S. EPA published a final risk evaluation for nPB in august 2020, finding unreasonable risks to the general population, as well as unreasonable risks to human health for consumers, by-standers, workers and occupational non-users. Among the 16 uses where unreasonable risks were found, are "*industrial and commercial use as solvent for cleaning and degreasing in vapour degreaser (batch vapour degreaser – open-top, inline vapour degreaser)*" and "*industrial and commercial use as solvent for cleaning and degreasing in vapour degreaser (batch vapour degreaser – closed-loop)*" (United States Environmental Protection Agency, 2020b).

[9] https://www.productionmachining.com/blog/post/the-right-solvent-creates-the-cleanest-parts

[10] Annex I in https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R1272&from=EN

Other cleaning solvents
Other cleaning solvents and methods include among others hydrocarbons, fluorinated solvents and carbon dioxide.

Hydrocarbons are petroleum-based solvents, with a chemical structure containing hydrogen and carbon. Some solvents can have complex chemical structures and consist of long carbon chains. Within hydrocarbon solvents, there are two main types: aliphatic and aromatic solvents. Aliphatic solvents have a straight-chain, branched or cyclic hydrocarbon structure and are used as metal cleaning solvents as well as in manufacturing. Some examples are gasoline, kerosene and hexane. Compared to the aromatic hydrocarbons, the aliphatic solvents have a narrower boiling range and higher solvency. Aromatic solvents are widely used as degreasing agents and contain a benzene ring structure. Examples of aromatic hydrocarbons are benzene, xylene, naphtha, white spirits, mineral spirits and toluene[11] (United States Environmental Protection Agency, 1994). Hydrocarbons work by dissolving organic soils.

Due to their chemical properties of non-flammability, low toxicity, and thermal and chemical stability, fluorinated solvents have been widely used in metal parts cleaning. In the early days, chlorofluorocarbon (CFC)-based and hydrochlorofluorocarbon (HCFC)-based solvents were frequently used in metal parts cleaning. CFCs and HCFCs were however included in the Montreal Protocol due to their ozone depletion and global warming potential and have since the mid-90s been phased out gradually (MicroCare Europe BVBA, 2020). The industry replaced CFCs and HCFCs partly with other fluorinated solvents, such as hydrofluorocarbon (HFC)-based and hydrofluoroether (HFE)-based solvents, with low or zero ozone depletion potential. However, both HFCs and HFEs have high global warming potential and HFCs were added to the list of controlled substances in the Montreal Protocol through the Kigali amendment in 2016[12]. Newer fluorinated substances with low or zero ozone depletion and global warming potentials, such as hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs), are replacing HFCs and HFEs in industrial solvent applications[13].

Fluorinated solvents are often blends, where added substances increase solvency properties or decrease costs. In several cases, the blends constitute a major part (70-90%) of the chlorinated substance called trans-1,2-dichloroethylene (personal communication with solvent supplier, 2021). Examples of such blends are Opteon SF80 Special Fluid[14] or the 3M Novec 72DE fluid[15].

Cleaning with carbon dioxide (CO_2) can be done by using blasting or super critical fluids. Carbon dioxide blasting begins with the conversion of liquid CO_2 into solid. As the CO_2 impact the metal surface, it sublimes, i.e. returns to the gaseous phase. The cleaning action occurs as the sublimation causes turbulence on the surface and lifts off the contaminants. The CO_2 gas and contaminants are then passed through a high-efficiency particulate air filter where the particles are collected and the gas released (Thomas & Ellenbecker, 1996). Super critical fluids are in the intermediate state between gas and liquid and benefit from physical properties combining the diffusivity of gases and the high solubility of liquids. Super critical CO_2 can thus easily penetrate the smallest holes on surfaces while at the same time dissolve contaminants. CO_2 is further non-toxic, non-flammable, and by using super critical CO_2, it is easily recycled and easily removable from metal parts. As supercritical CO_2 behaves as a non-polar solvent, it is most efficient in removing non-polar contaminates (Liu et al., 2015).

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[11] https://www.envirotechint.com/blog/basic-industrial-cleaning-types-of-chemical-solvents/
[12] https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol
[13] https://www.fluorocarbons.org/high-performance-solvents/
[14] https://www.opteon.com/en/products/specialty-fluids/sf80
[15] https://multimedia.3m.com/mws/media/1213830/3m-novec-72de-engineered-fluid.pdf

3.3 Comparison of metal parts cleaning solvents and methods

There exist several substances and methods, which may be used for metal parts cleaning purposes, as described in the above sections. The suitability of alternatives are however very case-specific and several factors influence a company´s choice of substitution substance or method.

Table 2 illustrates the main metal parts cleaning solvents and methods described previously in this chapter and compares their key chemical and technical properties.

Table 2 Chemical and technical properties of cleaning solvents and methods.

	Trichloroethylene	Perchloroethylene	Methylene chloride	Aqueous cleaning	Modified alcohols
Key chemical properties	Non-flammable Boiling point: 87°C Non-polar Volatile	Non-flammable Boiling point: 121°C Non-polar Volatile	Non-flammable Boiling point: 39°C Polar Volatile	Non-flammable Polar	Flammable Polar/Non-polar
Type of cleaning process	Vapour cleaning	Vapour cleaning	Vapour cleaning	Immersion (with ultrasonic) Spraying	Immersion (with ultrasonic) Spraying
Equipment specifics	Single chambers Open or closed equipment	Single chamber Open or closed equipment	Single chambers Open or closed equipment	Multi chambers	Single or multi chambers Closed equipment
Cleaning performance	High solvency for non-polar contaminants (e.g. oils, grease)	High solvency for non-polar contaminants (e.g. oils, grease)	High solvency for non-polar contaminants (e.g. oils, grease)	High solvency for polar contaminants (e.g. salts, dust, particles)	Good solvency for most contaminants
Cleaning process properties	High recycling of solvent Dried parts after the cleaning process	High recycling of solvent Dried parts after the cleaning process Higher energy demand, compared to TCE	High recycling of solvent Dried parts after the cleaning process Lower energy demand, compared to TCE	Limited recycling of water and chemical additives Drying required after cleaning process – high energy demand	Recycling of solvent Drying required after cleaning process
Environmental releases	Air emissions	Air emissions	Air emissions	Waste water	
Conversion of TCE machine possible	-	Yes	Yes	No	Yes/No

Sources: (Brautbar & Wu, 2019; Dekant et al., 2020; ECHA, 2021a, 2021b, 2021d, 2021e; ECSA, 2021; Kikuchi et al., 2010; Thomas & Ellenbecker, 1996; Underwood & Thomas, 1995). The information presented is also based on interviews with metal cleaning machine manufacturers and industry experts see appendix A.
Note: n-propyl bromide is not included in the comparison of cleaning solvents and methods, since there is no application for authorisation for the use of the substance within the EU.

One way to find an alternative to TCE is to search for a chemically similar substance, which is technically feasible with existing equipment and achieves similar cleaning quality, a so-called "drop-in" solvent. Substituting TCE with a chemically similar substance can be beneficial for companies, both from an economic and technical perspective. As large investments often have been made in the cleaning equipment, companies may wish to continue to use their equipment during its entire lifespan As a drop-in solvent may only require minor adjustments to existing equipment, companies can rather easily switch from TCE to a substance that does not require authorisation. Substituting TCE with a chemically similar substance, such as PERC, thus results in an incremental change, rather than a fundamental change (Fantke et al., 2015).

Chemical substitution may not only result in solvent replacement but could instead imply changes in operating processes or technology to reduce risks (Goldenmann et al., 2017). This could include a change of metal cleaning equipment or a change of operating processes. With changes in operating processes or better process timing, the need for metal cleaning could even be reduced.

A core element in the substitution decision of TCE is what type of metal parts are to be cleaned, the level of cleanliness required, and what type of contaminants the cleaning process should remove. This is mainly a function of the polarities[16] between the different substances (solvent and contaminant), which influence a substance´s solubility. The general rule within the industry is "*like dissolves like*" and thus, non-polar cleaning solvents (such as TCE or PERC) are appropriate for non-polar contaminants (such as fats and oils). While polar cleaning media (such as water) is more appropriate for polar contaminants (such as salts or dust).

Another factor influencing the decision on how to substitute TCE may be operating space in terms of area. As indicated by several industry experts, many metal part cleaners within Europe are small- and medium-sized companies, and may thus be limited in their substitution choice by physical constraints, as some cleaning equipment require a lot more space compared to others. According to one manufacturer of aqueous cleaning solutions, typical water-based cleaning equipment consist of between 5 to 20 tanks, depending on the cleanliness preference, compared to a single chamber used for chlorinated solvents. The size of the cleaning equipment is also dependent on the parts to be cleaned, for instance, larger metal parts (such as metal sheets) require large chambers. Smaller companies may therefore encounter problems with alternative cleaning solutions, compared to TCE and other chlorinated solvents.

Cleaning with chlorinated solvents, modified alcohols or aqueous cleaning media, differ in several aspects. As can be seen in table 2, TCE, PERC and methylene chloride operates under similar conditions and can be used with the same type of equipment, i.e. vapour degreasing machines type III-V. The difference between the chlorinated alternatives is mainly their respective boiling point. Due to the higher boiling point of PERC, more energy is required to make the solvent evaporate, while the opposite applies to methylene chloride. However, as pointed out by one metal degreaser machine manufacturer, there is only a small change in energy demand when switching from TCE to another chlorinated solvent.

The cleaning solvents and methods also differ in terms of air and water emissions. While the volatile chlorinated solvents and modified alcohols mainly cause air emissions, cleaning with water leads to emissions to water. For solvent cleaning, emissions consist of solvent vapour only, while in aqueous cleaning, emissions include both additives used in the cleaning water, as well as contaminants removed from the metal parts.

Another difference between aqueous cleaning and solvents cleaning is the possibility of solvent recycling when cleaning with solvents. Even though the water used for aqueous cleaning can be reused to some extent, (e.g. several cleaning processes goes through the same cleaning tanks),

[16] Polarity of a substance indicates how the electric charges are distributed within a molecule and how its electrostatic forces acts outside the molecule.

solvents can be reused for a longer time. As solvents are separated from contaminants through distillation, the solvents are "cleaned" between the metal parts cleaning processes and can thus be reused, achieving the same cleaning level. In aqueous cleaning, the contaminants are mixed into the cleaning media, and thus requires a change of water baths to renew the cleaning media.

A final difference between aqueous and solvents cleaning is the drying process of metal parts. When cleaning with solvents, the metal parts are dried as a final step in the cleaning process, while for aqueous systems, the parts are not dried in the cleaning process, but drying must be added as a second process step before further processing.

3.3.1 Trends in metal parts cleaning

Interviews with several machine manufactures indicate that there is a general trend towards increased use of modified alcohols and aqueous cleaning systems. One manufacturer mentions that 50% of their customers use aqueous cleaning systems and 50% use modified alcohols. This company also provides cleaning systems for chlorinated solvents, but its use has become negligible. A second manufacturer mentions that 90% of their customers use modified alcohols while 10% use PERC. A third manufacturer mentions that 60% of their customers use aqueous cleaning and 40% use modified alcohols. According to this manufacturer, the market segment using modified alcohols is increasing (personal communication with machine manufacturers, 2021).

Interviews also indicate that the use of different cleaning solvents and methods differ between countries. In Scandinavia, 90% of metal cleaning companies are estimated to use modified alcohols, while in the UK, the majority instead still uses chlorinated solvents.

3.3.2 Hazard classification

Table 3 illustrates the hazard classification within the EU of the different cleaning solvents and methods described in this chapter. The difference among chlorinated solvents is mainly the carcinogenic property. While TCE is a proven carcinogenic substance, PERC and methylene chloride is classified as suspected carcinogenic substances. For aqueous cleaning and cleaning with modified alcohols, no hazard classification is described, since their (potential) hazardous properties depend on the alcohols or additives used (in aqueous cleaning).

Table 3 Hazard classification in EU of key cleaning solvents and methods.

	Trichloroethylene	Perchloroethylene	Methylene chloride	Aqueous cleaning	Modified alcohols
Hazard classification (EU)	Carc. 1B Aquatic Chronic 3 Skin Irrit. 2 Eye Irrit. 2 Muta. 2 STOT SE 3	Carc. 2 Aquatic Chronic 2	Carc. 2	n.a.	n.a.
Inclusion in the candidate list	Yes	No	No	n.a.	n.a.
Inclusion in the authorisation list	Yes	No	No	n.a.	n.a

Source: C&L Inventory https://echa.europa.eu/information-on-chemicals/cl-inventory-database, (ECHA, n.d.-a, n.d.-e)

3.3.3 Costs related to different metal parts cleaning solvents and methods

There is little information available on investments and running costs for different cleaning solutions, partly due to competition issues making manufacturers unwilling to share price information. There is also a large case-specific variety of equipment requirements and thus, costs for different cleaning solutions may vary greatly.

There are only a few published papers on the costs of TCE substitution. Slunge and Sterner (2001) study costs among Swedish firms that substituted TCE in the 1990s in connection to the Swedish ban on TCE. They found that the marginal cost per kg of TCE substituted was between 0.6 and 4.8 EUR. The lower estimate is the median value reported by companies that had replaced TCE and the higher value is the median value stated by companies as an estimate of what it would cost if they were not granted an authorisation to continue using TCE after the Swedish ban entered into force. These costs included both investment and operating costs. The authors underline that the estimates by the Swedish companies applying for authorisation may be over-estimates, but the great variance between the cost estimates could also be explained by varying cleaning requirements and process complexity. The investigation showed that a large share of TCE used could be replaced at low costs.

Based on interviews with metal cleaning machine manufacturers and industry experts (see appendix A), the following observations about substitution costs are made:

Two machine manufacturers stated that the investment cost for aqueous cleaning equipment is generally lower compared to machines using solvents. However, another machine manufacturer stated that aqueous cleaning equipment is generally more costly, and can vary between 300 000 to 1 000 000€, depending on the number of washing and rinsing operations. One machine manufacturer stated that the investment cost for equipment using modified alcohols is approximately 150 000-200 000€ (personal communication with machine manufacturers, 2021).

Investment costs for the different types of vapour cleaning machines (type I-V) used for chlorinated solvents have not been identified. However, two companies estimated the investment cost for new machines for PERC in the application for authorisation sent by Blue Cube. One company estimated a new machine run with PERC to cost 247 000€, while the other company instead estimated it to be 400 000€ (DOW Deutschland Anlagengesellschaft mbH, n.d.). It should however be mentioned, that estimates made by companies in the Blue Cube application may have an overestimation bias since their purpose is to provide an argument for continued TCE use.

As PERC and methylene chloride are chemically similar substances to TCE, they can be used as drop-in solvents in companies' existing cleaning equipment. However, due to differences in boiling point and solvency power, it is likely that upgrades to existing equipment may be required, as indicated by several DUs (personal communication with notified downstream users, 2020). Two machine manufacturers estimated the conversion cost to be between 3 000 – 10 000€ and another manufacturer estimated the cost to be between 15 000 – 20 000€. The conversion cost is however dependent on the machine type. As mentioned by one manufacturer, the conversion estimate is only applicable for closed machines (type III-V) and does thus not apply for older open-top machines.

For changes in operating costs, there is little information available as well. However, two machine manufacturers estimate the operating costs for aqueous cleaning systems to be higher compared to solvent cleaning systems. This is partly due to higher energy demand due to an additional drying step in aqueous cleaning. Higher operating costs for aqueous systems can also come from the cost of chemical additives, wastewater treatment and downtime. When cleaning with solvents, high recycling is possible, and the need for new chemicals is lower compared to aqueous systems. In aqueous cleaning, the chemical additives are eventually either used up or removed from the cleaning media with the change of water. This results in another difference between solvents cleaning and aqueous cleaning. When changing the cleaning media, the aqueous system must be stopped, while for solvents cleaning, the cleaning process can continue during distillation (personal communication with machine manufacturers, 2021).

Several DUs have also indicated that cleaning with PERC entails higher operating costs compared to cleaning with TCE (personal communication with notified downstream users, 2020). Due to the higher boiling point of PERC, higher energy demand is thought to be required, through extra heating.

There is little information available about the cost of the different cleaning solvents. In 2011, the cost of PERC was estimated to be approximately 1 500€ per tonne[17], compared to 1 800€ per tonne TCE in 2009[18]. The cost per tonne of chlorinated solvents is also estimated to be in similar order of magnitude as for modified alcohols according to suppliers of these substances (personal communication with a solvent distributor, 2021).

17 https://www.icis.com/explore/resources/news/2007/11/06/9076130/perchloroethylene-prices-and-pricing-information/

18 https://www.icis.com/explore/resources/news/2009/09/15/9247357/dow-announces-400-tonne-europe-trichloroethylene-increase/

4 Results from the Industry survey

This chapter presents the results from the survey which was distributed to 38 DU notifiers who submitted notifications to ECHA and approximately 100 former TCE end-users in the United Kingdom. In total, 21 answers were received. However, two companies did not use TCE for metal parts cleaning purposes and were excluded from the analysis. Hence, the following presentation builds on the survey results from 19 companies, where 13 answers are DUs who notified their use to ECHA and 6 are former TCE DUs in the United Kingdom.

4.1 Descriptive statistics

Table 4 illustrates the distribution of companies across different sectors. This question was a multiple-choice question and 12 companies stated that they work within different sectors (ranging from two to eight different sectors). Seven companies also specified that they are operating in one or several of the following sectors: consumer goods, manmade fibre, chemical industry, household products, security, agricultural equipment, and chemical manufacturing.

Table 4 Distribution of responding companies across sectors.

Sector	Number responses
Aerospace	10
Automotive	9
Defence	7
Medical	7
Energy	6
High precision instruments	5
Marine	4
Optical	3
Railway	3
Others	7

Among the responding companies, 14 companies operate from the United Kingdom, 3 companies from Italy, 1 company from Romania and 1 company from Sweden. The seemingly uneven distribution is partly explained by the group of former TCE users only consisting of UK companies, as well as the UK being one of the largest subgroups within the DU notifiers group.

The sample of responding companies covers mainly small and medium-sized companies, see table 5.

Table 5 Distribution of responding companies by company size.

Number of employees	Number responses
0-10	1
11-50	7
51-100	6
101-500	5
>500	0

4.2 Substitution of TCE

Substitution substances and methods

Out of the 19 responding companies, 14 substituted TCE with other chlorinated solvents - PERC (12 companies) and methylene chloride (2), figure 3. After chlorinated solvents, cleaning with alcohols is the second-largest replacement substance (5 companies), followed by aqueous cleaning (3). Several of the companies substituting TCE with PERC also stated that they in parallel are using hydrocarbons (1 company), aqueous cleaning (3) and alcohols (2).

Figure 3 Solvents and methods used to substitute TCE.

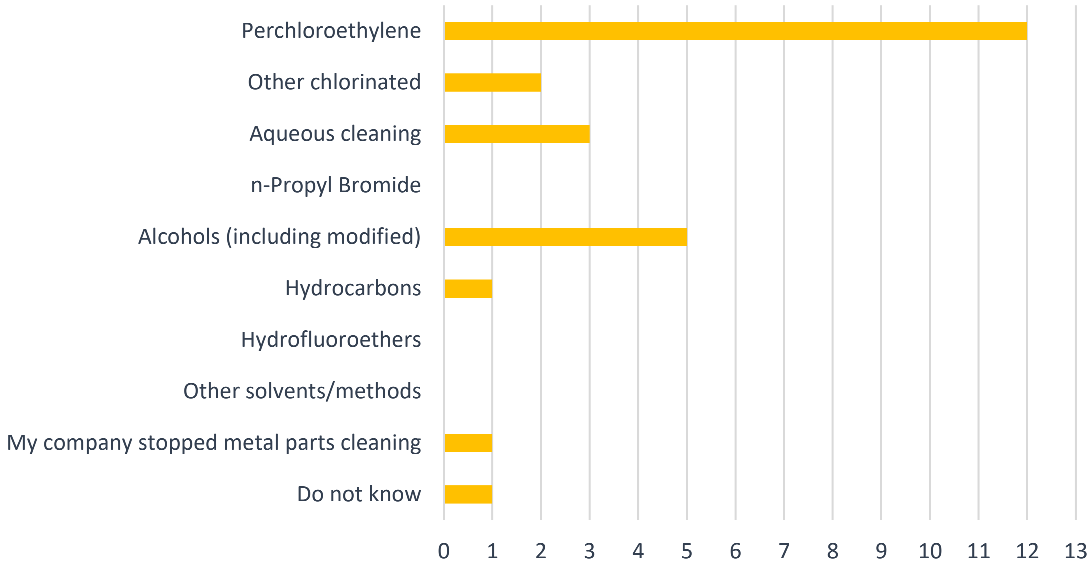


Table 6 illustrates the type of machines used with TCE and what solvent the 19 companies has replaced TCE with. The average machine age for companies still using their old TCE machine is 12.5 years. as the survey responses indicate that a few companies have continued to use older machine types (I-III) after the sunset date, even though their replacement was a condition in the authorisation decisions.

Table 6 Type and age of machines used with TCE and volumes of used cleaning solvent.

Company	TCE machine type	Year of TCE machine investment	Substitution solvent and/or method	Uses TCE machine after substitution	Machine age [years] *	Volume use TCE [tonne/year]	Volume use after substitution [tonne/year]
i	II	1991	Ceased metal cleaning	n.a.	n.a.	4.5	n.a.
ii	II	1993	PERC	Yes	27	n.a.	n.a.
iii	II	1998	Chlorinated (methylene chloride)	No	12	1	1
iv	II	2009	Chlorinated (methylene chloride)	Yes	11	1	1
v	III	1995	Alcohols	n.a.	n.a.	n.a.	n.a.
iii	III	2010	Chlorinated (methylene chloride)	No	10	1	1
vi	III	2015	PERC	Yes	5	n.a.	n.a.
vii	III	n.a.	Alcohols	n.a.	n.a.	n.a.	n.a.
viii	IV	2000	PERC & alcohols	Yes	20	n.a.	n.a.
ix	IV	2004	PERC	Yes	16	1	1
x	IV	2005	PERC & aqueous	Yes	15	1	n.a.
xi	IV	2010	PERC	Yes	10	1	1
xii	IV	2010	PERC & hydrocarbon	Yes	10	1	1
xiii	IV	2010	PERC & aqueous	Yes	10	0.6	n.a.
xiv	V	2008	PERC	Yes	12	0.007	n.a.
xv	V	2010	PERC	Yes	10	2	n.a.
xvi	V	2011	PERC & aqueous & aclohols	Yes	9	0.9	n.a.
xvii	V	2013	PERC	Yes	7	n.a.	n.a.
xviii	V	2015	Alcohols	n.a.	n.a.	1.5	0.9
xix	n.a.	n.a.	n.a.	n.a.	n.a.	1	n.a.

* Machine age calculated from the year of investment in TCE machine to 2020.

Type of machines used in metal parts cleaning with chlorinated solvents

Table 7 illustrates the type of machine companies used for metal parts cleaning with TCE and for the replacement substance. It only includes the 14 companies that replaced TCE with either PERC or other chlorinated substances. It appears that only one company has invested in a new machine and thereby upgraded from a type II to a type III machine[19]. The answers also indicate that two companies still use a type II machine.

[19] This investment in a new type III machine was made in 2010.

Table 7 Machines used for TCE and replacement substances.

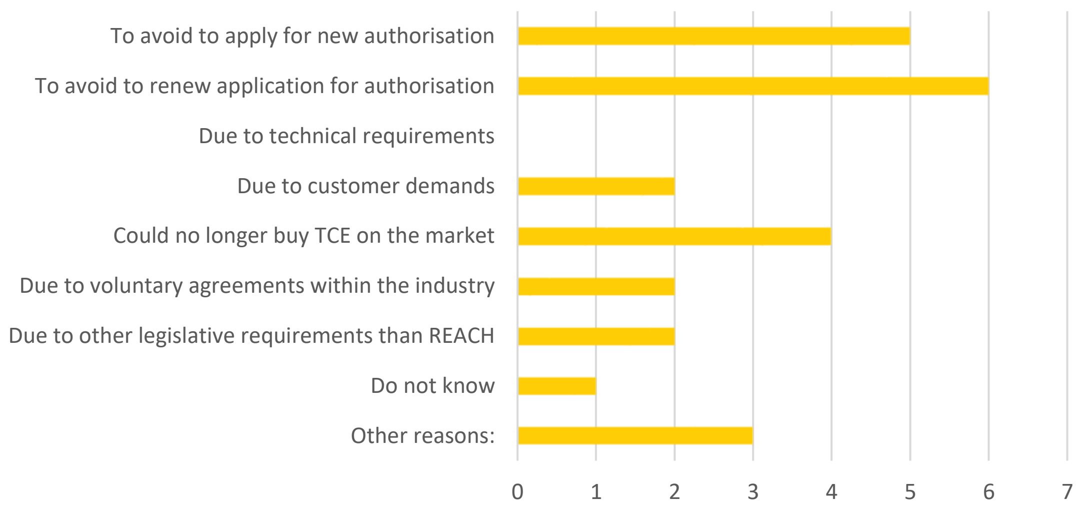
Type of machine used with TCE		Type of machine used with replacement substance	
Type I	0	Type I	0
Type II	3	Type II	2
Type III	1	Type III	2
Type IV	6	Type IV	6
Type V	4	Type V	4

Out of the 14 companies that have substituted TCE with either PERC or other chlorinated solvents, 12 answered that they have been able to continue to use their old equipment, although modifications have been required. One company stated that they can use their old equipment without modifications, and one company answered that they have not been able to use their old TCE equipment.

Reasons to substitute TCE

The reasons companies state for the decision to substitute TCE are summarised in figure 4. The most common reasons were to avoid having to apply for authorisation or renew the application for authorisation. Difficulties in acquiring TCE on the market was stated as a reason by four companies. Other legislative requirements than REACH included aerospace requirements and health- and safety requirements. Three companies stated that other reasons influencing the substitution. These reasons were difficulty in handling the solvent, and the need to replace the machine due to age and capacity. Several companies stated more than one reason behind their substitution decision.

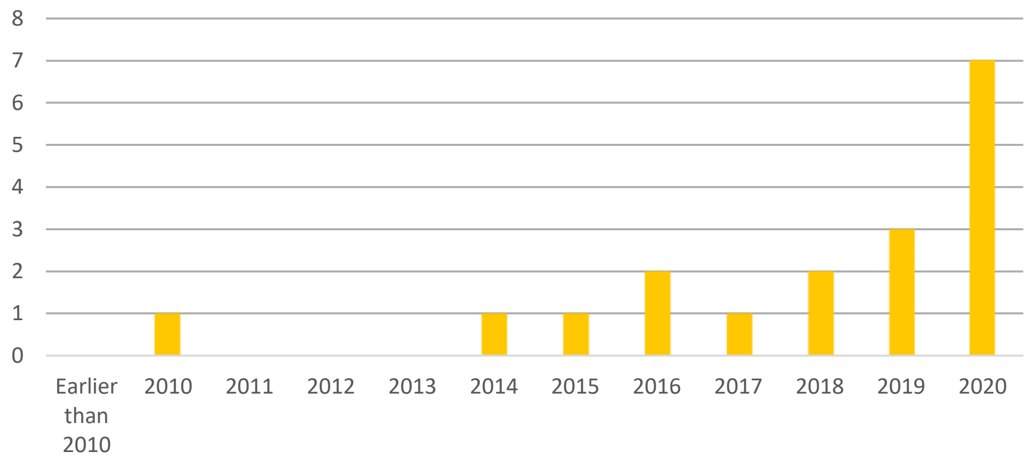
Figure 4 Reasons why companies substituted TCE.



Timing of the TCE substitution

The survey results show great variance in terms of the timing of TCE substitution (Figure 5). Ten of the responding companies substituted TCE during 2019 or 2020 which is close to the date of authorisation expiration. One company did not answer the question.

Figure 5 Year of TCE substitution.



4.3 Costs related to the TCE substitution

Among the 19 responding companies, 14 companies stated that the TCE substitution has required investments, while one company did not know and the remaining companies stated that no investments have been required. Table 8 illustrates investments made in relation to modifications of old TCE machines to cleaning with PERC.

Table 8 Investment costs related to the conversion of cleaning equipment to use of PERC.

Substitution substance	Type of investment	Machine type	Year of investment	Estimated lifetime [years]	Investment cost [€]	Annualised cost [€]	Discounted annualised cost [€] *	Average cost per kg TCE replaced [€/kg]
PERC	Equipment modification	IV	2016	10	4 000	400	493	4
PERC [20]	Equipment modification	IV	2020	10	5 000	500	616	5
PERC	Equipment modification	V	2020	10	10 000	1 000	1 233	n.a.
PERC	Equipment modification	II	2018	5	18 000	3 600	4 043	n.a.
PERC [20]	Equipment modification	IV	2020	10	25 000	2 500	3 082	25
Average					**12 400**	**1 600**	**1 894**	

*Annualised discounted cost was calculated by using a discount rate of 4% over the estimated lifetime of the investment

[20] These two investments were made by the same company.

Table 9 presents investments made in relation to equipment modifications for cleaning with PERC in combination with another cleaning solvent or method. Investments in table 9 could be investments made for either cleaning with PERC or for cleaning with an alternative cleaning solvent or media. Statements made in the survey have not been possible to use to identify which cleaning solvent or method the investment describes.

Table 9 Investment costs related to cleaning equipment modifications.

Substitution substance	Type of investment	Machine type	Year of investment	Estimated lifetime [years]	Investment cost [€]	Annualised cost [€]	Discounted annualised cost [€] *	Average cost per kg TCE replaced [€/kg]
PERC & hydrocarbon	Equipment modification & customer approval	IV	2019	10-20	Do not know	n.a.	n.a.	n.a.
PERC & aqueous cleaning & alcohols	Equipment modification	V	2020	20 +	20 000	1 000	1 472	23
PERC & aqueous cleaning	Equipment modification	IV	2020	10	30 000	3 000	3 699	30
PERC & alcohols	Equipment modification	IV	2014	n.a. **	30 000	2 400	3 097	n.a.
PERC & aqueous cleaning	Equipment modification	IV	2020	10	50 000	5 000	6 165	83
Average					**32 500**	**2 850**	**3 608**	

*Annualised discounted cost was calculated by using a discount rate of 4% over the estimated lifetime of the investment
** In the case where no estimated lifetime was given, an assumption of 12.5 years was made, which is equal to the average lifetime of TCE machines calculated from table 6.

Table 10 presents investments made in relation to other cleaning solvents or methods than PERC.

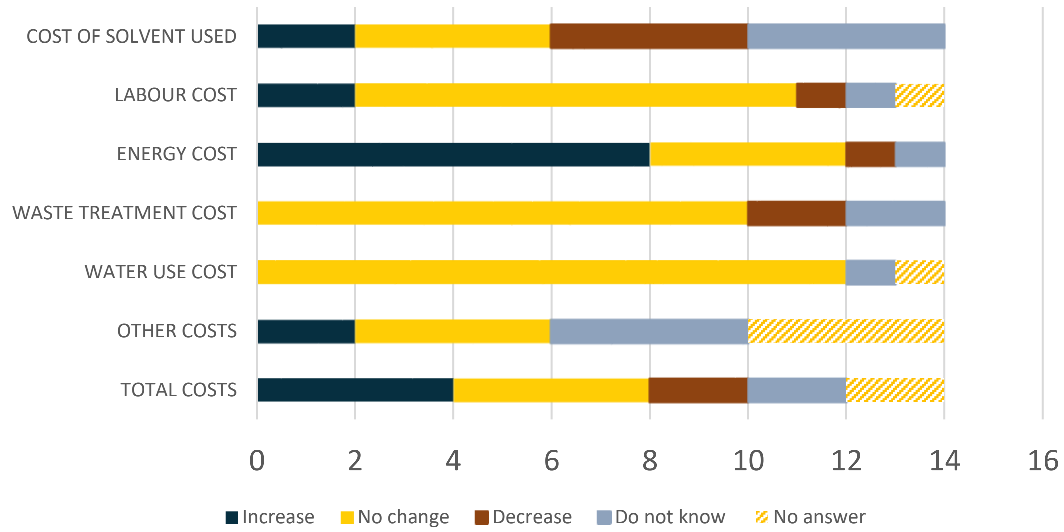
Table 10 Investment costs related to other cleaning solvents or methods than PERC.

Substitution substance	Type of investment	Machine type	Year of investment	Estimated lifetime [years]	Investment cost [€]	Annualised cost [€]	Discounted annualised cost [€] *	Average cost per kg TCE replaced [€/kg]
Alcohols	Equipment modification	n.a.	2019	5	25 000	5 000	5 616	17
Alcohols	Investment	n.a.	2018	20	100 000	5 000	7 358	n.a.
Alcohols	Investment machine	n.a.	2020	10	800 000	80 000	98 633	n.a.
Chlorinated solvents	Investment type III machine	III	2010	5	50 000	10 000	11 231	50
Average					**243 750**	**25 000**	**30 709**	

*Annualised discounted cost was calculated by using a discount rate of 4% over the estimated lifetime of the investment.

Figure 6 illustrates changes in operating costs for the 14 companies, which replaced TCE with either PERC or other chlorinated solvents. Four companies state that total operating costs increased, four stated that total costs did not change and two that costs decreased. The majority of the companies (eight) answered that the energy cost increased after TCE substitution. It should however be noticed that 5 of the 14 companies replaced TCE with either PERC or other chlorinated solvents in combination with another cleaning substance or method.

Figure 6 Changes in operating costs when substituting TCE with PERC.



Note: The 14 companies which are illustrated in Figure 6, are companies that have substituted TCE with either PERC or other chlorinated solvents.

In figure 7, changes in operating costs for the three companies that replaced TCE with alcohol cleaning are illustrated. As there were only three companies, it is difficult to say anything general for cleaning with alcohol. However, one indication from the results is that the cost of the solvent has decreased since the TCE replacement.

Figure 7 Changes in operating costs when substituting TCE with modified alcohols.

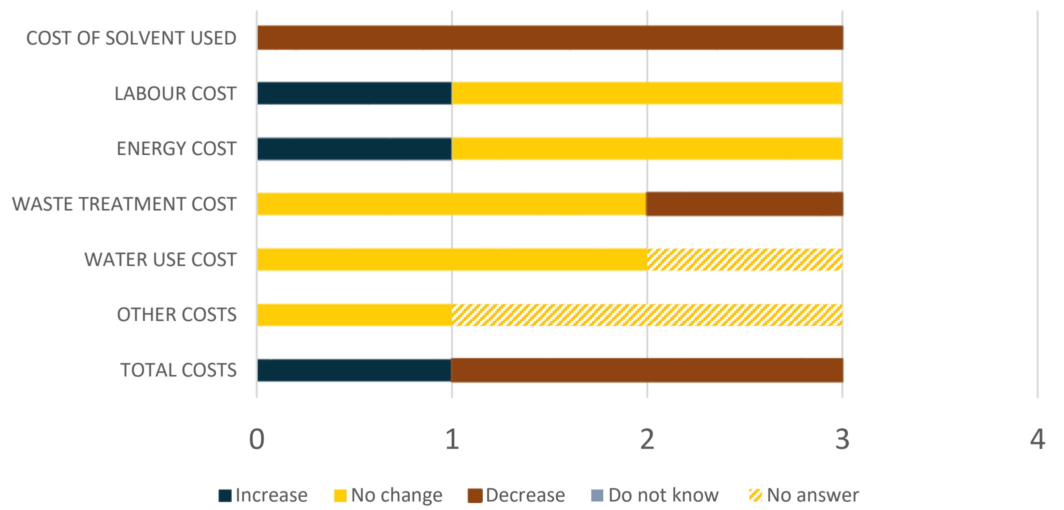


Table 11 includes other effects the companies have experienced when substituting TCE. Some companies mentioned positive effects such as decreased exposure to workers or increased cleaning quality; other companies have experienced no effects while others raised negative effects such as a decrease in cleaning quality.

Table 11 Experienced effects from TCE substitution.

Substitution substance	Experienced effects as a result of TCE replacement
Alcohols	Improved quality in metal parts cleaning
Alcohols	Reduction of the exposure of solvents to workers
Alcohols	Slightly higher end-of-cycle temperatures as opposed to TCE.
PERC & alcohols	Reduction in employee exposure. The quality of cleaning remained unchanged after all. On the other hand, PERC needs a more precise control of pH variations, as it is more subject to variations.
PERC, alcohols & aqueous cleaning	No obvious effects.
PERC	Improvement of production cost and plant maintenance.
PERC	We have to dry all parts before degreasing, as parts will water stain if not completely dry.
PERC	None.
PERC	Decrease in quality of cleaned parts, much longer operating times. Having to change previous cleaning operations as solvents are not compatible.
PERC	None as to date
PERC & aqueous cleaning	Similar cleaning standard. Some materials (Titanium alloys) cannot be processed through PERC so need to be aqueous cleaned.
PERC & aqueous cleaning	We are not sure if PERC degreases as well as TCE. This has been raised with technical engineering but we do not have a response currently.
Other chlorinated	Simpler safe operating procedures.

4.4 The role of REACH authorisation

The survey results show that the involvement in the authorisation process varies a lot between the responding companies. Two companies answered that their involvement was limited to being informed by the upstream user/supplier of the authorisation process. Four companies stated that they provided information about their operations to the upstream user/supplier and four companies that they *both* provided information and were informed by the upstream user/supplier. Five companies did not know how they were involved, and four companies stated that they were not involved in the process at all.

The majority of the responding companies (11 out of 19) stated that they did not consider the renewal of the authorisation for the continued use of TCE. Six companies did however consider participating in submitting a review report (i.e. renewed AfA) prepared by an upstream user/supplier, but eventually did not do so, mainly due to the costs related to such an application. One company stated that they considered to apply for a new authorisation themselves, but decided not to, due to the complexity and costs related to such a process.

Among the 19 responding companies, 12 believe that a longer review period would not have influenced their company´s choice of substitution substance or method, which for several reasons were given. Three companies mentioned that the substitution decision was already made and that they already had an alternative ready so additional time was not required. One company also raised that they "*would expect to have still changed to PERC, but maybe at a later date*" if given a longer time, but thus a longer review period would not have influenced their choice of substitution substance. Another company mentioned that they had already substituted so additional time was not required. Two companies answered that the substitution was driven by customer demands. One company raised the unavailability of TCE on the market as a reason and another company mentioned that the choice of substitution substance was dependent on the criteria that the old cleaning equipment could be used after the substitution.

Among the three companies, which answered that they believe a longer review period would have influenced their substitution decision, one company mentioned that a longer review period would have given them "*a less costly treatment*". Another company answered that if given a longer review period, they would not have upgraded their cleaning machine until necessary.

5 Discussion and conclusion

Trichloroethylene (TCE) has been a very common solvent used in metal parts cleaning in the European Union. While there were two authorisations, which also covered many downstream users, granted for the use of TCE in metal parts cleaning after the sunset date in 2016, no applications for renewed authorisations have been made. This means that the legal use of TCE in metal parts cleaning has effectively ended in the EU. Based on the industry survey, interviews and literature review conducted as part of this study, this section summarizes and discusses the main findings related to; (i) the solvents and methods that have replaced TCE in metal parts cleaning; (ii) the cost and benefits for companies that have substituted TCE; and (iii) the role played by the REACH authorisation requirements and other factors in the companies´ substitution decisions.

It is important to note that the study focuses on those European companies that have been the slowest in substituting TCE. The companies who substituted TCE prior to the sunset date have not been surveyed. Among the several hundred metal cleaning companies covered by the TCE authorisations, only 38 companies notified ECHA that they made active use of the authorisation. Based on the survey responses in combination with interviews with industry experts, we believe the findings of this study to be representative of the companies under the previous TCE authorisation.

5.1 Which solvents and methods have replaced TCE in metal parts cleaning?

The main finding of the study is that a large share of the companies that have used TCE in metal parts cleaning under the previous authorisation are instead using perchloroethylene (PERC). Some companies have combined the shift to PERC with the introduction of other solvents or methods. As PERC has similar chemical characteristics as TCE, companies can continue to use the same machines. Only minor modifications are necessary. Through the substitution of TCE with PERC, an incremental rather than fundamental chemical substitution has taken place (Fantke et al., 2015).

The study also finds that in some cases, companies continue to use older types of machines (type II and III) in metal parts cleaning with perchloroethylene. This is surprising since the authorisations for the use of TCE were only covering closed metal cleaning systems. Older types of machines greatly increase exposure risks.

5.2 Costs and benefits for companies that have substituted TCE

The findings indicate that the costs for substituting from TCE to PERC are low as only a modification of the existing machines is necessary. The annualised investment cost to modify machines from TCE to PERC use is 1894 EUR on average for the surveyed companies. Costs for energy increase somewhat with PERC as the boiling point is higher than for TCE, but there are no clear trends in terms of changes in other operating costs when substituting from TCE to PERC.

As there were only three of the surveyed companies that had substituted from TCE to only using a non-chlorinated solvent alternative, the cost estimates for this type of substitution are surrounded with large uncertainty. Interviews conducted indicate that substitution from TCE to modified alcohols or water-based cleaning methods can involve substantially higher costs compared to the cost of converting a machine to use PERC instead of TCE, but these costs are context and process specific. Water-based cleaning methods generally require more space than the one chamber systems used for metal parts cleaning with TCE or PERC. However, when comparing substitution costs it is important to not only consider the face value of a new alternative machine and compare it with the costs of continued use of TCE (or PERC) in an existing machine. The comparison should rather be with a new type IV or V machine for chlorinated solvents, as this is the alternative investment a company would need to make to comply with the regulation on exposure in the working environment (Slunge and Sterner, 2001). Making new investments when the life span of existing machines ends is an integral part of the business cycle. As most machines used with TCE have been in use for a long time, it is in principle only the difference in investment cost between a new type IV or V machine for chlorinated solvents and a machine for alternative solvents that should be included in the substitution cost estimate.

The surveyed companies provided mixed answers on the effects of TCE substitution on cleaning quality and exposure to workers. There is no clear trend.

The inclusion of TCE in the authorisation list was motivated by health and environmental concerns. As TCE is classified as a carcinogenic substance within the EU and PERC is classified as a suspected carcinogenic substance, the substitution from TCE to PERC may at best have created some marginal health benefits. However, as the substitution process in most cases seems not to have involved major changes in metal cleaning machines or processes, larger health and environmental benefits have not been achieved.

5.3 Factors influencing TCE substitution

For a majority of the surveyed companies, TCE substitution took place in 2019 or 2020, just before the expiry of the TCE authorisation. Several companies did consider participating in submitting a review report (i.e. renewing the application for authorisation) prepared by an upstream user or apply for a new authorisation. However, no review reports were submitted. The survey responses indicate that the main reason for substituting TCE has been to avoid the cost of having to renew the application for authorisation or to apply for a new authorisation. A couple of companies also indicate that it was increasingly difficult to obtain TCE on the market. The cost of applying for a renewed authorisation hence seem to have been higher than substituting TCE with PERC and in some cases also other substances.

As substitution processes can involve larger investments and adjustments of technical processes, a longer review period than the three to four years of the TCE authorisation could perhaps have given companies a greater opportunity to replace TCE with a less hazardous substance or method than PERC, the easiest “drop-in solvent”. However, the majority of the surveyed companies stated that a longer review period would not have influenced their substitution decision.

Substitution of TCE in European metal parts cleaning has been a gradual process influenced by factors such as regulation on exposure in the working environment, taxes and bans at the member state level, voluntary industry agreements and technological development of alternatives. As the two TCE authorisations for metal parts cleaning covered several hundreds of DUs, but only 39 notifications were made to ECHA, a large share of the companies must have substituted TCE between the years of application (2014) and the years of granted authorisation (2017 and 2018). Hence, it seems as the inclusion of TCE in the REACH authorisation list has incentivized TCE substitution. For example, the major solvent supplier Safechem initiated larger programs on risk management and TCE substitution with their customers in 2015. This included a leasing model which according to the firm has reduced emissions from the whole supply chain of solvents (including transportation, storage and disposal). Similarly, it is likely that the inclusion of TCE in the candidate list of substances of very high concern for authorisation in 2010 incentivized some companies to initiate a substitution process.

The late substitution of TCE among the companies that participated in the survey may partly be explained by specific requirements in the aerospace industry sector. Due to the high-quality requirements in the sector, changing any step in the production process must be carefully tested before approval and this process is often extensive and takes time. Ten of the surveyed companies operate in the aerospace sector.

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Appendix A. List of interviews

2020-11-11	Hans Thulin, AntiCorr AB, Sweden
2020-11-16	Frida Hök, Chemsec, Sweden
2020-11-17	Jan Skogsmo, RISE, Sweden
2020-11-19	David Northall, Bromford Industries Ltd, United Kingdom
2020-12-16	Bill Torrie, Abbey Metal Finishing Co Ltd, United Kingdom
2020-12-17	Ian McDonald, Robart Stuart Limited, United Kingdom
2020-12-18	Citadina 98 SA, Romania
2020-12-18	Protar Service, Romania
2021-03-12	Discussion with Safechem and UK distributors, Germany, the United Kingdom
2021-05-11	Arnaud Macabies, Amsonic AG, Switzerland
2021-05-12	Rainer Grenz, Ecoclean GmbH, Germany
2021-05-19	Bernd Stelzer, Karl Roll GmbH & Co. KG, Germany
2021-05-28	Mauro Cazzola, Union S.p.a., Italy
2021-05-31	Markus Mitschele, HEMO GmbH, Germany

Appendix B. Survey on replacement of trichloroethylene in metal degreasing

A. Information about your company

1. **What product(s) or service(s) involving metal parts cleaning is your company producing or performing?**

2. **Type of sector(s) in which your company operates?** [Select more than one option if applicable.]
   - ☐ Aerospace
   - ☐ Automotive
   - ☐ Defence
   - ☐ Energy
   - ☐ High precision instruments
   - ☐ Information systems and hardware
   - ☐ Marine
   - ☐ Medical
   - ☐ Optical
   - ☐ Railway
   - ☐ Shipping
   - ☐ Other, please specify:

3. **Country/Countries where your company operates:**

   [Role down list]

   (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom)

4. **Number of employees in the company:**
   - ☐ 0-10
   - ☐ 11-50
   - ☐ 51-100
   - ☐ 101-500
   - ☐ > 500

B. Replacement of trichloroethylene (TCE) in metal parts cleaning

5. **What type of equipment did your company use for metal parts cleaning with TCE, during the last three years of TCE use?** [Select more than one option if applicable.]
   - ☐ Type I – Open top machine
   - ☐ Type II – Enclosed open machine with either vented air lock or A-carbon filter
   - ☐ Type III – Closed with internal air cleaning prior to opening
   - ☐ Type IV – Closed with closed loop air drying without vent
   - ☐ Type V – Closed without vent and operation under vacuum
   - ☐ Other, please describe____
   - ☐ Do not know

6. **When did your company buy this equipment/machine?** (If your company used different equipment/machines for metal parts cleaning with TCE, please consider the newest.)
   - ☐ 2018
   - ☐ 2017
   - ☐ …
   - ☐ 1990
   - ☐ Earlier than 1990
   - ☐ Do not know

7. **What was the investment cost for this equipment/machine?** (Please state the approximate cost in EURO. Write do not know if you cannot give an estimate.)

8. **Approximately how much TCE did your company use <u>per year,</u> during the last three years of TCE use?** (Please specify in tonnes per year. Write do not know if you cannot give an estimate.)

9. **What was, approximately, the yearly operating costs for metal parts cleaning with TCE?** (Please state in EURO, considering different types of costs, such as the cost of the TCE solvent, labour, energy, waste treatment. Write do not know if you cannot give an estimate.)

10. **What solvents and/or methods has your company replaced TCE with for metal parts cleaning?** [Select more than one option if applicable.]
    - ☐ Perchloroethylene (PER)
    - ☐ Other chlorinated solvents
    - ☐ Aqueous cleaning
    - ☐ N-propyl bromide (nPB)
    - ☐ Alcohols (including modified)
    - ☐ Hydrocarbons
    - ☐ Hydrofluoroethers
    - ☐ Other solvents/methods
    - ☐ My company decided to stop conduct metal parts cleaning
    - ☐ Do not know

11. Please specify which solvents and/or methods your company uses currently for metal parts cleaning ______________________ *(this question only visible if chosen "other solvents/methods" in Q10)*

12. What happened with your metal parts cleaning business? *(this question only visible if chosen "my company decided to stop conduct metal parts cleaning" in Q10)*

- ☐ Another company/Other companies provides the service
- ☐ My client started to clean parts as part of their operations instead
- ☐ Other, please describe: ___________________________________
- ☐ Do not know

13. When did your company stop using TCE for metal parts cleaning? (Please mark the year.)

- ☐ 2020
- ☐ 2019
- ☐ …
- ☐ 2010
- ☐ Earlier than 2010
- ☐ Do not know

14. Why did your company replace TCE? [Select more than one option if applicable.]

- ☐ To avoid to apply for authorisation (latest application date was 2014)
- ☐ To avoid to renew application for authorisation for continued TCE use
- ☐ Due to technical requirements
- ☐ Due to customer demands
- ☐ Due to voluntary agreements within the industry
- ☐ Could no longer buy TCE on the market
- ☐ Due to other legislative requirements than REACH, please specify:
- ☐ Other reasons, please describe:
- ☐ Do not know

15. Please describe which other legislative requirements made your company replace TCE: *(this question only visible if chosen "due to other legislative requirements than REACH, please specify" in Q14)*

16. Approximately how much of the replacement solvent has your company used annually after the TCE replacement? (Please specify in tonnes per year. Write "do not know" if you cannot give an estimate.)

Question 17-21 only visible if chosen either "perchloroethylene (PER)" or "other chlorinated solvents in Q10

17. **Does your company currently use the same equipment/machine for metal parts cleaning as your company did with TCE?**
    - ☐ Yes
    - ☐ Yes, but modifications have been required
    - ☐ No
    - ☐ Do not know

18. **Did your company consider other alternatives to TCE when replacing TCE?**
    - ☐ Yes
    - ☐ No
    - ☐ Do not know

19. **Please tick which other alternatives your company considered** [select more than one option if applicable]:
    - ☐ Perchloroethylene (PER)
    - ☐ Other chlorinated solvents
    - ☐ Aqueous cleaning
    - ☐ N-propyl bromide (nPB)
    - ☐ Alcohols (including modified)
    - ☐ Hydrocarbons
    - ☐ Hydrofluoroethers
    - ☐ Other solvents/methods, please specify: ______________________

20. **What are the major reasons to use perchloroethylene (PER) solvents compared to other methods, to your company?** [Select more than one option if applicable.] *(this question only visible if chosen "perchloroethylene (PER)" in Q10)*
    - ☐ Technical performance superior to alternatives
    - ☐ Customer demands that we use PER
    - ☐ Other alternatives are more costly
    - ☐ We are uncertain about the technological performance of alternatives
    - ☐ Other, please describe:
    - ☐ Do not know

21. **What are the major reasons to use chlorinated solvents compared to other methods, to your company?** [Select more than one option if applicable.] *(this question only visible if chosen "other chlorinated solvents" in Q10)*
    - ☐ Technical performance superior to alternatives
    - ☐ Customer demands that we use chlorinated solvents
    - ☐ Other alternatives are more costly
    - ☐ We are uncertain about the technological performance of alternatives
    - ☐ Other, please describe:
    - ☐ Do not know

C. Costs and Benefits of replacing trichloroethylene (TCE)

Replacing TCE with alternative substances and methods involves one-off investments and changes in operating costs. In this section, we kindly ask you to give a rough estimate of these costs.

22. **What investments has your company undertaken to replace TCE?** [Select more than one option if applicable.]
    - ☐ Metal parts cleaning equipment/machine
    - ☐ Other investments
    - ☐ No investments have been needed
    - ☐ Do not know if any investments have been made

23. **Please describe the investment(s):** *(this question only visible if chosen either "metal parts cleaning equipment/machine" or "other investments" in Q22)*
    - ☐ Shortly describe the investment
    - ☐ When was the investment undertaken?
    - ☐ Investment cost (EURO)
    - ☐ Estimated life span of investment (years)

24. **Please describe how the replacement of TCE has *changed* the yearly operating costs for your company?** Please do not include costs that are caused by changes in production volumes or that are due to the initial adjustment process. [Select more than one option if applicable.]
    - ☐ The cost of used solvent(s)
    - ☐ Labour cost
    - ☐ Energy cost
    - ☐ Waste treatment cost
    - ☐ Water use cost
    - ☐ Other, please describe:
    - ☐ Total change in operating costs

    - ☐ Increased
    - ☐ No change
    - ☐ Decreased
    - ☐ Do not know
    - ☐ Comments (Please state the magnitude of the change in percentage)

25. **What other effects has your company experienced as a result of replacing TCE?** (E.g. improved quality in metal parts cleaning, reduced exposure of solvents to workers)

D. Involvement in the authorisation process

26. **Please describe how your company was involved in the process of applying for authorisation for TCE use:** [Select more than one option if applicable.]
    - ☐ My company supplied the upstream user/supplier with information about our TCE use
    - ☐ My company was informed by the upstream user/supplier of the application process
    - ☐ My company was not involved in the application process
    - ☐ Other involvement, please describe:
    - ☐ Do not know

27. **Did your company consider renewal of the authorisation for continued use of TCE?**
    - ☐ Yes, we considered participating in submitting a review report prepared by an upstream user/supplier
    - ☐ Yes, we considered applying for an authorisation ourselves
    - ☐ No
    - ☐ Do not know

28. **Why did your company´s upstream user/supplier <u>not</u> submit a review report for continued use of TCE?** *(this question only visible if chosen "yes, we considered participating in submitting a review report prepared by an upstream user/supplier" in Q27)*

29. **Why did your company <u>not</u> apply for an authorisation for continued use of TCE?** *(this question only visible if chosen "yes, we considered applying for an authorisation ourselves" in Q27)*

30. **The European Commission granted one authorisation in 2017 and one in 2018 for continued TCE use until 2019 and 2020 respectively. Would a longer review period have made a difference in your company´s choice of solvent or process as a replacement to TCE?**
    - ☐ Yes, most likely.
    - ☐ No, most likely.
    - ☐ Do not know

31. **Please describe how:** *(this question only visible if chosen "yes, most likely" in Q30)*

32. **Please describe why not:** *(this question only visible if chosen "no, most likely" in Q30)*

Additional comments

33. **Additional comments regarding the replacement of TCE?**

34. **Comments regarding the survey and/or the study?**

Thank you for your participation! Your answers are of great value to us. If you have further questions about the study, please contact Ms Ida Andersson (ida.andersson.2@gu.se, tel: +46 70 14 14 206).

35. **In case we need clarifications of your answers, please provide contact details (email and phone number):**