FACULTEIT BIO-INGENIEURSWETENSCHAPPEN

DEVELOPMENT OF A FRAMEWORK FOR EVIDENCE-BASED DECISION-MAKING ON DEALING WITH HUMAN (OPPORTUNISTIC) PATHOGENS IN THE MICROBIOME OF MINIMALLY PROCESSED VEGETABLES

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
BIOHAZ	Biological Hazards
CFU	Colony Forming Unit
CBA	Cost-Benefit Analysis
COD	Chemical Oxygen Demand
DALY	Disability-Adjusted Life Years
DBP	Disinfection by-product
DG	Directorate General
DM	Decision-maker
EC	European Commission
ECDC	European Centre for Disease Prevention and Control
ECHA	European Chemicals Agency
EEA	European Economic Area
EFSA	European Food Safety Authority
ELECTRE	Elimination Et Choix Traduisant la Realité
EU	European Union
FAO	Food and Agriculture Organization
FC	Free Chlorine
FoNOA	Foods of Non-Animal Origin
GAP	Good Agricultural Practices
GHP	Good Hygiene Practices
GMP	Good Manufacturing Practices
HAA	Haloacetic acid
HACCP	Hazard Analysis and Critical Control Points
HLY	Healthy Life Years
HUS	Hemolytic Uremic Syndrome
IA	Impact Assessment
IFPA	International Fresh-Cut Produce Association
LFMFP	Laboratory of Food Microbiology and Food Preservation
MAUT	Multi-Attribute Utility Theory
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MPV	Minimally processed vegetables
OTU	Operational Taxonomic Unit
PAA	Peracetic acid
PAH	Polycyclic aromatic hydrocarbons
PCWDE	Plant cell wall-degrading enzyme

PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation
rRNA	Ribosomal ribonucleic acid
RNA	Ribonucleic acid
RMOA	Regulatory Management Option Analysis
RTE	Ready-to-eat
SPS	Sanitary and Phytosanitary
STEC	Shiga-Toxin producing *Escherichia coli*
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TTHM	Total Trihalomethanes
UN	United Nations
VMM	Vlaamse Milieumaatschappij
VTEC	Vero-Toxin producing *Escherichia coli*
WHO	World Health Organization
WSM	Weighted Sum Method
WPM	Weighted Product Method
YOPI	Young Old Pregnant Immunocompromised

ABSTRACT

Introduction. The washing procedure of minimally processed leafy greens is a critical step within the production chain. This is the only step where some microbial reduction is possible, however the wash water could also act as a vector for cross-contamination. The use of chemical sanitisers in produce wash water as a means to prevent cross-contamination is divided over EU member states and regulations remain unharmonised. Here, multi-criteria decision analysis could serve as a decision support tool to make more evidence-informed decisions regarding this complex issue. The purpose of this thesis was to (1) find out how to apply the principles of multi-criteria decision analysis in food safety risk management; (2) investigate the current risk management decision-making process; (3) apply an MCDA for the leafy greens case study.

Methods. The methodologies used in MCDA applications for food safety risk management were investigated with a scientific literature study. A qualitative appreciation of published case studies looked at the applied methods and included evaluation criteria. Next, semi-structured interviews were organised with micro-, meso- and macro-level representatives from different domains aimed at understanding the current decision-making process and whether any structural approach is being applied. Finally, the MCDA methodologies were applied for the leafy greens case study. The most appropriate washing methodology for minimally processed leafy greens was determined, based on an evaluation of weighted performance criteria. Belgian stakeholders' preferences within the decision context were collected with an online stakeholder consultation. Information was aggregated with the PROMETHEE II algorithm.

Results. The inclusion of stakeholder and expert input is lacking in current food safety risk management MCDA applications. However, weighting and quantification of evaluation criteria are standard procedure. It seems that the current decision-making process lacks a structural approach and still relies heavily on discussions. Opportunities for the use of MCDA in risk management were identified by all interviewees. The application of the MCDA methodologies for the leafy greens case study revealed that washing with potable water, the method commonly applied in Belgium, after evaluation of performance criteria is considered the most appropriate control strategy. The positive consumer perception, harmonised regulations and reduced costs in comparison with disinfection methodologies are the most important contributors towards the prime position.

Conclusion. This thesis shows how the MCDA methodologies can be applied in food safety risk management as a means to make more evidence-informed decisions and to better understand complex issues, such as the leafy greens case study. It shows the relevance of stakeholder and expert inclusion, in order to increase transparency and credibility of food safety risk management decisions.

SAMENVATTING

Inleiding. Het wasproces van minimaal bewerkt bladgroenten is een kritische stap in het productieproces. Dit de enige stap is waar een reductie van de microbiële lading mogelijk is, het water kan echter dienen als vector voor kruiscontaminatie. Het gebruik van chemische ontsmettingsmiddelen is verdeeld over de EU-lidstaten en de regelgeving hieromtrent blijft ongeharmoniseerd. Hier zou een *multi-criteria decision analysis* kunnen dienen als hulpmiddel om meer wetenschappelijk gefundeerde beslissingen te nemen. Het doel van deze thesis was om (1) te ontdekken hoe de principes van MCDA in voedselveiligheidsrisicomanagement toegepast kunnen worden; (2) te onderzoeken hoe het huidige beslissingsproces voor risicomanagement gebeurt; (3) de MCDA-principes toe te passen voor de *case study* rond het wassen van bladgroenten.

Methoden. De gebruikte MCDA-methodes in voedselveiligheidsrisicomanagement werden onderzocht met een literatuurstudie. Via een kwalitatieve beoordeling van de gepubliceerde *case studies* werd een inschatting van de toegepaste methodes en gebruikte evaluatiecriteria gemaakt. Vervolgens werden semi-gestructureerde interviews georganiseerd met vertegenwoordigers van het micro-, meso- en macro-niveau uit verschillende domeinen, met als doel te achterhalen of er momenteel een gestructureerde aanpak wordt toegepast in het beslissingsproces. Uiteindelijk, werden de MCDA-principes toegepast in de *case study*. Aan de hand van een evaluatie van gewogen criteria werd de meest gepaste wasmethode bepaald. De belangen van Belgische stakeholders binnen de beslissingscontext werden achterhaald via een online stakeholderconsultatie. De verzamelde informatie werd geaggregeerd met het PROMETHEE II algoritme.

Resultaten. De MCDA-voorbeelden binnen het domein van voedselveiligheidsrisicomanagement tonen dat er in beperkte mate rekening gehouden wordt met input van stakeholders en experten. Daartegenover, worden criteria over het algemeen gewogen en waar mogelijk gekwantificeerd.
Het huidige beslissingsproces ontbreekt een gestructureerde aanpak en is nog steeds voornamelijk gebaseerd op discussies. Verschillende opportuniteiten voor de toepassing van MCDA werden aangehaald door geïnterviewden. Het toepassen van MCDA voor de *case study* toonde aan dat wassen met drinkbaar water, wat de gebruikelijke methode in België is, de meest gepaste controlestrategie blijkt. De belangrijkste bijdragen aan deze eerste positie zijn de positieve perceptie van consumenten, de geharmoniseerde regelgeving en verminderde kosten in vergelijking met waswaterdesinfectiemethodes

Conclusie. Deze thesis toonde aan hoe de MCDA-principes kunnen toegepast worden in voedselveiligheidsrisicomanagement, om meer geïnformeerde beslissingen te maken en complexe onderwerpen, zoals deze *case study*, beter te begrijpen. Het belang van stakeholder- en experten input, om transparantie en geloofwaardigheid van beslissingen te verhogen, werd aangetoond.

INTRODUCTION AND OBJECTIVES

Since the introduction of minimally processed fruits and vegetables (F&V) in the early 1980's, the market has been characterised by a double-digit growth. Cut and packaged lettuce dominates the fresh-cut F&V market with a market share of about 50% of the total fresh-cut market volume (Baselice et al. 2017). The market size increase can be attributed to multiple factors, including changes in consumers' dietary habits, and the demand for fresh, healthy and convenient food (Cook 2016; Foong-Cunningham, Verkaar, and Swanson 2012).

Fresh-cut vegetables are not subjected to any complete microbial inactivation, which makes them of high concern for the industry and governments regarding potential involvement in foodborne outbreaks (Valdramidis 2018). The consumption of fresh-cut vegetables has been increasingly associated with foodborne pathogen outbreaks (De Corato 2020), of which leafy greens are amongst the most implicated in fresh-cut vegetables associated outbreaks (Mogren et al. 2018). Considering only foods of non-animal origin, the food/pathogen combination *Salmonella* spp. and leafy greens eaten raw as salads was indicated to be of highest concern by the EFSA BIOHAZ panel (2013).

Currently, different chemical and physical methods are being applied in the processing industry to reduce the microbial load of produce, to maintain product quality and extend shelf-life, and/or to eliminate pathogens in the wash water, thereby reducing the risk of cross-contamination. Some European countries allow the use of chemical sanitisers in the wash water of minimally processed fruits and vegetables, while other EU member states have prohibited the use of chemical disinfectants, and only potable water is used to reduce potential contamination of fresh-cut vegetables (Gil et al. 2009).

In the past decade decision-makers in the food safety area began to realise that a unilateral focus on mitigating the human health impacts of foodborne illnesses might not be sufficient to make effective decisions in real-world situations, and recognised that the decision-making process for foodborne pathogens operates within a socioeconomic and political context (Ruzante et al. 2010, 2017). Food safety decision-making continues to evolve, and the risk analysis paradigm remains the cornerstone, however risk managers are more and more aware of the importance of considering other factors when making food safety decisions. Faced with this complexity, decision-makers can be aided by structured methods that are based on multiple decision factors. A multi-criteria decision analysis (MCDA) could act as a decision support tool for the selection of appropriate interventions when decisions are affected by trade-offs between different criteria (Bartolini and Viaggi 2010; FAO 2017). A multi-criteria decision analysis assures that the decision-making process is structured, accountable and transparent, and allows the decision-maker to prioritise interventions in an evidence-based, yet multidisciplinary manner. This methodology allows the aggregation of heterogeneous data, either qualitative, semi-quantitative or quantitative data, giving a wide range of possibilities for criteria metrics (FAO 2017; Van der Fels-Klerx et al. 2018; Ruzante et al. 2017). This research wants to apply the principles of multi-criteria decision analysis for the evaluation of different mitigation/intervention strategies in the production of fresh-cut vegetables, for the case of leafy greens, as the most important product. The research questions this thesis sets out to answer are:

1. **The MCDA methodology in food safety risk management.** How to apply the principles of multi-criteria decision analysis, specifically:
    a. The identification of the criteria relevant to the evaluation of food safety interventions.
    b. Expert consultation to fill in data gaps in identified criteria.
    c. The identification of the stakeholders relevant to food safety decision-making.
    d. The elicitation of stakeholders' interests.
    e. Different MCDA models to rank food safety interventions.
2. **The risk management decision-making process**. Does decision-making in food safety risk management rely on a systematic approach and what can we learn from other domains (e.g. ecotoxicology)?
3. **The application of an MCDA for the leafy greens case study.** How can MCDA be utilised to select the most appropriate intervention strategy to minimise risks associated with (microbiological) hazards of fresh-cut leafy greens?

Flow of this thesis is illustrated in Figure 1.

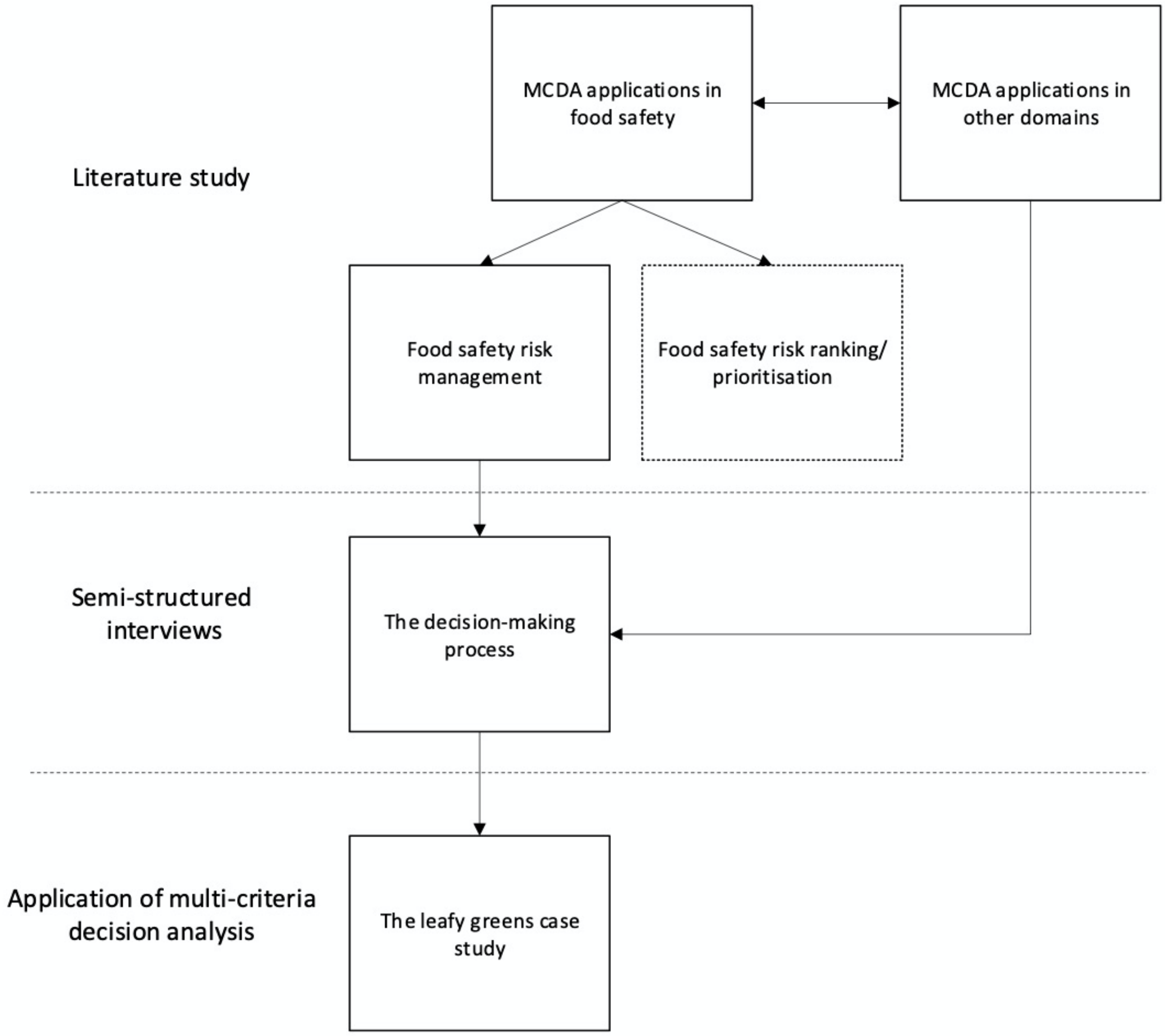

Figure 1. Schematic overview of this thesis.

1 LITERATURE STUDY

1.1 Minimally processed vegetables

1.1.1 Definition of minimally processed vegetables

The consumption of minimally processed fruits and vegetables (MPVs), also referred to as ‘fresh-cut’, ‘ready-to-eat’, ‘easy-to-use’ or ‘pre-cut’ produce, has known a sharp increase in recent decades as a result of changes in consumer attitudes (De Corato 2020; Rico et al. 2007). The benefits of fresh fruits and vegetables have been well established and widely documented in literature. This was confirmed by the EAT-Lancet Commission, who recognised that fruits and vegetables play an important role in the human diet, as they are an important source of micronutrients, fibres and antioxidants (Willett et al. 2019). Besides the health factor, also the image of convenience plays an important role in the increase of sales. Especially in the case of pre-packed ready-to-eat fresh-cut produce, such as packaged salads (Heaton and Jones 2008; Ragaert et al. 2004). Lifestyle changes resulted in the fact that consumers demand quick and less time-consuming foods (Ahvenainen 1996), which has led to the development of ready-to-eat (RTE) fresh-cut fruits and vegetables. According to the International Fresh-Cut Produce Association (IFPA) these products are defined as “any fresh fruit or vegetable or combination thereof physically altered from its original form but remaining in a fresh state” (IFPA 2001). Usually this consists of a series of possible steps including harvesting, cold storage, trimming, shredding, washing/rinsing, draining, packaging, cold storage and distribution (Garrett et al. 2003). This results in a 100% usable product, which enables the consumer to simply open the bag and eat its content (De Corato 2020).

1.1.2 Microbiome of leafy greens

Raw leafy vegetables harbour a large and diverse microbial population, including bacteria, moulds and yeasts. They are highly perishable and prone to rapid microbial spoilage, and in some cases even pathogenic contamination. Total counts of microbiological populations on leaf surface (the phyllosphere) after processing between 3.0 and 9.0 log CFU/g have been documented (Nguyen-the and Carlin 1994), however large differences in plate counts have been reported between batches of produce. The natural microbial load in vegetables can be attributed to numerous factors such as environmental conditions, growing conditions, the presence of soil accompanying the product, postharvest handling procedure, seasonality and the natural variability of the product (Pradhan, Mishra, and Pang 2018). Most microorganisms associated with leafy greens are considered harmless, however occasionally human pathogens may occur due to exposure to contaminated irrigation water, cross-contamination via animals, dirty equipment and handling (Söderqvist et al. 2017).

The complete identification of the fresh-cut produce microbiota is of high importance, since this might provide insights into produce-borne outbreaks of disease (Jackson et al. 2013). In the past two decades efforts have been made to generate huge amounts of metagenomic data to profile the food microbiome. However, the knowledge about the fruit and vegetable microbiome is still scarce. Traditionally, food microbiological analysis is based on culture-dependent approaches, however now the phyllosphere and endophyte bacterial diversity is more frequently being analysed using culture-independent methods (Gorni et al. 2015). These molecular approaches in microbial ecology enable detection of a broader range of bacteria and allow for the assessment and monitoring of complex bacterial communities (Söderqvist et al. 2017). Pyrosequencing of 16S ribosomal RNA gene amplicons has revealed that microbial communities were much more complex than previously identified and that perhaps only 1% of the bacteria had been identified using culture-dependent methods (Gorni et al. 2015). Table 1 shows the results from studies published in the last decade, based on culture-independent analysis of leafy vegetables' phyllosphere using 16S rRNA pyrosequencing. Different studies show a large variety in the composition of the most prominent bacterial operational taxonomic units (OTUs). However, some general remarks on the leafy green microbiome can be made. *Pseudomonas* spp. has been reported as the most prevalent genus in the phyllosphere of lettuce by multiple studies (Hunter et al. 2010; Jackson et al. 2013; Lopez-Velasco et al. 2011; Rastogi et al. 2012). Next to this, *Xanthomonas spp.*, *Masilia* spp., *Acinetobacter* spp. and *Pantoea* spp. are some recurring genera of the core microbiome of leafy vegetables.

Table 1. Relative abundance of microbial genera in the phyllosphere of minimally processed leafy greens determined with culture-independent analyses.

Study	Product	Most abundant genera
Lopez-Velasco et al. 2011	Fresh packaged spinach	*Pseudomonas* (9%), *Massilia* (7%), *Sphingomonas* (6%)
Rastogi et al. 2012	Field-grown Romaine lettuce at time of harvest	*Pseudomonas* (17%), *Bacillus* (7%), *Pantoea* (6%), *Massilia* (5%), *Xanthomonas* (4%), *Alkanindiges* (3%), *Erwinia*, *Duganella* and *Acinetobacter* (2% each)
Leff and Fierer 2013	Pre-rinsed & pre-package Romaine lettuce	*Xanthomonas* (10.0%), *Pantoea* (8.9%), *Pectobacterium* (8.0%), *Leuconostoc* (6.9%) *Janthinobacterium* (5.7%)
Jackson et al. 2013	Packaged Romaine lettuce	*Xanthomonas* (47.4%), *Pseudomonas* (23.9%), *Stenotrophomonas* (20.2%)
Erlacher et al. 2014	Greenhouse-grown lettuce	*Pseudomonas* (53%), *Acinetobacter* (10%), *Alkanindiges* (5%), *Pantoea* (4%)
Wang et al. 2019	Lettuce	*Xanthomonas* (24.73%), *Sphingomonas* (15.85%), *Massilia* (10.23%), *Alkanindiges* (9.00%), *Acinetobacter* (7.57%), and *Pseudomonas* (6.02%).

1.1.2.1 Quality – spoilage indicators

Despite the major improvements in food processing, packaging technologies and maintaining the cold chain of fresh-cut produce, microorganisms still remain an important cause for spoilage of fresh-cut produce and continue to have immense effects on quality and reduced shelf-life in most fresh-cut vegetables (Kaczmarek, Avery, and Singleton 2019; Nguyen-the and Carlin 1994; Olaimat and Holley 2012). The shelf-life of MPVs should be at least 4 to 7 days, ideally even longer up to 21 days (depending on the market condition), by preserving the microbiological, sensory and nutritional qualities. It is well known that processing promotes faster physiological, biochemical and microbial degradation of the product, and in the end also degradation of colour, texture and flavour, even when only slight processing operations are applied (De Corato 2020). Cutting of minimally processed vegetables influences microbial growth, since the wounded tissue provides nutrients for microorganisms in the released plant juice or cell contents. The high water-activity, nutrients in the cut surface and the lack of preservative processes that sufficiently slow down biological and biochemical changes make MPVs highly susceptible of microbiological spoilage (Yildiz and Wiley 2017). The aerobic plate count is used as a key indicator of the extent of contamination in fresh produce (Wang et al. 2019). As indicated hereabove, fresh-cut vegetables harbour a very diverse microbial population and populations of mesophilic aerobic bacteria of up to 9 log CFU/g were reported on produce at various points in the food chain from farm-to-retail (FAO/WHO 2008; Francis, Thomas, and O'Beirne 1999). Bacterial counts exceeding 8 log CFU/g or yeast counts exceeding 5 log CFU/g are usually accompanied by the detection of off-odours or obvious visual defects on fresh-cut vegetables, however this may vary depending on the type of microorganism and type of product (Ragaert, Devlieghere, and Debevere 2007; Yildiz and Wiley 2017). Most microorganisms responsible for spoilage of vegetables are Gram-negative bacteria, among which *Pseudomonadaceae* and *Enterobacteriaceae* prevail. Lactic acid bacteria represent an important group of Gram-positive spoilers (Pradhan et al. 2018; Ragaert et al. 2007).

An important group of microorganisms contributing to the biodeterioration of fresh-cut leafy vegetables, are the Gram-negative, strict aerobic psychotrophic *Pseudomonas* spp., which were identified to play a prominent role in the lettuce microbiome (Table 1) (Barth et al. 2009; Erlacher et al. 2014). Several *Pseudomonas* species are involved in vegetable spoilage, such as *P. marginalis, P. chlororaphis* and *P. fluorescens.* The latter represents the majority of these (Nguyen-the and Carlin 1994), and due to the production of plant cell wall-degrading enzymes (PCWDEs), such as cellulase, xylanase, pectate lyase, and polygalacturonase, *P. fluorescens* acts as a soft rot bacterium (Kaczmarek et al. 2019; Lee et al. 2013; Ragaert et al. 2007). Another important group of spoilage causing microorganisms, are the Gram-negative *Erwinia* spp., such as *E. carotovora, E. herbicola*, *E. agglomerans,* which are among the most aggressive spoilage bacteria. Gram-positive spoilage bacteria are represented by lactic acid bacteria, of which the most notable genera are *Lactobacillus, Leuconostoc, Pediococcus, Lactococcus*, and *Enterococcus* (Kaczmarek et al. 2019; Ragaert et al. 2007; Yildiz and Wiley 2017). Moulds and yeasts are also present on raw fruits and vegetables, however in lower numbers than bacteria (Yildiz and Wiley 2017). *Botrytis cinerea* and *Botryotinia fuckeliana* cause gray mould on leafy greens and *Sclerotinia* spp. causes watery soft rot (Pradhan et al. 2018).

1.1.2.2 Pathogens

The microbial safety of leafy vegetables is a continual cause for concern throughout the world, as a number of foodborne pathogen outbreaks have been assigned to minimally processed leafy greens. In particular pathogens that maintain their infectious potential under mild preservation conditions and psychotrophic pathogens are of high concern. Human pathogenic Shiga-Toxin producing *Escherichia coli* (STEC), *Salmonella* spp., *Listeria monocytogenes* and Norovirus and hepatitis A virus are among the most noteworthy (Acar and Soyer 2017; Francis et al. 1999; Mogren et al. 2018).

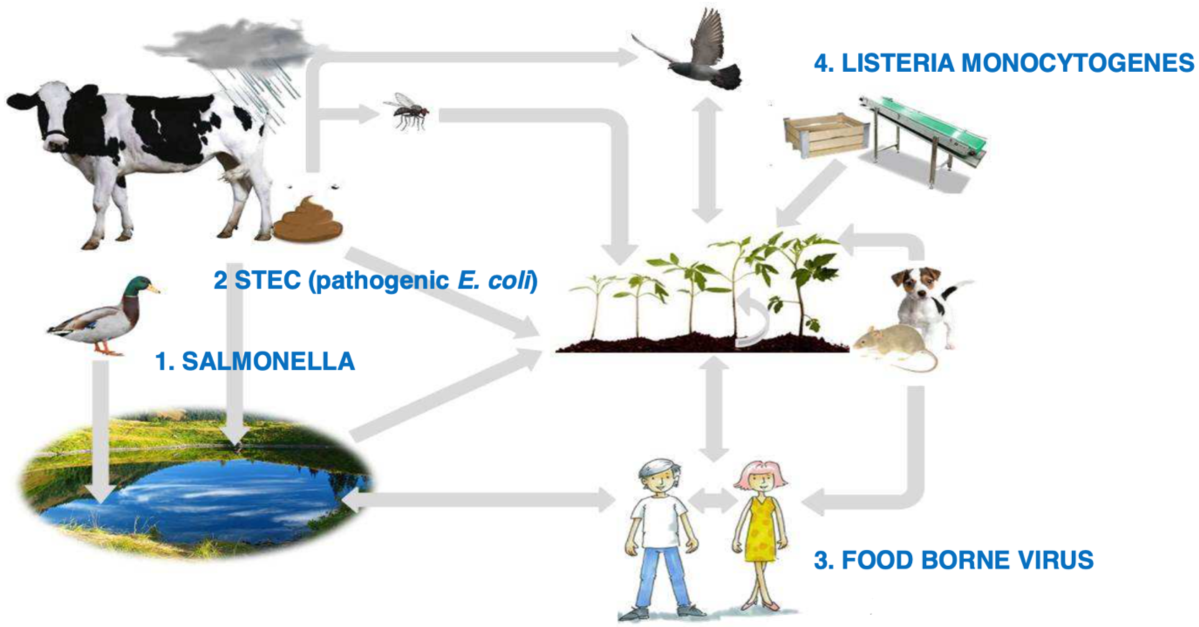

Figure 2. Overview of pathogens of highest concern for minimally processed leafy greens and possible transmission routes (Delbeke 2015).

Contamination can occur through various pathways at every stage of the food chain, from cultivation to processing (Figure 2) (Nguyen-the and Carlin 1994). In the primary production this could happen pre-harvest while growing in the field or during harvesting. Sources include soil, faeces, irrigation water, air, insects, birds, manure, animals and human handling. Processes which wet the edible part of the leafy greens, were identified as the most important risk factors for the contamination of leafy greens with *Salmonella* spp. and Norovirus during primary production. These processes include spraying prior to harvest, direct application of fertilisers, pesticides and other agricultural chemicals and overhead irrigation. Post-harvest contamination with pathogens, could occur during post-harvest handling, processing, or distribution. Factors contributing to contamination are human handling, harvesting equipment, cross-contamination and improper storage (Gil et al. 2015; Pradhan et al. 2018). Some preventive measures should be taken to minimise pathogen contamination of fresh produce, this entails an appropriate implementation of a quality management system, including Good Agricultural Practices (GAP), Good Hygiene Practices (GHP), Good Manufacturing Practices (GMP) and the hazard analysis and critical control points (HACCP) principles. Compliance with hygiene requirements by the food businesses is a necessity at all stages of the food chain (Cuggino et al. 2018; EFSA Panel on Biological Hazards (BIOHAZ) 2014b).

The EFSA BIOHAZ panel (2013) concluded from outbreak data from 2007 to 2011 that 10% of the reported foodborne pathogen outbreaks were associated with foods of non-animal origin (FoNOA) such as vegetables. In addition, FoNOA were responsible of 35% of the hospitalisations and 46% of the deaths. However, trends were strongly influenced by the 2011 VTEC O104 outbreak. Outbreaks associated with food of non-animal origin generally involve more cases, but tend to be less severe, meaning lower proportion of hospitalisations and deaths, than those associated with foods of animal origin (EFSA Panel on Biological Hazards (BIOHAZ) 2013). The same trends were observed in the United States, analysis of outbreak data from 1998 to 2008 in the US indicated that 22% of illnesses, 14% of hospitalisations and 6% of deaths could be assigned to leafy greens (Painter et al. 2013). The majority of illnesses linked to leafy greens were caused by Norovirus and the major bacterial causes of illness were *Salmonella* and Shiga-toxin producing *Escherichia coli* (STEC).

A risk ranking conducted by the EFSA panel on Biological Hazards in 2013 aimed at ranking foods of non-animal origin commodities revealed that the food/pathogen combinations of highest concern are *Salmonella* spp. and leafy greens eaten raw and *Salmonella* spp. and bulb and stem vegetables, *Salmonella* spp. and tomatoes, *Salmonella* spp. and melons, and pathogenic *Escherichia coli* and fresh pods, legumes or grain. It was recognised that the model used in the analysis may overestimate the importance of some food/pathogen combinations and underestimate the importance of diseases which seem to be of a more sporadic nature, such as listeriosis, campylobacteriosis and parasite infections.

There have been some extensive outbreaks related to **pathogenic *E. coli*** in the last few decades. In May 2011 the major outbreak of Shiga toxin-producing *Escherichia coli* (STEC) O104:H4 in Germany caused about 4,000 illnesses, more than 2,300 hospitalisations and 56 deaths. This Enterohaemorrhagic *Escherichia coli* strain causes severe illness, and in some cases, this can progress into hemolytic uremic syndrome (HUS), which can lead to severe kidney damage and possibly even death. The minimal processing steps that fresh-cut produce undergo, include peeling, cutting and removal of the natural protection of fruits and vegetables. Several authors have shown that *Escherichia coli* O157:H7 attaches preferentially to the cut edges of lettuce leaves, but also characteristic features of the lettuce leaf such as trichomes, stomata, and cracks in the cuticle (Brandl and Amundson 2008; EFSA Panel on Biological Hazards (BIOHAZ) 2013).

While infections with ***Salmonella* spp**. are usually linked to foods of animal origin, several outbreaks have been traced back to the consumption of foods of non-animal origin, such as tomatoes, sprouts and leafy greens (Delbeke 2015; EFSA Panel on Biological Hazards (BIOHAZ) 2013). Infections remain a worldwide health concern, as strains of non-typhoidal *Salmonella* may cause intestinal infections, with symptoms like diarrhoea, fever, nausea and abdominal cramps (EFSA Panel on Biological Hazards (BIOHAZ) 2014b). Some important outbreaks related to the combination of *Salmonella* spp. and leafy vegetables include two outbreaks of *Salmonella* Typhimurium in the year 2000 in the UK through the consumption of lettuce, which caused over 361 and 362 infections respectively (Crook et al. 2003; Horby et al. 2003), and in 2004 *Salmonella* Newport caused over 360 infections in the UK due to the consumption of lettuce (Little and Gillespie 2008).

Due to the sporadic nature of ***Listeria monocytogenes,*** the model used by the EFSA BIOHAZ panel (2013), may have underestimated the importance of diseases such as listeriosis. *L. monocytogenes* is considered ubiquitous in environment and foods (FAO/WHO 2004). Since it is widely distributed in the agricultural environment, it is naturally present on many vegetables (Beuchat 2002; Francis et al. 1999). A wide range of food types have been related with the transmission of listeriosis, however for the majority of the cases, a specific vehicle cannot be identified (EFSA Panel on Biological Hazards (BIOHAZ) 2013). The first foodborne illness outbreak associated with *Listeria monocytogenes* was in 1981 in Canada, that was linked to cabbage in coleslaw and has been associated with several outbreaks since then (Schlech et al. 1983). The Annual Epidemiological Report from the ECDC for the year 2017 reported 2502 confirmed listeriosis cases in the EU/EEA. This report indicates that the annual number of listeriosis cases in the EU/EEA shows an increasing trend. A study by Little et al. (2007) examined 2686 samples of pre-packaged mixed raw vegetables in the UK and revealed that *L. monocytogenes* was detected in 4.8% of samples and in two samples *L. monocytogenes* was present in levels above 100 CFU/g, which is the food safety criterion for *L. monocytogenes* in RTE foods placed on the market during their shelf-life (EC Regulation 2073/2005). In humans, foodborne listeriosis is considered an opportunistic infection (McLauchlin et al. 2004). It has a low incidence rate, however with a high morbidity and mortality, especially within the YOPI (young, old, pregnant, immunosuppressed) group, compared to other bacterial foodborne illnesses (FAO/WHO 2004).

Norovirus and hepatitis A virus are the most significant viral food-related pathogens. The major foodborne viral infection route is the faecal-oral route, via direct contact or via consumption of contaminated food and water (Acar and Soyer 2017; Francis et al. 1999). In 2016 a series of Norovirus outbreaks in Denmark were linked to the consumption of fresh green coral lettuce (Lollo Bionda lettuce) from France. Fresh lettuce increasingly seems to be a risk for Norovirus outbreaks (Müller et al. 2016).

1.1.3 Processing of fresh-cut leafy greens

Processing operations are applied to raw leafy vegetables in a factory environment to physically alter the greens from their original form, yet to keep them in a fresh state and obtain a ready-to-eat (RTE) product. During processing, leafy greens may be exposed to microbial contamination and microorganism may persist and grow. On the other hand, some processes have the potential to reduce microbial risks, control microbial growth and protect the product from further exposure. Processing steps include, but are not limited to grading, removing outer or damaged leaves, coring, cutting, washing, sanitising and packaging (FAO/WHO 2008). Here the main interest will go out to the washing and sanitising steps. Washing of fresh-cut leafy greens after size reduction (shredding, cutting, slicing and chopping) is a critical step in the production chain. It is the only step where some reduction of the microbial load is possible. If properly controlled, the overall microbiota of leafy greens can be reduced, thus minimising populations of potential pathogens (Artés and Allende 2005; FAO/WHO 2008). Washing with potable water removes the microorganisms to some degree, however the efficiency is limited, at best 1 log CFU/g reductions of surface microbiota can be achieved (Rodgers et al. 2004). Therefore, it is assumed that if fresh-cut vegetables are being washed without the use of sanitisers, large amounts of water are needed in order to achieve an adequate level of microbial reduction (Gil et al. 2009). As it will remove microorganisms to a certain extent, it is a useful tool for reducing potential contamination, however the water could act as a vector for cross-contamination between clean and contaminated product and allow for the transfer of pathogenic microorganisms (Gil et al. 2009).

An alternative option is water sanitation, which is used to maintain water quality during the washing process. Thus, to avoid that the wash water enables cross-contamination of pathogens. Proper dosing of disinfectants before (re)use of the water in washing steps could be an appropriate strategy to avoid cross-contamination and reduce the formation of disinfection by-products (Banach et al. 2015; Van Haute et al. 2013). For the disinfection of process water different methods, besides chlorination, are being used in the fruits and vegetables processing industry. The applied disinfection technology will determine the microbiological safety of the treated water and/or product and the formation of chemical contaminants in the wash water. Some chemical disinfectants that appear to be appropriate for process water disinfection, besides chlorine, are chlorine dioxide, ozone and peracetic acid (Banach et al. 2015; Ölmez 2016). Some physical methods with adequate disinfection potential are membrane filtration and ultraviolet irradiation (Banach et al. 2015; Sam Van Haute et al. 2015). Chlorine-based sanitisers are one of the most effective sanitisers to assure product safety at a low cost and have been applied widely in the disinfection of minimally processed fruits and vegetables (De Corato 2020; Gil et al. 2009). The reaction between wash water constituents and chemical disinfectants may lead to the formation of disinfection by-products (DBPs), such as trihalomethanes and haloacetic acids (Banach et al. 2015). Due to this, antimicrobial agents are prohibited in the fresh-cut industry in some EU member states, such as Denmark, the Netherlands and Germany (Gil et al. 2015). Here, the use of potable water, instead of water containing chemical disinfection agents for washing of fresh-cut vegetables, is being applied.

1.1.4 Legal considerations of process water sanitation

Chemical disinfectants used to control microbial quality of wash water or produce are classified as processing aids in the European Union. Processing aids, as defined in EC Regulation 1333/2008, are used intentionally in the processing of raw materials, which may lead to the unintentional but technically unavoidable presence in the final product of residues of the substance or its derivatives, provided that they do not pose any health risk or have a technical function in the final product. This means that disinfectants can be introduced in the process water, however washing of produce with sanitised water should be followed by a rinsing step with sanitiser free water. This is required to achieve produce without residual disinfectants or disinfection by-products, which could remain in the vegetable tissue. Only unintentional presence of the sanitiser substance in the final product is allowed (Van Haute et al. 2015). However, up till now there is no specific European legislation regarding processing aids. In some member states, such as The Netherlands, Germany and Denmark, the use of disinfectants in the fresh-cut industry is in principle prohibited, and strict criteria apply for possible approval (Gil et al. 2015). Other countries like Spain, Italy and France allow the use of chlorine in washing processes. In France washing fruits and vegetables with sodium hypochlorite is allowed. This is regulated by limiting the concentration of free chlorine in the washing bath to 80 mg/L, produce should be rinsed after washing, and the absorbed organics should not exceed 200 µg/kg (Van Haute et al. 2015; MINISTÈRE DE L'ÉCONOMIE 2006). The Codex Alimentarius commission on food additives composed a list of possible antimicrobial substances which could be considered for the use as disinfectant. The 'Inventory of substance used as processing aids' should be used as a reference tool, not a Codex standard (FAO/WHO 2012).

1.2 Multi-criteria decision analysis (MCDA)

Multi-criteria decision analysis (MCDA) was originally developed and utilised in the field of operations research and has seen an incredible amount of use over the last few decades in a variety of fields to address a range of decision problems (Fazil et al. 2008; Velasquez and Hester 2013). MCDA is an approach which has the ability to evaluate multiple, often conflicting, criteria in decision-making. The simultaneous consideration of technical information, uncertainty and different stakeholder preferences, and the integration of both qualitative and quantitative data allows for the comparison of different options. It is a decision tool that helps structuring and solving problems, in order to make more informed decisions (Van der Fels-Klerx et al. 2018). A wide range of MCDA methods have been proposed to address multi-criteria decisions problems, which vary in their complexity (Fazil et al. 2008). Despite the diversity of MCDA approaches, methods and techniques, the basic elements of MCDA are very simple: a set of actions (alternatives, solutions, courses of action, …), at least two criteria and at least one decision-maker (DM) (Figueira, Greco, and Ehrgott 2005).

1.2.1 MCDA applications in food safety

The FAO guidelines on food safety risk management (2017) elaborate on the use of the MCDA methodology for both ranking/prioritisation of food safety problems, as well as the selection of the preferred risk management options. There are multiple examples of risk ranking of food safety issues, based on a multi-criteria decision analysis available in literature (Bouwknegt et al. 2018; Eygue et al. 2020; Garre et al. 2020; Ruzante et al. 2010). The MCDA applications selected here are all examples of the use of a multi-criteria decision analysis in the field of food safety risk management, aimed at selecting which control strategy to apply. It was observed that similar methods were applied, and similar evaluation criteria were included in the MCDA. However, there are significant differences in the degree of quantification and the inclusion of stakeholder and/or expert input. There seems to be a general distinction between studies, as some studies seem to focus more on the quantification and computation of the MCDA algorithm, compared to other studies where the analysis is carried out in a more qualitative manner. In Table 2 these distinctions are highlighted. A traffic light system was used to indicate the degree to which certain methods were applied in the example. Green means that the study extensively applied the technology/methodology and elaborates on the method of execution in the study. Yellow was assigned to those studies that included the methodology to some extent, but an explanation of the execution was not provided, and the study does not go into depth on it. Red means that the methodology was not applied whatsoever. Seven evaluation criteria were selected, based on an exploratory literature study. The selected criteria are cost, effectiveness, consumer acceptance, environment, practicality, workplace safety and distributional impacts. The inclusion of the criteria in the MCDA applications was assessed in a binary manner. A check mark was given to the examples that included the criterion in some way, different names might have been used. An explanation of the specific methodologies and evaluation criteria is given below.

Table 2. Qualitative evaluation of MCDA applications in food safety risk management, mentioning the applied algorithm, methods and included criteria.

Publication		Methodology						Criteria							Other criteria
	Algorithm	Expert input	Stakeholder input	Weighing of criteria	Sensitivity analysis	Quantification	Probabilistic methods	Cost	Effectiveness	Consumer acceptance	Environment	Practicality	Workplace safety	Distributional impacts	
The selection of interventions to reduce microbial risks (Fazil et al. 2008)	PROMETHEE							✓	✓	×	×	✓	×	×	- Quality of evidence
Establishing Priorities for SPS Capacity - building: A Guide to MCDM (Henson and Masakure 2012)	PROMETHEE							✓	✓	×	✓	×	×	✓	- Impact on poverty in the implementing country
A fuzzy MCA for the ex-ante IA of food safety policies. With an illustrative application on regulating mycotoxin content in cereals and cereal products (Mazzocchi, Ragona, and Zanoli 2013)	SCRYER							✓	✓	✓	✓	×	×	✓	- Eight other criteria

Publication		Methodology						Criteria							Other criteria
	Algorithm	Expert input	Stakeholder input	Weighing of criteria	Sensitivity analysis	Quantification	Probabilistic methods	Cost	Effectiveness	Consumer acceptance	Environment	Practicality	Workplace safety	Distributional impacts	
A Multi-Criteria Approach to the Evaluation of Food Safety Interventions (Dunn 2014)	WSM, AHP, PROMETHEE							✓	✓	✓	✓	×	×	✓	- Market impacts - Quality of science - Quality or suitability - Cultural impact - Animal welfare
Exploring a Multi-criteria Scenario Analysis Tool to Study Future Food Safety. Assessment of microbial safety for pre-harvest leafy greens in Spain (Liu 2016)	WSM							✓	✓	×	✓	×	×	×	- Yield - Nutrient loss from soil/soil health
Comparing interventions to reduce risks caused by aflatoxins in maize (FAO 2017)								✓	✓	×	×	✓	×	×	- Food accessibility - Food nutritional status

Publication		Methodology						Criteria							Other criteria
	Algorithm	Expert input	Stakeholder input	Weighing of criteria	Sensitivity analysis	Quantification	Probabilistic methods	Cost	Effectiveness	Consumer acceptance	Environment	Practicality	Workplace safety	Distributional impacts	
Combining Quantitative Risk Assessment of Human Health, Food Waste, and Energy Consumption: The Next Step in the Development of the Food Cold Chain? (Duret et al. 2019)	CBA-analysis, ELECTRE III, AHP							✓	✓	✗	✓	✓	✗	✗	- Food waste
MCDA for the Selection of an Intervention to Reduce Exposure to PAHs in Smoked Fish in Ghana (Bomfeh 2020)	PROMETHEE I & II							✓	✓	✓	✓	✗	✓	✗	- Sustainability of the intervention

Publication		Methodology						Criteria							Other criteria
	Algorithm	Expert input	Stakeholder input	Weighing of criteria	Sensitivity analysis	Quantification	Probabilistic methods	Cost	Effectiveness	Consumer acceptance	Environment	Practicality	Workplace safety	Distributional impacts	
MCA to evaluate control strategies for preventing cross-contamination during fresh-cut lettuce washing (Banach, Zwietering, and van der Fels-Klerx 2021)	WSM							✓	✓	✓	✓	✓	✓	✗	
OVERALL	PROMETHEE: 5 WSM: 3 AHP: 2 ELECTRE: I SCRYER: I							9/9	9/9	5/9	7/9	4/9	2/9	3/9	

1.2.1.1 Methodology

The algorithm used to rank the intervention options is what differentiates different MCDA methods. The weighted sum model (WSM) is a simple method applied by Dunn et al. (2014), Liu (2016) and Banach et al. (2021). These are the simplest multi-criteria tools for solving problems related to the ranking of alternatives. It allows for a maximal consideration of trade-offs among indicators. The Analytical Hierarchy Process (AHP) is an example of a single synthesising criterion method. In these methods the choice of the alternative that provides the higher value of decision-makers' utility function decides the preference. This method was applied by Dunn et al. (2014) and Duret et al. (2019). PROMETHEE, a popular model in MCDA from the outranking family, was used to rank interventions by five out of nine papers. PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) measures performances as preference flows (represented by a Greek letter Phi (ϕ)). The algorithm compares every pair of interventions on each criterion and measures the degree to which an intervention outperforms all others (the positive flow ($\phi+$)), in a similar manner the degree to which an intervention is outperformed (the negative flow ($\phi-$)) is determined. PROMETHEE II combines these two flows into one net flow (ϕ), which allows for a 'complete' ranking of options. The Visual PROMETHEE software ® computes these flows and ranks interventions based on these values (Bomfeh 2020; VPSolutions 2013).

Expert input can be utilised to fill data gaps. Since the majority of the studies presented here, were merely illustrative and hypothetical examples, this was not generally included in the MCDA. Qualitative scores and weights were developed by Dunn et al. (2014) based on consultation with a food safety modelling expert. Duret et al. (2019) included expert opinions where data was lacking. Banach et al. (2021) defined criteria and sub-criteria based on expert input from scientists in the field of food safety and chemical engineering.

Stakeholder input was not generally considered in the MCDA case studies presented here and received a 'red' label, probably because most studies here were illustrative examples in which hypothetical data was used. The studies that included stakeholders' views used different methods to elicit their opinions. Henson and Masakure (2011) used the Delphi method and a structured stakeholder workshop to elicit responses from stakeholder group representatives. The stakeholder groups that seemed relevant were public sector policymakers and technicians engaged in the management and implementation of SPS controls, private sector, consumer groups and producer representatives. Dunn et al. (2014) proposed nine different key stakeholder groups: regulators, public health authorities, food safety scientists/academics, consumers, food businesses (farmers, processors, food retailers and exporters). The stakeholder selection was based on informant interviews. Informants were asked to identify 'key stakeholders', both inside and outside their own industry or stakeholder group. Based on semi-structured interviews with these stakeholder representatives a core list of criteria and how to measure performance on each criterion was highlighted. Banach et al. (2021) surveyed thirty-six stakeholders in total. The key stakeholder groups included in this study were fresh-cut processors, producers and suppliers of disinfectants and equipment, scientists and government representatives. An online survey was developed to collect stakeholders' views on the importance of criteria and sub-criteria. It was recognised that having stakeholder input may increase the acceptance of the chosen intervention strategy.

Weighing of criteria is usually the final step before performance scores are aggregated, but can be an important source of uncertainty. In general, weights were assigned to the evaluation criteria, to reflect their relative importance. There are several methods of generating weights. Henson and Masakure (2011) used a Delphi approach to allocate weights to the evaluation criteria. Respondents were asked to allocate 100 points across a list of criteria according to their relative performance. Based on these results, the mean decision weights are calculated and recalibrated as necessary to sum to 100. Banach et al. (2021) collected stakeholders' views on the importance of the sub-criteria to consider. The averaged preference weights were calculated based on an online survey, in which respondents were asked to divide 100 points over nine sub-criteria and were asked not to use the same points for two or more criteria.

Sensitivity analysis is a common method used to verify the 'trustability' and credibility of the results. It is used to determine how the results would change as a result of changes in parameters or assumptions (Bartolini & Viaggi 2010). In all cases, sensitivity towards changes in criteria weights were analysed, since criteria weights could be a great source of uncertainty. Dunn et al. (2014) performed a variability analysis on criteria weights using the @Risk software ® and conducted a Monte Carlo analysis for the simulation of the effect of varying multiple performance scores. Banach et al. (2021) and Bomfeh (2020) on the other hand, performed a scenario analysis, in which an alternative score was assigned to the criteria and the influence on the final ranking was determined.

The extent to which input was **quantified** varied over the different studies. The MCDA methodology allows for the aggregation of qualitative, semi-quantitative and quantitative data (Ruzante et al. 2017). This is represented in the studies observed here, as most of them included a wide range of data. Except for Banach et al. (2021), who assessed evaluation criteria on a qualitative scale only.

Probabilistic methods were only included in a few studies. The MCDA spreadsheet model developed by Mazzocchi et al. (2013), known as SCRYER uses a very complex fuzzy-outranking algorithm. This consists of an explicit scoring system with indicators of uncertainty in assessments and the application of fuzzy logic. The fuzzy measurements allow for the discrete qualitative impact evaluation to be accompanied with an indication of uncertainty. Duret et al. (2019) built a model to predict the risks of listeriosis associated with the consumption of cooked ham, the food waste caused by the growth of spoilage microorganisms and the energy requirement of the equipment of the cold chain to cool down the product and maintain product temperature. Model predictions were thereafter used as input data for two different MCDA models. Bomfeh (2020) evaluated the food safety criterion based on reduction of PAH4 in products. @Risk software ® was used to estimate the exposure to PAH4 in a probabilistic manner.

1.2.1.2 Criteria

The evaluation criteria are aimed at quantifying the consequences of the alternative actions. The MCDA applications related to food safety risk management all included some kind of criteria and/or sub-criteria related to the costs and the effectiveness of the intervention option. Most studies also included a factor taking environmental impacts into account.

Some studies, however, made a distinction between different **costs**. Fazil et al. (2008) differentiated between capital, material and labour costs. It was also recognised that the inclusion of different types of costs may require additional calculations, as they are on different measurement scales. The capital costs tend to occur at the implementing stage of the intervention, while material and labour costs tend to be ongoing costs. Henson and Masakure (2011) divided the ‘cost’ criteria into two similar sub-criteria, namely up-front investments and on-going costs. Mazzocchi et al. (2013) considered fourteen different impacts, divided into multiple sub-impacts, which mainly focused on the economic impacts of food safety interventions. Dunn et al. (2014) included the direct costs of implementing and maintaining an intervention. In the FAO case study, the cost of intervention was monetised and considered in the MCDA. Duret et al. (2019) included costs related to DALY, food waste, energy consumption, and the total cost. Bomfeh (2020) measured the cost criterion as the upfront financial investment required for each intervention. Maintenance costs were not included. The study by Banach et al. (2021) included an economics criterion, of which costs for the producer was a sub-criterion. Both direct (e.g. equipment and purchase of chemicals) and indirect costs (e.g. energy use, depreciation, quality control) were included, and costs were considered over a five year period. The reduction in water use, which was also a sub-criterion of the economics criterion, considered the amount of water that can be saved during processing by applying the technology. The inclusion of a time dimension further allowed the assessment of advantages and disadvantages of the intervention. Fazil et al. (2008) recognised that deriving cost information for interventions can be a difficult task, since a lot of information is in grey literature. Therefore, an expert consultation may be a starting point.

A second criterion that 9 out of 9 studies considered, was the **effectiveness** of the intervention. Fazil et al. (2008) made a distinction between the point of application and the point of interest, for the latter a model may be required. Mazzocchi et al. (2013) takes both acute effects on human health as well as chronic effects into account. Dunn et al. (2014) defines effectiveness as the intervention’s ability to reduce the burden of foodborne illness and/or the contamination of food products and also recognised that multiple measures of effectiveness are available. Dunn et al. (2014), the FAO case study and Duret et al. (2019) measured effectiveness using Disability-Adjusted Life Years (DALYs). Cheng Liu (2016) measured the effectiveness as the calculated *E. coli* concentration on spinach. In the study by Banach et al. (2021) the effectivity of the control strategy was based on the microbial reduction ($\log_{10}$ reduction in the water) and in the study by Bomfeh (2020) the effectiveness was defined as the extent to which each intervention reduces the PAH4 levels in products.

Consumer acceptance was included in four out of nine studies. In the case study studied by Banach et al. (2021) the consumer acceptance criterion was divided into two sub-criteria, namely consumer perception and organoleptic effects. The first reflects the consumer perception towards the use of this technology and the latter refers to the possible side-effects or undesired effect on lettuce in terms of sensory quality.

Half of the studies did not include a criterion that accounted for **environmental** implications of the intervention. Bomhef (2020) took the environmental sustainability of the intervention in consideration and Mazzocchi et al. (2013) qualitatively accounted for the environmental criterion. Banach et al. (2021) included a criterion related to the reduction in water use, which refers to the amount of water that can be saved during processing by applying the technology. Liu Cheng (2016) included the nutrient loss from soil/soil health, which was identified as an important factor by environmental scientists.

Practicality or ease of implementation or use was included by six studies. Henson and Masakure (2010) included the difficulty of implementation, and the FAO case study included the feasibility. Banach et al. (2021) refers to the ease of use as the easiness for employees to apply the technology. According to Fazil et al. (2008) practicality refers to the nature of the intervention and an assessment of its ability to be implemented within the industry. This includes infrastructure change or the change in the structure of the industry as a whole. They also recognise that this is a relatively subjective criterion, that requires expert or stakeholder input, especially from those that will be implementing the intervention. Besides this, the ease of implementation is highly industry specific.

Some studies take **workplace safety** and the possible side-effects on employees into consideration. For example, Dunn et al. (2014) included a workplace safety criterion. It was recognised that the safety criterion was important to stakeholders where potentially dangerous interventions could be implemented. Bomfeh (2020) included the exposure to occupational hazards in the MCDA. It was claimed that an intervention that is effective for food safety must also support decent work for the processors. Banach et al. (2021) included the possible side-effects and worker's safety as two sub-criteria of a public health criterion. The first refers to the possible production of by-products with unknown or adverse human health effects and the latter refers to the effect of the technology on the worker's safety (e.g. irritation).

Three studies included a **consideration of distributional impacts** in the analysis. Henson and Masakure (2011) included the impact on vulnerable groups, Mazzocchi et al. (2013) included societal concerns, which accounts for the public opinion and media and consequences on vulnerable groups, and positive distributive effects, which reflects the fact that regulations could decrease health risks for certain vulnerable categories such as infants and pregnant women, and negative distributive effects, which implies that regulations could also be more burdensome to small and medium enterprises. Dunn et al. (2014) included the equity of benefits.

1.2.1.3 Other criteria

Both Dunn et al. (2015) and Fazil et al. (2008) included the quality of evidence as one of the evaluation criteria. This refers to the scientific evidence underpinning a specific intervention. It is measured by the number of research papers evaluating the intervention, the proportion of studies showing results with no effect or negative effects compared to those showing positive, and the type of studies conducted. This was qualitatively assessed by the first, in comparison to the latter who calculated a strength-of-evidence (SoE) index as a measurement of the quality of science.

Henson and Masakure (2011), Mazzocchi et al. (2013) and Dunn et al. (2014) included market impacts in the evaluation criteria of the MCDA. This was divided into domestic market effects, equity of costs/benefits and international market impacts by Dunn et al. (2014). This was represented by a few criteria in the study by Mazzocchi et al. (2013), namely firm competition and international competition, which were divided into several sub-criteria.

1.2.2 MCDA applications in other domains

The MCDA methodology has been applied extensively in different domains, e.g. the field of healthcare decision-making (Marsh et al. 2017), financial decision-making (Zopounidis and Doumpos 2002) and environmental risk management (Huang, Keisler, and Linkov 2011; Linkov, Satterstrom, Kiker, Batchelor, et al. 2006). These domains have in common that decisions are becoming increasingly complex, information-intensive and sophisticated, which is why multi-criteria decision analysis could provide support for better decision-making (Linkov, Satterstrom, Kiker, Batchelor, et al. 2006).

Some examples related to MCDA in **environmental risk management** are presented in Table 3. The illustrative examples provided here are related to the policy selection for the management of contaminated sediments (Linkov, Satterstrom, Kiker, Seager, et al. 2006), water management (Zyoud et al. 2016) and waste management (Cheng, Chan, and Huang 2003).

The methodology was assessed in the same way presented in Section 1.2.1. However, only four criteria were included, since consumer acceptance, workplace safety and distributional effects did not seem relevant in these examples.

Table 3. Qualitative evaluation of MCDA applications in environmental risk management, mentioning the applied algorithm, methods and included criteria.

Publication		Methodology						Criteria				Other criteria
	Algorithm	Expert input	Stakeholder input	Weighing of criteria	Sensitivity analysis	Quantification	Probabilistic methods	Cost	Effectiveness	Public acceptance	Environment	
Environmental risk management												
MCDA: A Comprehensive Decision Approach for Management of Contaminated Sediments (Linkov, Satterstrom, Kiker, Seager, et al. 2006)	PROMETHEE							✓	×	×	✓	- Human habitat - Ecological habitat
A framework for water loss management in developing countries under fuzzy environment: Integration of Fuzzy AHP with Fuzzy TOPSIS. (Zyoud et al. 2016)	Fuzzy AHP Fuzzy TOPSIS							✓	✓	✓	✓	

An integrated MCDA and inexact mixed integer linear programming approach for solid waste management (Cheng et al. 2003)	WSM, WPM, Co-operative game theory, TOPSIS, ELECTRE							✓	✓	✓	✓	- Land value drop - Extensibility - Reliability - Political concern - Heritage - Transportation
OVERALL	TOPSIS: II WSM: I WPM: I AHP: I PROMETHEE: I ELECTRE: I							3/3	2/3	2/3	3/3	

1.2.2.1 Methodology

These examples uncover that a large diversity within different approaches towards MCDA in the field of environmental management exists. On the one hand, this refers to the different kinds of MCDA algorithms being applied, of which the major MCDA methods are MAUT, outranking and AHP (Huang et al. 2011). Chen et al. (2003) applied 5 different MCDA algorithms, which didn't lead to the same ranking, therefore rankings were aggregated into one final ranking. Stakeholder and expert involvement were extensive in the MCDA applications presented here. The quantification of criteria was rather limited.

These examples provide evidence that uncertainty, originating from different sources, can be incorporated in the MCDA in multiple manners. One example is fuzzy set theory, applied by Zyoud et al. (2016). This methodology transforms qualitative data into a quantitative equivalent measure. Pelissari et al. (2021) identified several methods to model uncertain input data in MCDA. Besides fuzzy set theory, also probability theory, evidential reasoning (ER) theory, rough set (RS) theory and others are being used to deal with uncertainty. A review paper by Rigo et al. (2020) on MCDA for sustainable energy management, revealed that 34 out 163 conducted a sensitivity analysis, and five out of 163 papers applied a Monte Carlo simulation for the sensitivity analysis, i.e. to analyse the MCDA process' robustness.

1.2.2.2 Criteria

Criteria usually considered, besides the effectiveness of intervention options, are the economic, social and environmental impact.

To conclude, it should be mentioned that MCDA has more applications in the field of environmental risk management, in comparison to food safety risk management. A review paper by Huang et al. (2011) on MCDA in environmental sciences revealed an annual percentage growth of 7.5% of MCDA papers between 1990 and 2009, with MCDA applications being 1.66% of all environmental papers published in 2010 on Web of Science. This growth was attributed to the increased decision complexity and information availability, and regulatory and stakeholder push for transparency in the decision-making process. The extensive number of applications should be considered as a source of information for MCDA applications in food safety risk management. For example, in order to improve methods for expert and stakeholder consultations and the application of sensitivity analyses could be informed by MCDA papers related to environmental risk management.

1.3 Development of an MCDA framework

The following steps could be followed when developing a multi-criteria decision analysis.

1. **Establish the decision context:**
   In the first step the purpose of the MCDA is determined. It is important to know the overall ambition of the analysis. The key stakeholders should be identified at this stage, as they will provide input. Stakeholders are often referred to as those who may be affected by the decision. They might not participate in the MCDA physically, however, their values should be represented by one or more key players. The MCDA is not limited to the views of stakeholders. Additional key players, such as experts, will need to be considered, as they hold knowledge and expertise about the subject matter (Spackman, Pearman, and Phillips 2009).

2. **Identify the alternative intervention options to be appraised:**
   This may be determined through stakeholder discussions and information sharing between stakeholders. The set of alternatives to be analysed, may be preceded by an initial screening process, where options which are infeasible or unacceptable are eliminated. In the end, the decision-maker(s) will be in charge over which alternatives are included in the formal analysis (Dunn 2014).

3. **Identify the evaluation criteria against which intervention options will be appraised:**
   Criteria could be viewed as measurable objectives (Spackman et al. 2009). They should capture all relevant positive and negative effects of each option. Overall, the performance criteria should adequately assess the overall performance of each intervention option (Dunn 2014).

4. **'Scoring'. Assess the performance of the intervention options on each criterion:**
   At this stage, the performance measurement is carried out. This is also referred to as 'scores', which are often numerical, but can be qualitative or ordinal of nature (Spackman et al. 2009). Analysts will need to consider how the performance against the criteria will be measured. The metric used to measure the criteria will depend on the kind of alternatives being considered, the selected criteria and the availability and quality of data. Sources of data can be diverse, ranging from quantitative risk assessments, surveillance reports to results from focus groups (Ruzante et al. 2017).

5. **'Weighing'. Allocate weights to each criterion, reflecting their relative importance in the final ranking:**
   The process of deriving weights is essential for the effectiveness of the MCDA. Often, they will be derived by the opinions of a group of people. When setting weights, the question rises whose preferences counts most (Spackman et al. 2009). Most MCDA studies don't elaborate on the elicitation of weights (Dunn 2014).

6. **Determine of the overall weighted scores and ranking of intervention options:**
   The aggregation of the overall performance of each intervention option across all criteria is what differentiates all decision support tools (Alberto and Donoso 2008). A suite of different MCDA methods is available (e.g. outranking methods, analytical hierarchy process, linear additives models, …) (Greco, Ehrgott, and Figueira 2016).

7. **Uncertainty analysis and sensitivity analysis of the results:**
   In an uncertainty analysis the limitations in scientific knowledge are identified and their implications on scientific conclusions are evaluated (EFSA 2018). It has the aim to ensure increased transparency regarding the results of the MCDA and enables decision-makers and stakeholders to gain a better understanding in the content of the MCDA (EFSA 2018).
   The sensitivity analysis involves altering model inputs, such as criteria weights and performance scores to see if the model outputs (i.e. rankings) are significantly affected. At this stage inputs to which the model is insensitive can be identified, so that further analysis can focus on those inputs which do have potential to affect the final ranking (Dunn 2014).

8. **Examine the results and evaluate the ranking:**
   Regardless what MCDA method is applied, an examination of the results is always warranted (Alberto and Donoso 2008). It is a crucial step in any MCDA. The outputs of the model should never be accepted blindly. This step should include an analysis of why a model has produced the results that it has and a discussion regarding the interpretation of the results. At this point it may be decided to redo an analysis with alternative options, criteria, scores or weights (Dunn 2014).

2 MATERIALS AND METHODS

2.1 Semi-structured interviews with MCDA practitioners

To gain understanding on the practicalities of the decision-making process in risk management four semi-structured interviews were conducted with representatives from different sectors and from different levels. It was noticed that the MCDA methodology has had multiple applications in other domains, such as environmental decision-making (Linkov, Satterstrom, Kiker, Seager, et al. 2006), therefore two representatives from these sectors were also included, as they could provide additional insights. The main objective of this thesis is to gain understanding in food safety risk management, therefore two representatives from the food sector were included.

As a representative of the macro-level a member of the unit on Food Hygiene and Fraud, from the Directorate General on Health and Food Safety (DG Health and food safety) from the European Commission was interviewed, as food safety is a European competence. On the other end of the spectrum, what is referred to as the micro-level, a regulatory affairs manager from a business in agricultural sciences was included in the discussion. The meso-level was represented by a representative from a research institution on marine science and two representatives from a sector association on chemicals management.

Each discussion started with a short introduction on the subject of this thesis and the goal of the interview. Interviewees were asked 10 questions (Addendum 1) related to the MCDA methodology. The literature study on MCDA applications had highlighted multiple specific methods and criteria included in risk management decision-making, both in food safety and other domains. Based on this the questions were defined. Participants were asked to provide examples where possible and follow-up questions were asked to clarify their answers. Interviews lasted from 30 minutes to one hour and were conducted online.

The answers provided by interviewees were reviewed and scored in a qualitative manner, to give an indication of the degree to which methodologies and criteria are currently being applied at different levels in different sectors. A traffic light system was used to present the answers gained in the interviews. Green indicates that it is generally applied and is common procedure, which means that the interviewee elaborated on the topic and provided examples of the application. Yellow indicates that it is not general practice, however some instances do exist in their sector, thus when interviewees mentioned that the methodology and/or criteria are currently deemed relevant, but no further elaboration happened, nor examples were given. Red indicates that this method or criterion is not applied or deemed relevant in their sector, i.e. when the interviewee explicitly mentioned that the use of methodologies and/or criteria are currently not being applied. A description of each interview is provided.

2.2 Development of MCDA in the leafy greens case study

The steps presented in Section 1.3 were followed during the development of the MCDA for the leafy greens case study (Figure 3).

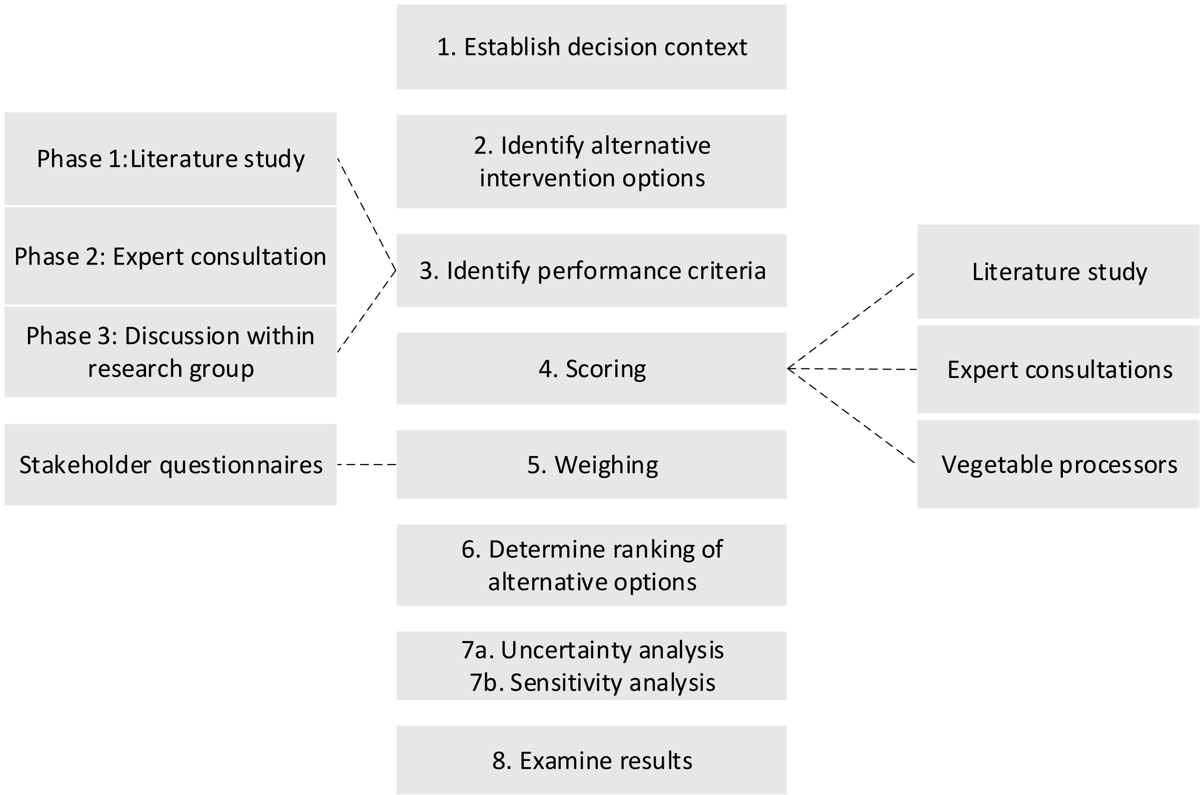

Figure 3. Overview of stages of an MCDA. Boxes on the sides indicate steps specific to the leafy greens case study.

2.2.1 Step one and two

The establishment of the decision context (step 1) and the identification of alternative intervention options (step 2) happened based on an evaluation of current available scientific literature regarding the topic of leafy greens processing and discussions within the research group LFMFP.

2.2.2 Step 3: identification of performance criteria

The final list of performance criteria was established in three phases (Figure 3). In phase 1 evidence on leafy greens processing and food safety risk management MCDA examples was collected from literature. In phase 2 an online discussion was held with three international academic experts, with a long-standing expertise on the washing process of minimally processed vegetables. In phase 3 the list of evaluation criteria was finalised based on discussions within the LFMFP research group.

2.2.3 Step 4: 'scoring' of main criteria and sub-criteria

Information needed to determine the performance scores of different criteria was collected based on three methodologies (Figure 3):

- Probabilistic distributions were fit to quantitative data extracted from scientific literature;
- Qualitative expert scores were gathered with answers forms;
- Quantitative input data was collected from industrial vegetable processors and supplemented with input from scientific and grey literature.

2.2.3.1 Quantitative input data: scientific literature

A literature search was performed on Web of Science, PubMed and Google Scholar. Experimental studies performed on laboratory-, pilot- and industrial scale were selected when deemed relevant and a 'good' representation of reality. Subsequently, quantitative data were extracted, and distributions were fitted to the data using @Risk ® software version 8 (Palisade 2021).

2.2.3.2 Qualitative input data: expert scoring

Five scientific experts were contacted to provide a qualitative assessment of five sub-criteria. A form was sent to the experts to collect responses. For each (sub-)criterion additional evidence from both scientific and grey literature evidence was collected and added to the form in order for the final score to be as transparent as possible. Experts were asked to correct the provided evidence and/or to provide additional information and were asked to score the sub-criteria using a five-point Likert-type answer scale (1→ 5: 'totally disagree', 'disagree', 'neither agree, nor disagree', 'agree', 'totally agree'). In the MCDA the 50^{th} percentile (P50) of collected responses is used, as this is the recommended measure for central tendency and dispersion of ordinal data (Boone and Boone 2012; Joshi et al. 2015).

2.2.3.3 Quantitative input data: (fresh-cut) vegetable processing plants

Input data from three Belgian fruits and vegetable processing plants, of which minimally processed fruits and vegetables and frozen vegetables are the most important end products, was collected in order to make a quantitative assessment of four evaluation sub-criteria.
An interview was organised with quality managers from each processing plant to explain the objectives and methodologies of the study. A form was later provided to clarify the details of the required information. The provided information of multiple processing plants was selected and combined to attain an average input value. If the provided information was insufficient for the evaluation of the different control strategies, additional information was collected from scientific and grey literature.

2.2.4 Step 5: preference weight elicitation

The weight elicitation process can be associated with multiple difficulties. The first issue is the identification of stakeholders participating in the weight elicitation process. Secondly, the relative importance should be expressed in numerical terms. Finally, the methodology used to obtain weights and the aggregation procedure may affect the preference weights (Bartolini and Viaggi 2010).

1. **Identification of stakeholder groups and stakeholder groups representatives:**
   Different stakeholder groups relevant to the case study were identified after discussions within the LFMFP research group. Stakeholder groups were divided according to the micro-, meso- and macro-level, in order to have an overview and to assure that all those involved with - or affected by - the decision were represented properly. Individual stakeholder group representatives were selected to be involved in the weight elicitation process. Only Belgian stakeholders were involved in the weight elicitation process.

2. **Weight elicitation process: online questionnaire**
   A written questionnaire was developed using SurveyMonkey Software ® (SurveyMonkey, 2021) and sent to stakeholder representatives via email. Participants were personally addressed as representatives of their stakeholder group and were asked to answer the survey accordingly.
   The survey was prefaced by a short introduction to provide some background on the issues related to the washing procedure of leafy vegetables. This was written in an accessible manner and had the aim to inform those without a scientific background and to assure that all participants started the survey with the same background knowledge. Participants were asked to divide 100 weights over the 5 main criteria according to their judgement of the relative importance of the criteria within the decision context. It was then asked to divide the given weights over the sub-criteria.

3. **Aggregation procedure**
   The provided weights from different stakeholder groups representatives were aggregated. For each stakeholder group the minimum, maximum and P50 of the collected weights were derived.

2.2.5 Step 6: ranking of alternatives

The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) methodology was applied for the ranking of alternative intervention options. This methodology is part of the family of outranking methods. This section will describe the steps of PROMETHEE II, which allows a complete ranking of a finite set of alternatives (Behzadian et al. 2010; Figueira et al. 2005; Greco et al. 2016).

Let A be a set of potential alternatives $\{a_1, a_2, \dots, a_i, \dots, a_n\}$ and $\{g_1(\cdot), g_2(\cdot), \dots, g_j(\cdot), \dots g_k(\cdot)\}$ a set of evaluation criteria. The methodology is based on the pairwise comparison of alternative options. Thus, the deviation between the evaluations of two alternatives on a particular criterion is determined as follows:

$$d_j(a,b) = g_j(a) - g_j(b) \qquad \forall a,b \in A \tag{1}$$

A small deviation implies a small preference for the best alternative. The preferences can be considered as real numbers between 0 and 1, which can be defined by a preference function $Pj(a,b)$:

$$P_j(a,b) = F_j\big[d_j(a,b)\big] \tag{2}$$

In this case study, the default preference function will be used, here presented for a generalised criterion:

$$P(d) = \begin{cases} 0, & d \leq 0 \\ 1, & d > 0 \end{cases} \tag{3}$$

Consider a set of weights $\{w_j, j = 1, 2, \dots, k\}$, which are normalised, so that:

$$\sum_{j=1}^{k} w_j = 1 \tag{4}$$

Now the overall or global preference index can be calculated:

$$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b) * w_j \qquad \forall a,b \in A, \tag{5}$$

$$\pi(b,a) = \sum_{j=1}^{k} P_j(b,a) * w_j \qquad \forall a,b \in A \tag{6}$$

$\pi(a,b)$ expresses to which degree a is preferred over b over all criteria, and $\pi(b,a)$ expresses to which degree b is preferred over all other criteria. Next, the outranking flows can be calculated. Each alternative option a will face $(n-1)$ other alternatives, thus a positive and a negative outranking flow for each alternative can be calculated:

$$\phi^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a,x) \tag{7}$$

$$\phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x,a) \tag{8}$$

In PROMETHEE II a net outranking flow $\phi(a)$ for each alternative is calculated:

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \tag{9}$$

The higher the net outranking flow, the ‘better’ the alternative. This algorithm was applied in the Visual PROMETHEE software ®.

2.2.6 Step 7a: uncertainty analysis

The uncertainty related to input data (Section 2.2.3 Step 4: ‘scoring’ of main criteria and sub-criteria) of the multi-criteria decision analysis was assessed using an ordinal scale (Table 4). A critical evaluation of input data was performed based on input from experts and scientific literature.

Table 4. Ordinal scale for assessing uncertainty as proposed by Bfr's guidelines (EFSA 2018)

Degree of potential effect	Possible direction		
	Underestimation	Not known	Overestimation
Not discernible/ Negligible	0: Uncertainty has no discernible or negligible effect on results	0: Uncertainty has no discernible or negligible effect on results	0: Uncertainty has no discernible or negligible effect on results
Low	–: Uncertainty can result in a low underestimation of the results	–/+: Uncertainty can result in a low deviation of the results in both directions	+: Uncertainty can result in a low overestimation of the results
Moderate	– –: Uncertainty can result in a moderate underestimation of the results	– –/++: Uncertainty can result in a moderate deviation of the results in both directions	++: Uncertainty can result in a moderate overestimation of the results
High	– – –: Uncertainty can result in a high underestimation of the results	– – –/+++: Uncertainty can result in a high deviation of the results in both directions	+++: Uncertainty can result in a high overestimation of the results
Not known	? –: Uncertainty can result in an underestimation of the results of unknown magnitude	? –/+: Uncertainty can result in a deviation of the results in both directions and of unknown magnitude	? +: Uncertainty can result in an overestimation of the results of unknown magnitude

2.2.7 Step 7b: sensitivity analysis

A scenario analysis was used to assess the robustness of the MCDA and to determine how the results would change as a result of changes in parameters and assumptions. The impact of varying preference weights was assessed by running scenarios using the median value of collected preference weights for each stakeholder group. Each stakeholder group was thus represented by a different scenario.
Based on the assigned degrees and directions of uncertainty (Step 7a: uncertainty analysis), various scenarios were identified in which input data for criteria evaluation ('scores') were varied. Input data assigned with a blue or red label were considered of highest relevance.

2.2.8 Step 8: examination of results

The ranking of alternative intervention options for each scenario was determined. Either an alternative set of weights or alternative scores (Step 7b: sensitivity analysis) were implemented in the Visual PROMETHEE software ®. The net outranking flows (ϕ) for each scenario were collected. A visualisation of rankings was retrieved from the Visual PROMETHEE software ® for those scenarios that lead to an alternative ranking in comparison to the baseline scenario. Results were compared to gain better understanding in the leafy greens case study and further recommendations were made.

3 RESULTS

3.1 Semi-structured interviews with MCDA practitioners

A critical view on the current decision-making process based on semi-structured interviews with MCDA practitioners is presented by Table 5.

Table 5. Qualitative evaluation of decision-making process in various domains based on semi-structured interviews with MCDA practitioners.

Domain	Methodology						Criteria				MCDA applications
	Expert input	Stakeholder input	Weighing of criteria	Sensitivity analysis	Quantification	Probabilistic methods	Cost	Effectiveness	Public acceptance	Environment	
Macro-level											
EC DG Health and Food safety: Food Hygiene and Fraud unit											- Cost-benefit analysis
Meso-level											
Marine sciences research institution											
Sector association on chemicals management											- Cost-benefit analysis - RMOA
Micro-level											
Company in agrisciences											
Overall											

3.1.1 Macro-level

The systematic approach towards policymaking suggested by the EC is impact assessment, which aims at assessing whether EU action is justified and how such action can best be designed to achieve policy objectives. The impact assessment system follows an integrated approach which assesses the environmental, social and economic impacts of a range of policy options (European Commission 2017a). This was confirmed during the interview, as all four selected criteria were highlighted as relevant in the

decision-making process. However, the interview clarified that the impact assessment system is only employed when important decisions, with a potentially large impact, are made.
A cost-benefit analysis was given as an MCDA example. This method was utilised to decide on a control measure for the reduction of *Campylobacter* in broiler meat at different stages of the food chain. Ten control measures were evaluated on five criteria namely reduction in incidence (%), the costs per DALY avoided (€), availability, industry impact and consumer impact. The last three were assessed in a qualitative manner. Uncertainty on data was not considered and a sensitivity analysis was not performed. Several experts were consulted for the study. However, stakeholder interests were not included.

3.1.2 Meso-level

The representative from a marine research institution mentioned that besides the impact on ecosystems, also social and economic criteria are increasingly taken into account both in research and at the decision-making level. A reference to the quadruple helix framework was made, which describes the interactions between industry, citizens, governments and research institutions, and some practical examples to maintain these relationships were given, such as multi-actor labs and brainstorm sessions with multiple actors.
The representatives from an association representing the metal industry at the European Commission mentioned a cost-benefit analysis of chemicals as a basis for decision-making on chemical policy. This socio-economic assessment includes the trade-off between risk frequency of chemicals, the benefits towards health and environment and the costs for society. These factors should be quantified as much as possible. Besides this, the enforceability of an intervention was mentioned as an important qualitative parameter. As a response to the chemical management objectives, stated by the 2020 Green Deal, the regulatory management option analysis (RMOA) was mentioned, which could be considered as an MCDA. It is an analysis carried out by member states or ECHA at the request of the European Commission, which should help authorities clarify whether regulatory action is necessary for a given substance and to identify the most appropriate measures (ECHA 2021). Three criteria, being circularity, impact on the climate and risks associated with the substance are considered. This method was referred to by the interviewees as a holistic approach, that eliminates emotions from the equation. This example clearly shows that the MCDA methodology can provide a structured foundation for decision-making, which allows to make more objective decisions and provide transparency to stakeholders.

3.1.3 Micro-level

This representative expressed the importance of sector-associations, as a channel for multiple competing companies with the same interests to unite and share their interests with decision-makers. As the business operates in a European setting, the importance of member states was mentioned and the lack of evidence-based evaluation of policy proposals was highlighted.

3.1.4 General results of semi-structured interviews

A general conclusion of the semi-structured interviews was the fact that decision-making still mainly relies on discussions and that it lacks a structural approach. However, all parties expressed that where possible data is provided and quantified, if this is not possible expert input should be used to fill in data gaps. Risk assessments were identified as an important source of information. The probabilistic methods applied during these assessments were indicated by multiple interviewees, however in general probabilistic methods are not being applied. The interviewees all confirmed that stakeholders and experts are generally consulted, but methods differed. Costs and effectiveness were expressed as the most important factors in the decision-making process, yet weights are not assigned to criteria.

In food safety risk management, the position of the European Food Safety Authority was identified by multiple interviewees as a central player. Also, the importance of sector-associations, as a representation of the industry, was expressed by multiple interviewees. These organisations can bring important insights on the public perception of risk management interventions.

All interviewees implied that currently multiple opportunities for the application of multi-criteria decision analysis exist.

3.2 MCDA in the leafy greens case study

3.2.1 Step 1: establishment of the decision context

3.2.1.1 Decision scope

The purpose of the decision analysis is determining the most appropriate washing methodology for minimally processed leafy vegetables. This means that only the washing step of the vegetables will be considered, and pre-washing, cutting or shredding, rinsing, drying and packaging will not be included. This is relevant since input data will only cover this specific processing step.

Leafy vegetables are defined as follows: “all vegetables of a leafy nature and of which the leaf (and core) is intended to be consumed raw”. These are also referred to as “leafy greens”. Some examples are lettuce (cos, iceberg, romaine, baby, red and green butter, red and green leaf, oak), endive, escarole, spinach, baby spinach and arugula (FAO/WHO 2008). Minimal processing refers to the fact that these vegetables undergo some kind of value-added operation. This could include a form of size reduction, e.g. shredding, cutting, slicing or chopping, which is followed by a washing procedure and potential sanitation (FAO/WHO 2008).

This MCDA is a case study for the Belgian situation and preference weights of Belgian stakeholders only are elicited. It is generally known that the washing procedure of minimally processed leafy vegetables differs across European member states and the world (Gil et al. 2009), therefore it was concluded that preferences might be region specific and culturally dependent.

3.2.1.2 Stakeholder identification and classification

The stakeholders of the Belgian food chain relevant to this case study, selected to participate in the preference weight elicitation process (Section 2.2.4), were classified into three categories, namely the macro-, meso- and micro-level (Figure 4). The macro-level, consisting of policymakers, is represented by governmental organisations and competent authorities, responsible for the safety of the food chain and environment. The meso-level provides support to both companies and organisations, as well as the macro-level. This category consisted of universities and other research institutions, responsible for providing scientific advice to the macro-level, consumer organisations, which represent the Belgian consumers and defend their interests, and sector associations, which represent the interests of the industry. Primary producers, vegetable processors and retailers represent the micro-level. Primary producers were represented by vegetable auction houses. Quality managers of vegetable processing companies and large-scale Belgian retailers represented the processing industry and retail stakeholder groups, respectively.

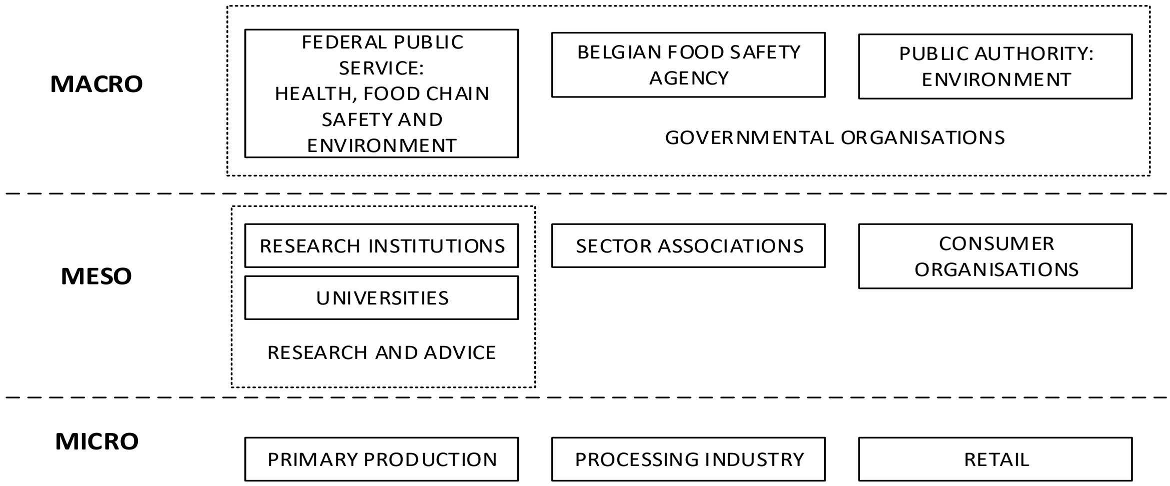

Figure 4. Step 1: establishment of decision context; stakeholder mapping. Classification of stakeholders included in the leafy greens case study (Baert et al. 2012).

3.2.2 Step 2: identification of alternative intervention options

The following leafy green washing strategies were selected to be included in the MCDA as alternative interventions options to be compared:

- Washing with potable water;
- In-line wash water disinfection with sodium hypochlorite (NaOCl);
- In-line wash water disinfection with peracetic acid (PAA);
- Wash water reconditioning to potable water by off-line disinfection with sodium hypochlorite (NaOCl).

The four intervention options were selected based on the potential for industrial application, i.e. they either are already generally applied in the fresh-cut industry in Belgium, or the washing procedures are currently applied abroad, and sufficient information in literature is available. This allows the collection of adequate data and evidence for the quantitative and qualitative scoring of the selected evaluation criteria.

3.2.2.1 Washing with potable water

Washing leafy vegetables with potable (ice)water is currently common procedure in the Belgian fresh-cut industry. It relies on large volumes of water, which are continuously added to the wash baths/flumes with high refreshment rates to minimise the accumulation of the microbial load and reduce the risk of (cross-)contamination (Holvoet et al. 2014). However, this method cannot assure that pathogen survival and cross-contamination is prevented, therefore wash water disinfection is being advocated in many European countries (Gil et al. 2009). Different methods for disinfection are available, however only three will be included in the decision analysis (see Section 1.1.3).

3.2.2.2 In-line wash water disinfection with sodium hypochlorite (NaOCl)

Chlorine is a cheap and easy to use option for process water disinfection, which explains why it is still the most widely applied disinfectant in the fresh-cut industry (Gil et al. 2009). Chlorine is commercially available in multiple forms, such as chlorine gas (Cl_2), calcium hypochlorite ($CaCl_2O_2$) and sodium hypochlorite (NaOCl) (Suslow 1997). Only data concerning the use of NaOCl is included, because of the fundamental differences between these sources of free chlorine. Cl_2 is the cheapest form of chlorine, however from a safety, monitoring and complexity point of view, it is the most demanding option. $CaCl_2O_2$ comes in the form of granules or tablets, while sodium hypochlorite is used in a liquid form (Suslow, 1997). An important difference is the much slower decomposition of $CaCl_2O_2$ in comparison with NaOCl. This leads to the formation of chlorate and chlorite ions, as this happens the available chlorine concentration decreases, and one will need to dose more to achieve the desired free chlorine concentration. Consequently, an increased amount of chlorate will be added to water (WHO 2000). The use of low concentration solutions and short storage times of NaOCl at low temperatures in a dark area is therefore suggested (ADAS 2016).

Sodium hypochlorite will dissociate in water into hypochlorous acid (HOCl) and the hypchlorite ion (OCl^-). Both have antimicrobial activity, however effectiveness of HOCl has been shown to be much greater compared to OCl^-.

$$NaOCl + H_2O \leftrightarrow NaOH + HOCl \tag{10}$$

$$HOCl \leftrightarrow H^+ + OCl^- \tag{11}$$

The presence of a specific chlorine species in the water is pH dependent (Figure 5). In order for the balance to shift towards hypochlorous acid, the pH should be below 7. On the other hand, if the pH is too low, the toxic gas Cl_2 will be formed.

$$HOCl + HCl \leftrightarrow H_2O + Cl_2 \tag{12}$$

A good control of the pH of the wash water is therefore of critical importance (Gombas et al. 2017; Suslow 1997). Free chlorine is defined as the sum of HOCl and OCl^- and the dissolved Cl_2 (g) present in the water. The term free available chlorine is used to refer to free chlorine that works as an oxidising agent (Gombas et al. 2017).

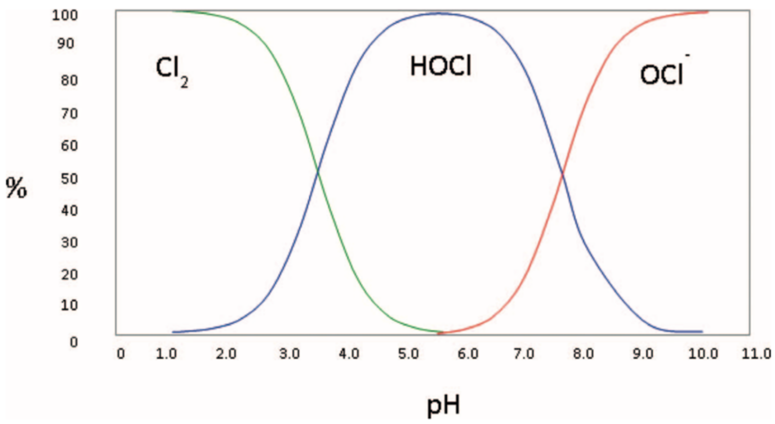

Figure 5. Proportion of chlorine in water in function of pH. Green, chlorine (Cl_2); blue, hypochlorous acid (HOCl); red, hypochlorite (OCl^-)(Gombas et al. 2017).

3.2.2.3 In-line wash water disinfection with peracetic acid (PAA)

Peracetic acid has gained increasing attention as a sanitisation agent. It is a strong oxidant, with a wide spectrum of antimicrobial activity. It is considered a good alternative to chlorine, which is associated with multiple drawbacks, such as the dependency on the pH and the sensitivity to the organic load. PAA on the other hand shows good antimicrobial activity on a wide pH and temperature range and is less susceptible to the wash water organic load (Kitis 2004; Vandekinderen et al. 2009). PAA decomposes into acetic acid, hydrogen peroxide, oxygen and water. Little or no toxic disinfection by-products are formed after reaction with organic matter (Kitis 2004). A drawback is the higher cost of PAA, and it is assumed to be more cost-effective on small scale applications (Van Haute et al. 2015).

Peracetic acid is commercially available as an equilibrium of peracetic acid (PAA), hydrogen peroxide, acetic acid and water.

$$CH_3CO_2H + H_2O_2 \leftrightarrow CH_3CO_3H + H_2O \quad (13)$$

Commercial solutions usually contain 15% peracetic acid and about 10 - 20% hydrogen peroxide (Tsunami 100; Ecolab Inc. 2017). The latter also exhibits antimicrobial activity, however PAA is a more potent antimicrobial agent (Kitis 2004).

3.2.2.4 Wash water reconditioning to potable water by off-line disinfection with sodium hypochlorite (NaOCl)

Figure 6 explains the difference between wash water disinfection and the reconditioning treatment. The main difference is the place of disinfection. Wash water disinfection happens in the washing bath, here a residual disinfectant is maintained, and all the water is treated. In the case of reconditioning, the water treatment is applied off-line, where only a portion of the wash water is treated at one point in time (Van Haute et al., 2015).

Figure 6. Schematic overview of the reconditioning treatment, i.e. off-line disinfection of process water with NaOCl (Van Haute et al. 2015).

Various types of water can be identified and used in food operations. First-use water is considered potable water from an external source that can be used in any food operation. Alternatively, there is reuse water, which can be defined as water that has been recovered from a processing step within a food operation, that after potential reconditioning treatments, is intended to be (re-)used in a food processing operation. This can be divided into three types of reuse water, namely reclaimed water, recycled water and recirculated water. Water that is reused in the same operation after reconditioning is considered recycled water. Since fresh-cut processors are amongst the most intensive consumers of potable water, the possibility for water reuse to conserve water is important to consider in the decision analysis (FAO/WHO 2019).

3.2.2.5 Some other disinfectants

Chlorine dioxide (ClO_2) and ozone (O_3) are some highly investigated disinfectant options (e.g. Van Haute et al. 2017; Nahim-Granados et al. 2020; Singh et al. 2002) which show strong antimicrobial activities, however the reactive nature of these compounds has implications on the worker's safety and the required on-site generation (Suslow 1997). The quantification of multiple performance criteria was expected to be difficult for these alternatives.

3.2.3 Step 3: identification of performance criteria

The performance criteria used in the evaluation should meet a number of specific characteristics (Alberto and Donoso 2008; Bartolini and Viaggi 2010; Maystre, Pictet, and Simos 1994):

- Exhaustiveness or completeness: criteria should cover all relevant economic, environmental, and social factors;
- Non-redundancy: overlapping and duplication of criteria should be avoided;
- Mutual independence of preferences: the performance of one criterion should not be dependent on the performance of another criterion;

- Minimal size: the number of criteria should be kept as small as possible, in order to keep the data requirement minimal and reduce the 'elicitation burden' of stakeholders (Karvetski, Lambert, and Linkov 2011);
- Operational: criteria and metrics should be relevant and easily understood by stakeholders and should be considered as a communication tool of strengths and weaknesses to stakeholders.

3.2.3.1 Phase 1: criteria identification based on literature study

A first list of evaluation criteria was drafted based on a literature study (Table 6). The literature search on MCDA applications in food safety risk management (Section 1.2.1), uncovered that all of the investigated studies included both cost and effectiveness of the risk management option. The effectiveness of the washing process, from a microbiological point of view, can be considered as a combination of the reduction of microbial contamination and the prevention of the spreading of potential pathogenic contamination, i.e. prevention of cross-contamination (Banach et al. 2021). Costs related to the washing process can be divided into an initial investment cost, i.e. the capital cost, and the operational costs, which includes costs related to personnel, maintenance, energy- and water use, chemicals and training of personnel (Van Haute et al. 2015).

Seven out of nine studies included at least one criterion that considered the environmental impact of the risk management strategy. This is in accordance with sustainable development goal 13, which advocates for action to tackle climate change and its impacts (UN 2021). The fresh-cut vegetable industry is highly water demanding, and water is a diminishing resource globally, therefore it is of high relevance to quantify the water used in the washing process, taking into consideration the possible water reuse (FAO/WHO 2019). On the other hand, the impact of the washing methodology on the shelf-life of fresh-cut produce, and subsequent impact on food waste due to early spoilage of produce could be included in the decision analysis.

Five studies included a criterion that considered the consumer acceptance of the risk management option. The relevance of consumer perception was also confirmed during the discussion with a policymaker (Section 3.1.1). The EU better regulation toolbox also mentions the acceptability as an evaluation criterion of interventions, which refers to the perception of the intervention changes (positive or negative) of the targeted stakeholders and/or the general public (European Commission 2017a).

About half of the studies included the practicality of the intervention option. The ease of implementation and robustness of the washing methodology are included with the aim to capture the technological and managerial aspects of the process.

The consideration of distributional impacts was included by three out of nine studies. This refers to the equity of benefits and is defined in the EU toolbox as the fairness of distribution of effects across stakeholders, regions, genders or social groups (European Commission 2017a). In this case study, subpopulations such as YOPIs could be disproportionally affected by the presence of *Listeria monocytogenes*, considering that this is an opportunistic pathogen (FAO/WHO 2004). Only two studies included the workplace safety in the decision analysis. However, the presence of hazardous compounds when disinfectants are being applied could impact the occupational health and safety. Multiple methods exist to measure and analyse the health impacts of a risk management option. Quality Adjusted Life

Years (QALY), Disability Adjusted Life Years (DALY) and Healthy Life Years (HLY) are some non-monetary approaches which try to quantify the health benefits of an intervention. For this case study, the impact on human health can be divided into three sub-criteria, namely the microbiological-, chemical- and workplace safety.

Table 6. Step 3: identification of performance criteria based on literature study (phase 1).

Main criteria	Sub-criteria	Metrics
Public health impact	Microbiological food safety	Log reductions *Listeria monocytogenes*
	Chemical food safety	µg DBP/g product
	Workplace safety	Exposure to chemicals
Environment	Water use	L/kg product
	Food waste	% Change in shelf-life
Cost	Capital cost	€
	Operational costs	€/year or cost/cubic meter treated water or €/kg treated product
Consumers	Consumer acceptance	Qualitative
	Consideration of distributional impacts	Qualitative
Practical impact	Ease of implementation / complexity	Qualitative
	Robustness	Qualitative

3.2.3.2 Phase two: expert consultation

The expert consultation had the aim to evaluate the relevance of performance criteria in the chosen decision context, to remove or add any criteria and to review the definition and the metric of each criterion. Some critical questions about the MCDA were raised, which resulted in a more clearly defined decision scope. An alternative list of evaluation criteria was made up based on the discussion (Table 7).

1. **Discussion of the decision context:**

- It was emphasised that only the washing process should be considered and that other processing steps should be neglected. This is important since *Listeria monocytogenes* is a microorganism that could contaminate the product at any processing step, since it should be considered ubiquitous and its presence is not limited to the washing area, but also other processing areas.
- Experts believed that the MCDA should focus on wash water safety, not product safety. It was mentioned that if pathogens were to be present on the product, the washing procedure would be unable to remove them due to internalisation and attachment.
- The goal of the MCDA and for whom this MCDA will be developed was questioned. The experts mentioned that it should be a way to demonstrate companies and policymakers the reasoning

behind the application of chemical disinfectants by aggregating all available evidence, and that the MCDA should be a means to question the current legislation.

2. Discussion of main criteria:

- The ‘consumers’ main criterion was removed (Table 6) and the ‘legal considerations’ sub-criterion was introduced. The experts expressed that current regulations should not be considered as a restriction for the MCDA, but rather as a criterion. It should not be assumed that the legislative situation is a good representation of the current situation. It was suggested to run some scenarios and to determine which fall within the current legislative framework and which don’t. The very strict Flemish regulations on the levels of pesticides in the wastewater were given as an example.
- The ‘practical impact’ criterion was renamed to ‘operations’.
- Government acceptance and the resulting implications on trade were mentioned but not included.

3. Discussion of sub-criteria:

- Experts were confused by the choice for log reductions of *Listeria monocytogenes*, as a metric for the microbiological safety. They expressed that the levels of *E. coli* in the wash water would be a better indicator for the process water quality. Here, it was noticed that the ‘impact on vulnerable groups’ sub-criterion might overlap with the ‘microbiological safety’, if it is measured by the log reductions of *L. monocytogenes*, since this is considered by some as an opportunistic human pathogen.
- It was expressed that trihalomethanes are not considered relevant anymore as a disinfection by-product, due to the low levels present on the product after rinsing and instead levels of chlorates in the process water were suggested as measurement for chemical food safety.
- The ‘workplace safety’ sub-criterion was renamed to ‘occupational health and safety’. It was suggested that this criterion should be considered as sub-criterion for the ‘operations’ main criterion, as it is being assumed that all processes are working effectively and efficiently and therefore should not pose a risk towards workers, because the washing procedure should be under control. The implementation of any disinfection technology should not be possible without proper knowledge and safety training was deemed very important here. However, some methods could get out of hand more easily, which then could put the occupational health of the workers in danger. The context of the occupational health and safety criterion was also identified as very important. A cleaning and disinfection system usually already exists in a vegetable processing company, which often leads to the introduction of chemicals to a processing facility.
- The storage of chemicals was introduced as a new sub-criterion for the ‘operations’ main criterion. According to the experts, companies are trying to go chemical free as much as possible, due to the difficulties associated with the storage of chemicals.
- The ‘robustness’ sub-criterion was replaced by ‘monitoring and control’. This sub-criterion reflects the difficulty of controlling the washing process and the associated monitoring of the process. For example, are measurable process indicators available and are the measurements direct or indirect.

- The 'food waste' sub-criterion was removed and a criterion about wastewater discharge was added as a sub-criterion for the 'environment' main criterion. Very strict regulations, especially in the Flemish region of Belgium, on the levels of pesticides in the wastewater are in place. The accumulation of these chemicals in the wash water after recirculation, do not pose a risk to human health, however it could lead to the fact that discharge would not be allowed, even after treatment in the company's own wastewater treatment plant.
- The 'complexity' sub-criterion was moved under the 'costs' main criterion, since the complexity of any technology usually will be expressed in multiple costs. For example, a more complex technology could lead to higher labour costs, as it might require higher educated workers. Also, more complex technologies might need more expensive infrastructure and equipment, such as additional workspace or monitoring devices.

Table 7. Criteria identification based on expert consultation (phase 2).

Main criteria	**Sub-criteria**	**Metrics**
Public health impact	Microbiological food safety	Load of E. *coli* in the wash water
	Chemical food safety	Levels of chlorates and pesticides in the wash water
Operations	Occupational health and safety	Qualitative
	Storage of chemicals	Qualitative
	Monitoring and control	Qualitative
Environment	Water use	L/kg product
	Wastewater discharge	Levels of pesticides in the wash water
Costs	Capital cost	€
	Operational costs	€/kg treated product
	Complexity	Qualitative
Legal considerations	*NA*	Qualitative

3.2.3.3 Phase 3: group discussions

After a discussion within the LFMFP research group, the final list of evaluation criteria which will be used in the multi-criteria decision analysis was established (Table 8).

It was decided to measure the 'microbiological food safety' sub-criterion with two parameters, being the reductions of *E. coli* (O157:H7) in log CFU/g on the end product and the leaf – to – leaf transfer coefficient of *E. coli* (O157:H7). There is an extensive amount of scientific literature available investigating the reduction or inactivation of pathogens on minimally processed vegetables after treatment with different kind of disinfectants. It appears that surrogates of *E. coli* O157:H7 are the most commonly used microorganisms in these inoculation experiments. The transfer coefficient can be considered as a fraction of initial contamination that will be distributed in the wash water and via the wash water will be redistributed to initially uncontaminated product (Chardon et al. 2016). This parameter is used to quantify the process of water-mediated cross-contamination, which is further explained in Figure 7. Cross-contamination through the direct contact between contaminated and uncontaminated leaves will not be considered.

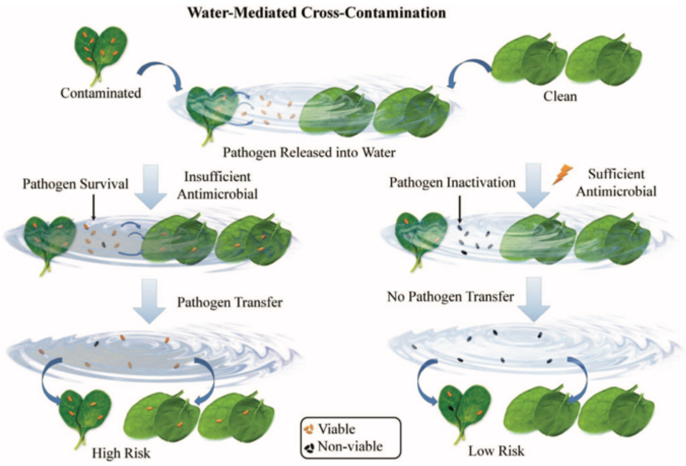

Figure 7. Illustration of cross-contamination risk during washing of leafy greens (Gombas et al. 2017).

The concentration of total trihalomethanes (TTHMs), which is the sum of chloroform, bromoform, bromodichloromethane and dibromochloromethane, and chlorate concentration on the end product will be used to quantify the 'chemical food safety' (US EPA 2012) . These compounds are related to chemical disinfection using chlorine-derived compounds. The disinfection by-products related to chlorination found in the highest concentrations are haloacetic acids (HAAs), THMs and chlorate. Halogenated DBPs, such as HAAs and THMs, are formed due to the reaction of chlorine with organic matter, in contrast to chlorate which is a degradation product of chlorine (EFSA 2019). Peracetic acid forms no or little toxic DBPs in reaction with organic matter, only modest concentrations of carboxylic acids and aldehydes have been found after treatment with PAA (Henao, Turolla, and Antonelli 2018; Kitis 2004). Since, these show little to no impact on human health, the quantification was concluded to be uninteresting in the MCDA.

'Occupational health and safety', 'ease of implementation', 'robustness' and 'consumer acceptance' will be assessed in a qualitative manner. 'Storage of chemicals' and 'monitoring and control' were replaced again by the original 'ease of implementation' and 'robustness'. These are more exhaustive, i.e. cover the scope of the decision context better. Finally, 'wastewater discharge costs' and 'pressure from national/international authorities' sub-criteria were added to be part of the evaluation criteria. The latter has the aim to make an estimation of the legislative discrepancies on a regional, national and international level. For example, how is the use of disinfectants regulated and how is the water quality in terms of chemical and microbiological contamination regulated, and how will this influence the implementation of a specific washing methodology in the Belgian fresh-cut industry. Besides the capital cost and operational costs, also wastewater discharge costs will be included in the MCDA. These costs will reflect the quality of discharged process water (VMM 2021).

Table 8: Criteria identification. Final list of performance criteria (phase 3).

Main criteria	Sub-criteria	Metrics
Public health impact: this main criterion reflects the impact of the washing method on the health of consumers.	**Microbiological food safety**	Log CFU/g reductions of *E. coli* (O157:H7)
		% transfer rate (leaf – to – leaf) of *E. coli* (O157:H7)
	Definition: this reflects the effectiveness of the technology in terms of microbiological safety. This covers the microbiological load of the product and the impact of the washing methodology on microbial load of the wash water, thus the probability of cross-contamination.	
	Chemical food safety	µg/kg TTHMs
		mg/kg chlorate
	Definition: this reflects the concentration of chemical contaminants on the product. Both disinfection by-products and other degradation products are considered.	
	Occupational health and safety	Qualitative: 5-point scale
	Definition: this reflects the safety and health of workers involved with the washing process.	
Technological impact (operations): this main criterion reflects the effective implementation of the technology and the associated practical consequences for both producers and operators.	**Ease of implementation**	Qualitative: 5-point scale
	Definition: this reflects the complexity of the used technology. This is correlated to the required amount of operator skill and training and the ability of the technology to be implemented within the industry.	
	Robustness	Qualitative: 5-point scale
	Definition: this criterion reflects the reliability of an applied technology, and the associated monitoring and control to assure that the technology works effectively.	
Environmental impact: this main criterion covers the impact of the applied washing technology on the environment.	**Water use**	m^3/ton end product
	Definition: this reflects the volume of H_2O used during washing of a certain amount of product, taking into account the ability of water-recirculation during processing.	
	Wastewater discharge	Qualitative: 5-point scale

	Definition: this reflects accumulation of different components (pesticides, metals, …) in the wash water during prolonged water use, and how it influences subsequent possibilities for wastewater discharge.	
Economic impact (costs): this main criterion reflects the costs for producers related to the applied washing technology.	**Capital cost**	€
	Definition: this reflects the capital investment to acquire the necessary equipment and infrastructure.	
	Operational costs	€/ton end product
	Definition: this reflects the costs related to the implementation of the technology. These include chemicals, supplies and other maintenance costs, equipment repairs, the storage of chemicals and spare parts, operator and management personnel costs, training of personnel and power consumption.	
	Wastewater discharge costs	€/m^3
	Definition: this reflects the costs related to the discharge of wash water used during the washing process.	
Societal impact (stakeholders): this main criterion covers the perception of society and authorities, and the consequential actions towards the applied washing methodology.	**Consumer acceptance**	Qualitative: 5-point scale
	Definition: this reflects the acceptance and perception of consumers towards the applied technology.	
	Pressure from national/international authorities	Qualitative: 5-point scale
	Definition: this criterion reflects whether or not regulations concerning the washing and potential disinfection (of the wash water) of leafy greens are harmonised on an international, European and Belgian level	

3.2.4 Step 4: 'scoring' of main criteria and sub-criteria

3.2.4.1 Quantitative input data: scientific literature

Metric: log CFU/g reductions of *E. coli* (O157:H7) on the end product ('microbiological food safety' sub-criterion)

A distribution was fit to data found in literature from industrial/pilot scale washing experiments using the @Risk software ® version 8 (Palisade 2021) (Addendum 2; Figure 8 (1)). The best fitting distribution was selected based on the Chi-square criterion and a comparison of the mean, maximum and minimum value. Distributions with extreme values of $-\infty$ or $+\infty$ were excluded. The distribution fit to data extracted from literature was combined with probabilistic distributions found in scientific literature (Figure 8 (2) and (3)) using the Monte Carlo technique with 100 000 iterations, and a final probabilistic distribution was fit to the data (Figure 8 (4)). The same methodology was used for each risk management intervention options (Addendum 4; Addendum 6). In the multi-criteria decision analysis the 50th percentile (P50) values will be used (Table 9). It is assumed that the achieved log CFU/g reductions of *E. coli* (O157:H7) on the end product will be similar when vegetables are washed with potable water and water reconditioned to potable water quality.

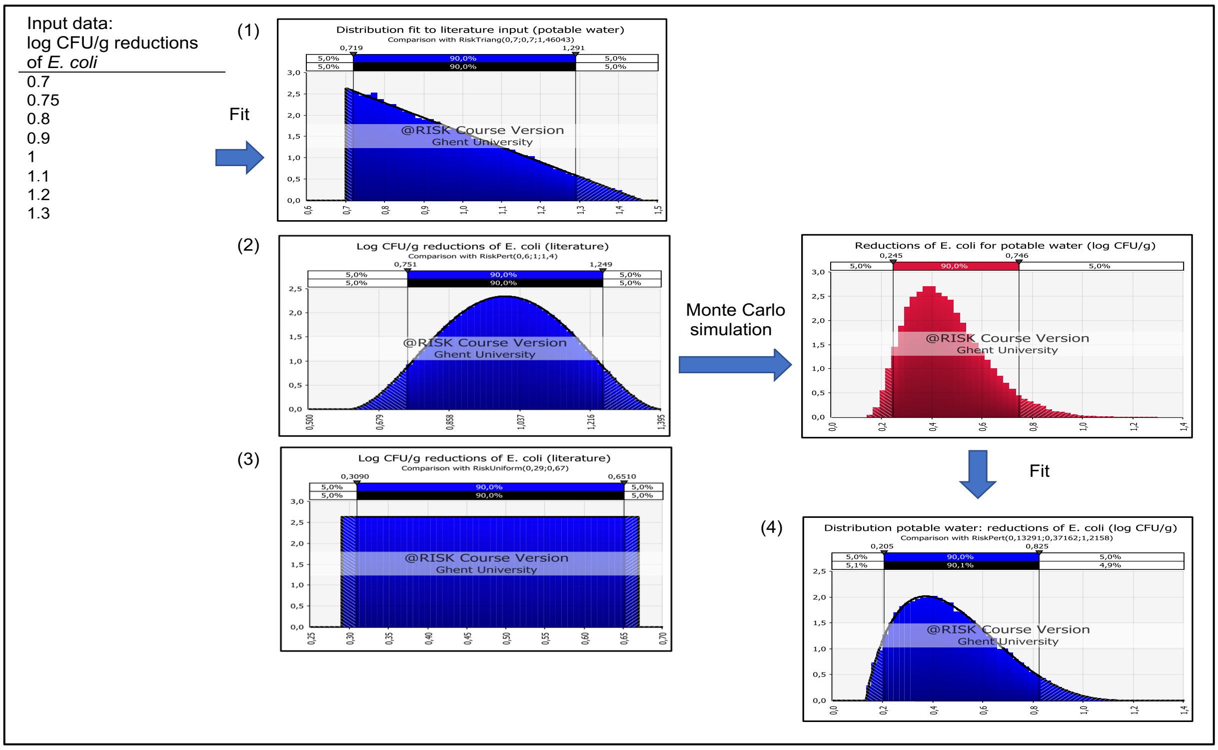

Figure 8. Schematic overview of steps taken in development of the probabilistic distribution for the log CFU/g reductions of E. coli (O157:H7) for the 'potable water' intervention option based on input data found in literature

Metric: leaf-to-leaf transfer rate (%) of *E. coli* (O157:H7) ('microbiological food safety' sub-criterion)

Three studies were included for the leaf-to-water transfer rate and one study for the water-to-leaf transfer rate (Addendum 7). Studies were performed on laboratory scale and measured the transfer of *E. coli* (O157:H7) from inoculated leafy greens to uninoculated leaves during the wash procedure. Since only limited values were available, uniform distributions were fit to the experimental data (Addendum 8). The Monte Carlo technique was used to combine two distributions Equation (14) and (15), which lead to the final distribution Equation (16).The transfer in sanitised wash water was considered zero.

$$= \mathrm{RiskUniform}(43{,}92)\ (\%) \tag{14}$$

$$= \mathrm{RiskUniform}(0.7{,}1.3)\ (\%) \tag{15}$$

$$= \mathrm{RiskTriang}(0.298{,}0.55{,}1.19)\ (\%) \tag{16}$$

This distribution (Equation (16)) has a mean transfer rate of 0.675% and a P50 of 0.655%.

Metric: concentration of TTHMs on the end product (µg/kg) ('chemical food safety' sub-criterion)

The accumulation of disinfection by-products on the end product was calculated based on the production of DBPs in the wash water and the sorption or uptake of DBPs on leafy greens. The sorption is considered equal for all washing procedures. An uptake of 4 to 15% was considered (Gómez-López et al. 2013; López-Gálvez et al. 2010). The concentration of DBPs on the end product when sanitising with peracetic acid is considered to be similar to the potable wash water procedure. For potable water the maximum limit according to the newly updated Directive (EU) 2020/2184 on potable water quality was used as an upper limit. Studies based on simulated wash water were used for the assessment of DBP production in the wash water for the reconditioning treatment. In the MCDA the P50 value of distributions will be utilised (Table 10).

Metric: concentration of chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion)

The concentration of chlorate on the product was calculated in a similar manner. An uptake of 1.5 to 4.7% was considered (Garrido et al. 2019; Gil et al. 2019). The distribution for the chlorate concentration in the wash water when NaOCl is used as a reconditioning agent was based on a study where sodium hypochlorite is applied in simulated wash water. See Addendum 15, Addendum 17 and Addendum 19 for input data. See Addendum 16, Addendum 18 and Addendum 20 for a schematic overview of steps taken in development of probabilistic distributions. Final probabilistic distributions are summarised in Table 11.

Table 9. Probabilistic distributions for the log CFU/g reductions of E. coli (O157:H7) ('microbiological food safety' sub-criterion).

Washing methodology	Distribution fit to literature data	Distributions extracted form literature	Final distribution	Mean value	P50
Potable water and wash water	= RiskTriang(0.70, 0.70, 1.46)	= RiskPert(0.6,1,1.4) [1] = RiskUniform(0.29,0.67)[2]	= RiskPert(0.13,0.37,1.22)	0.473	0.449
Wash water disinfection with NaOCl	= RiskTriang(0.77,0.77,1.32)	= RiskNormal(0.87,0.32, RiskTruncate(0.36,1.38)[3]	= RiskKumaraswamy(1.86,6.91,0.53,1.91)	0.940	0.921
Wash water disinfection with PAA	= RiskUniform(0.93,1.5)	= RiskPert(0.46,1.12,1.34)[4]	= RiskBetaGeneral(4.57,4.97,0.47,2.15)	1.272	1.270
Reconditioning with NaOCl	= RiskTriang(0.70, 0.70, 1.46)	= RiskPert(0.6,1,1.4)[5] = RiskUniform(0.29,0.67)[6]	= RiskPert(0.13,0.37,1.22)	0.473	0.449

[1,5] Extracted from Pang et al. (2017)

[2,3,4,6] Extracted from Bozkurt et al. (2021)

Table 10. Probabilistic distributions for the TTHMs concentration on the end product (µg/kg) ('chemical food safety' sub-criterion).

Washing methodology	Distribution fit to sorption data	Distribution fit to TTHM wash water concentration (µg/L)	Final distribution: concentration of TTHM on the end product (µg/kg)	Mean value	P50	P5
Washing with potable water	= RiskUniform(0.04,0.15)	= RiskUniform(22,100)	= RiskPert(0.882,4.022,17.9)	5.812	5.395	1.800
Wash water disinfection with NaOCl	= RiskUniform(0.04,0.15)	= RiskTriang(46;46,322.1)	= RiskPert(1.8604,6.9983,50.273)	13.354	11.891	3.387
Wash water disinfection with PAA	= RiskUniform(0.04,0.15)	= RiskUniform(22,100)	= RiskPert(0.882,4.022,17.9)	5.812	5.395	1.800
Reconditioning with NaOCl	= RiskUniform(0.04,0.15)	= RiskTriang(7.8,7.8, 207.95)	= RiskBetaGeneral(1.29,7.36, 0.32,45.66)	7.084	5.857	1.018

Table 11. Probabilistic distributions for the chlorate concentration on the end product (mg/kg) ('chemical food safety' sub-criterion).

Washing methodology	Distribution fit to sorption data	Distribution fit to DBPs wash water concentration (mg/L)	Final distribution (mg/kg)-	Mean value	P50	P5
Washing with potable water	= RiskUniform(0.015, 0.047)	= RiskUniform(0.1,0.7)	= RiskBetaGeneral(1.57,3.48,0.0015, 0.037)	0.012	0.012	0.003
Wash water disinfection with NaOCl	= RiskUniform(0.015, 0.047)	= RiskPert(0,10.82, 49.20)	= RiskBetaGeneral(1.87,11.34,0,3.39)	0.478	0.417	0.086
Wash water disinfection with PAA	= RiskUniform(0.015, 0.047)	= RiskUniform(0.1,0.7)	= RiskBetaGeneral(1.57,3.48,0.0015, 0.037)	0.012	0.012	0.003
Reconditioning with NaOCl	= RiskUniform(0.015, 0.047)	= RiskUniform(0.1,13)	=RiskKumaraswamy(1.14,2.51,0.0017 ,0.63)	0.203	0.182	0.022

3.2.4.2 Qualitative input data: expert scoring

Scores were provided by experts on a 5-point Likert-type answer scale (1→ 5: ‘totally disagree’, ‘disagree’, ‘neither agree, nor disagree’, ‘agree’, ‘totally agree’). Based on forms with additional background information (Addendum 22, Addendum 23, Addendum 24 and Addendum 25) the four different washing procedures were scored on the following statements:

- **Occupational health and safety**: The washing procedure has the possibility of negatively impacting the health and safety of workers (min → best);
- **Ease of implementation**: The washing methodology is easy to be implemented in the industry (max → best);
- **Robustness**: This washing methodology is reliable and allows for adequate monitoring and control (max → best);
- **Wastewater discharge**: This washing procedure allows for the accumulation of components in the wash water during prolonged water use, and therefore negatively affects subsequent wastewater discharge (min → best);
- **Consumer acceptance**: The applied washing methodology is accepted by consumers (max → best);
- **Pressure from national/international authorities:** Regulations concerning the washing and potential disinfection (of the wash water) of leafy greens are harmonised on an international, European and Belgian level (max → best).

See Addendum 27 for collected expert scores. In the MCDA, P50 values of collected expert scores will be used (Table 12).

Table 12. P50 of qualitative input data collected from experts using a 5-point Likert-type answer scale.

	Potable water	Wash water disinfection (NaOCl)	Wash water disinfection (PAA)	Reconditioning (NaOCl)
Occupational health and safety	1	4	4	3
Ease of implementation	5	4	4	5
Robustness	1	5	5	2
Wastewater discharge	2	5	4	4
Consumer acceptance	5	1	3	3
Pressure from national/international authorities	4	1	1	1

3.2.4.3 Quantitative input data: (fresh-cut) vegetable processing plants

See Addendum 28 for information requested from fruits and vegetable processors.

Sub-criterion/metric: water use ('environmental impact' main criterion)

Processing plant A is a smaller scale vegetable processing plant, which produces about 1.7 ton processed lettuce/day. Processing plant B produces on a larger scale, with about 5.3 - 8.3 ton lettuce/day. Based on the provided data, 7.5 m^3/ton water on average is used for the washing of leafy greens (Table 13). Both processing facilities only use potable (ice)water during the washing procedure of leafy greens.

Table 13. Water use for the washing procedure of leafy greens in m^3/ton when washed with potable water.

	Processing plant A	**Processing plant B**	**Average water use**
Water consumption (m^3 /ton)	5.88	5.98 - 9.11	7.5

The water consumption is considered equal for the remaining washing methodologies considered. They all have the aim of controlling the microbial load in the wash water. The reuse will therefore be limited by other factors such as the accumulation of organic matter and chemicals. The water consumption is extracted from four studies, which studied the application of different chemical disinfectants on an industrial scale (Table 14). An average of ± 5 m^3/ton wash water is used for the washing procedure of minimally processed leafy greens.

Table 14. Water use for the washing procedure of leafy greens in m3/ton when washed in sanitised wash water.

	Banach et al. 2018	**Tudela et al. 2019**	**Maffei et al. 2016**	**López-Gálvez et al. 2019**	**Average water use**
Scale	Commercial scale	Industrial scale	Industrial scale	Industrial scale	/
Disinfection methodology	Peracetic acid NaOCl	Cl_2 NaOCl	NaOCl	$Ca(ClO)_2$	/
Water consumption (m^3/ton)	2.5 - 3.75	1.37 - 2.05	10	10	5

Sub-criterion/metric: capital costs ('economic impact' main criterion)

Based on the information provided by fresh-cut processors the investment costs for a washing line were derived (Table 15). Only costs related to wash tanks and centrifuges are considered, other parts like packaging machines and conveyer belts are not included here. The capital investment is directly related to the scale of operation. Therefore, the costs for the other washing methodologies are determined proportionately to the capital costs for the potable water washing methodology.

For the wash water disinfection with NaOCl and PAA the following assumptions were made:

- Costs related to storage(tanks) of chemicals, feeding pumps, monitoring & control system: + 10% of the potable water capital cost.

For the reconditioning treatment the following assumptions were made:

- The costs related to an off-line disinfection system are approximately those of a wash tank plus the costs related to a disinfection system: + 20% of the potable water capital cost.

Table 15. Capital costs related to washing methodologies of leafy greens based in input from industrial processors and assumptions.

	Potable water	**WW disinfection NaOCl/PAA**	**Reconditioning (NaOCl)**
Costs for wash tanks and water recirculation installation (€)	± 150 000 - 400 000	± 165 000 - 440 000	± 180 000 - 480 000
Capital costs (€)	± 275 000	± 300 000	± 330 000

Sub-criterion/metric: operational costs (‘economic impact’ main criterion)

Operational costs when washing with potable water were based on input provided by processing plant A (Table 16). Costs were calculated per ton of processed leafy greens. Plant A processes ± 2 ton leafy greens/day.

Table 16. Calculations for the operational costs (€/ton) of washing procedure when washing with potable water based on input from processing plant A.

	Processing plant A
Personnel costs	5 workers x 20 €/h x 8 h = 800 €/day
Maintenance costs	± 10 000 €/year
Training of personnel	(5 workers + 1 line manager) x 1 h x 23 €/h = 140 €/year
Chemicals (cleaning and disinfection)	2000 €/month
Total €/day	± 900
Total (€/ton leafy greens)	± 450

Operational costs when sanitising with NaOCl were based on an estimation by UMASS (2015), which estimated a cost of 2 €/m^3 sanitised water, if 25 mg/L free chlorine is maintained in the wash tank using a 10 - 15% NaOCl solution. Luo et al. (2018) and Tudela et al. (2019) recommend a residual free chorine concentration of 10 - 20 mg/L. An average of 5 m^3 water/ton leafy greens is considered. Phosphoric - or citric acid are usually used to buffer the pH. Garrett et al. (2003) estimates the use of acids (phosphoric or citric acid) to be a quarter of the rate of NaOCl. He suggests a cost of 5 $/gallon acid, which is about 1.1 €/L. Finally, a total cost of 18.5 €/ton leafy greens is estimated for the use of sodium hypochlorite (Table 17).

It was assumed that disinfection methods will require an additional worker. The personnel costs and training costs will therefore be higher compared to the washing with potable water methodology. The operational costs for wash water disinfection with sodium hypochlorite sum up to ± 540 €/ton leafy greens.

Table 17. Costs related to the use of NaOCl for the wash water disinfection with NaOCl based on information from literature.

	UMass 2015	**Garrett et al. 2003**
Chemicals (€/m^3)	NaOCl: ± 2 €/m^3 water	Acids ± 1.7 €/m^3 water
Chemicals (€/ton leafy greens)	10	8.5
Total (€/ton leafy greens)	18.5	

The cost of peracetic acid was estimated at ± 6 €/L (UMass 2015). According to EPA dosing directions, for a concentration of 30 - 80 ppm peracetic acid in the process water, 0.0002 - 0.001 L Tsunami100 per litre process water should be dosed. Using on average 5 m^3 water/ton leafy greens this leads to a cost of 25 €/ton leafy greens for the use of peracetic acid. The total operational costs related the wash water disinfection with PAA equal to ± 550 €/ton leafy greens.

The reconditioning treatment will require a lower dosage of total added chlorine compared to the in-wash tank disinfection. It is assumed that 50% less chemicals and 5 m^3 water/leafy greens will be used for the off-line disinfection, which equals to 9.25 €/ton leafy greens (see Table 17).
The operational costs related to the water reconditioning treatment are estimated at ± 535 €/ton leafy greens.

Sub-criterion/metric: wastewater discharge costs ('economic impact' main criterion)

Wastewater discharge costs were based on input from processing plant B, which accounted ± 2 €/m^3 for the discharge of wash water. The wastewater discharge costs are considered similar for all wash water disinfection/reconditioning options. For these options, an online tool provided by a local environmental organisation (VMM 2021) was used. The online tool has an option to calculate the discharge costs for companies based on wastewater measurement data. Since these types of data were unavailable, an estimation was made based on measurement data from experimental studies performed on an industrial scale. The wizard predicted a cost of about 4 €/m^3 water for the discharge of water in surface water (Table 18).

Table 18. Details of the calculations for the wastewater discharge costs.

	Luo et al. 2018	Lehto et al. 2014	Banach et al. 2018
Input information used in the VMM wizard	COD: ± 2000 mg/L BOD: ± 2000 mg/L TSS: ± 2000 mg/L	P = 3 mg/L N = 13 mg/L	1500 L/h, 8 h/day, 5 d/week, 52 weeks; 3120 m^3/year; 12 000 L/d
Wastewater discharge costs (VMM wizard)		± 4 €/m^3	

The collected input data for each control strategy is summarised in Addendum 29. This will be used in two baseline scenarios (Step 6: ranking of alternatives).

3.2.5 Step 5: preference weight elicitation

A total of 28 stakeholders were invited by email to fill out the questionnaire, belonging to seven stakeholder groups. 19 fully completed surveys were obtained (response rate of 67%). The response rate was highest for the stakeholder group of sector associations (Figure 9).

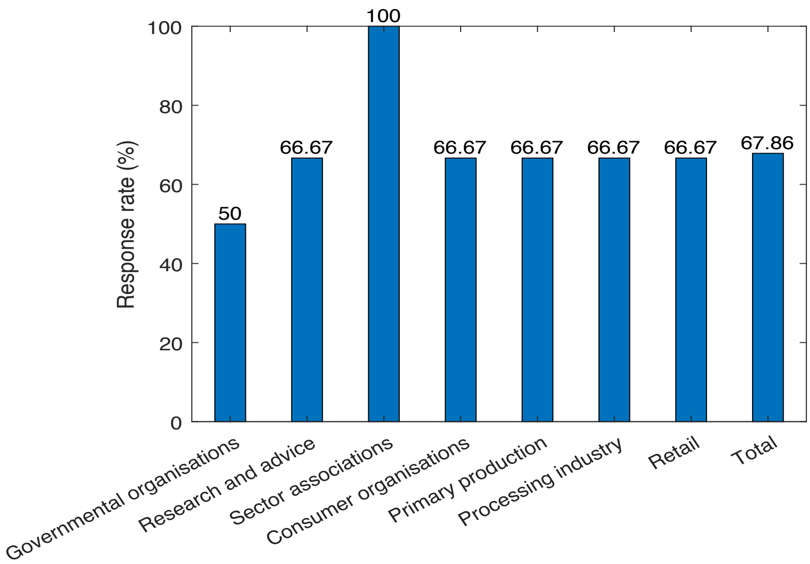

Figure 9. Response rate of preference weight elicitation survey for stakeholder group representatives from macro-, meso- and micro-level.

Figure 10 shows the distributions of the collected preference weights from nineteen stakeholders. Overall, the 'public health impact' main criterion was considered to be the most within the decision context and the 'microbiological food safety' sub-criterion was given the largest weight. However, the large interquartile range shows that the agreement among stakeholders is limited. The 'water use' and 'wastewater discharge' sub-criteria, which reflect the environmental impact of the washing methodologies were also considered as important sub-criteria. Three main criteria, 'technological impact', 'economic impact', 'societal impact' were generally assigned less weights.

Addendum 30 shows the distribution of preference weights within stakeholder groups for the main criteria. Public health impact was indicated as most important by all stakeholder groups, except the 'governmental organisations' and 'primary production', who indicated 'environmental impact' and 'technological impact' respectively as most important. The 'processing industry' representatives ranked the 'technological impact' and 'economic impact' higher in comparison to other stakeholder groups.

The small interquartile range of the 'consumer organisations' and 'retail' stakeholder groups indicate a high agreement among stakeholder representatives.

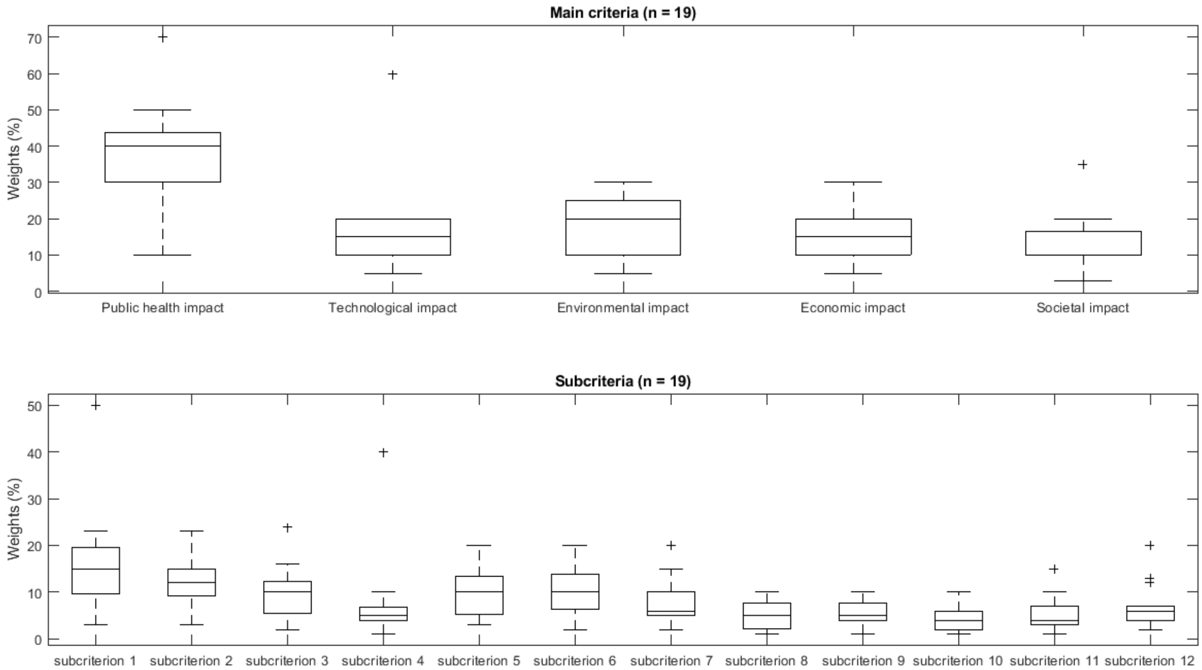

Figure 10. Boxplots representing distribution of preference weights over main criteria and sub-criteria for all stakeholder group representatives (overall). Sub-criterion 1: 'microbiological food safety', 2: 'chemical food safety', 3: 'occupational health and safety', 4: 'ease of implementation', 5: 'robustness', 6: 'water use', 7: 'wastewater discharge', 8: ''capital costs', 9: 'operational costs', 10: 'wastewater discharge costs', 11: 'consumer acceptance', 12: 'pressure from international/national authorities'.

3.2.6 Step 6: ranking of alternatives

The ranking of two baselines scenarios was determined with the PROMETHEE II algorithm (Table 19). Input data used for baseline scenarios is given in Addendum 29. In scenario 1a all sub-criteria were weighted equally, while in scenario 1b overall median weights collected in the stakeholder consultation were used (see Addendum 31). The potable water intervention option received the highest net phi flow in both baseline scenarios and wash water disinfection with NaOCl resulted in the lowest net phi flow (ϕ).

Table 19. Net phi flows for baseline scenarios for four different intervention options based on PROMETHEE II.

	Scenario 1a: equal weights	**Scenario 1b: P50 (overall)**
Intervention options	**Phi (ϕ)**	**Phi (ϕ)**
1. Washing with potable water	0.4048	0.2295
2. Wash water disinfection (PAA)	0.0714	0.1331
3. Reconditioning (NaOCl)	-0.1667	-0.1520
4. Wash water disinfection (NaOCl)	-0.3095	-0.2106

Figure 11 and Figure 12 show the contribution of main criteria towards the net phi flow (ϕ) in baseline scenario 1a for the potable water intervention option and wash water disinfection (PAA) respectively. Economic and societal impact are the most important contributors towards the positive outranking flow (ϕ+) of the potable water intervention option, while for peracetic acid the human health impact is the most important main criterion contributing to the positive outranking flow (ϕ+). See Addendum 32 and Addendum 33 for contributions of main criteria towards the net outranking flow of other intervention options.

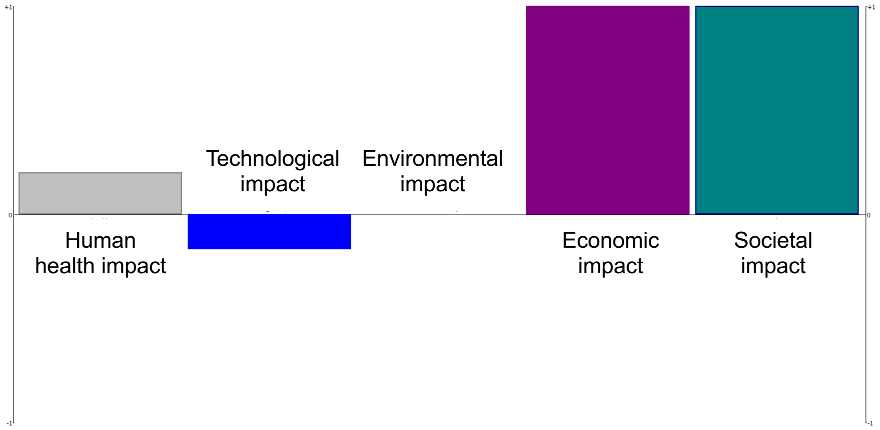

Figure 11. Contribution of main criteria towards net flow of potable water intervention option for baseline scenario 1a (equal weights).

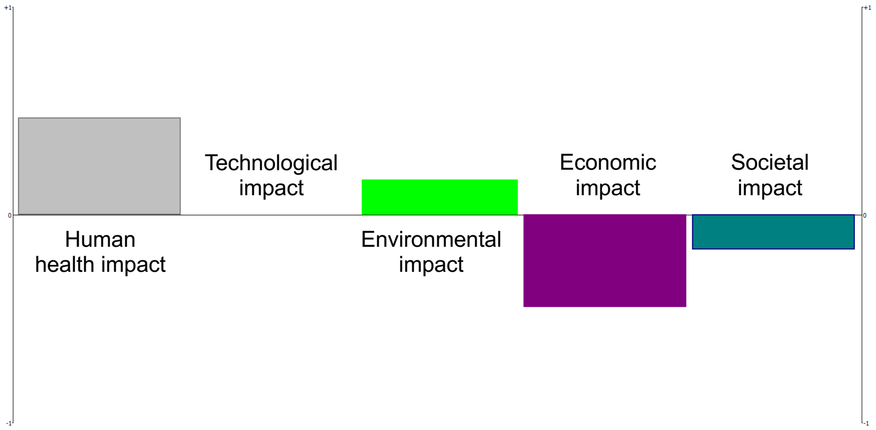

Figure 12. Contribution of main criteria towards net flow of wash water disinfection with PAA intervention option for baseline scenario 1a (equal weights).

3.2.7 Step 7a: uncertainty analysis

Table 20, Table 21 and Table 22 display the qualitative uncertainty analysis of collected input data, supplemented with issues, assumptions and comments provided by experts. The analysis is divided according to the methodology of input data collection. A discussion clarifying the degree and direction of uncertainty is provided for each sub-criterion. See Table 4 for an explanation of the ordinal scale.

3.2.7.1 Uncertainty analysis: quantitative input data from scientific literature

Metric: log CFU/g reductions of *E. coli* (O157:H7) on the end product ('microbiological food safety' sub-criterion)

- The distribution fit to literature input data for the potable water washing methodology resulted in a higher mean log CFU/g reductions of *E. coli* (O157:H7), in comparison to the NaOCl sanitisation washing method. The final distribution exhibits a lower mean reduction.
- Reductions for peracetic acid might be overestimated, since it was informed by experts that PAA is not as efficient as chlorine in maintaining the quality of process water. The high reductions found by Davidson, Kaminski and Ryser (2014) were not included (Addendum 5).
- It was assumed that reductions of *E. coli* (O157:H7) of the reconditioning treatment are comparable to washing with potable water, which could be an underestimation.

Metric: leaf-to-leaf ('microbiological food safety' sub-criterion)

- The water-to-leaf transfer part of the leaf-to-leaf transfer is based on one study, which was performed on laboratory scale (Holvoet et al. 2014). This information is highly uncertain, since the transfer rate depends on multiple factors such as the type of lettuce, cut-surfaces and the internalisation of pathogens. Artificial contamination will lead to less adherent (internalised) bacterial cells, which could cause an overestimation of pathogen transfer (Holvoet et al. 2014; Van der Linden et al. 2016). Additional experiments quantifying the transfer of pathogens in the wash water on an industrial scale seem interesting. Buchholz et al. (2012) quantified the *E. coli* O157:H7 transfer on a pilot-plant scale via equipment and Luo et al. (2012) quantified the leaf-to-water transfer of *E. coli* O157:H7 on semi-commercial scale. These results are important, as they are being used as input data for probabilistic risk assessments (e.g. Mokhtari et al. 2018; Pang et al. 2017; Pérez Rodríguez et al. 2011).
- It was assumed that the leaf-to-leaf transfer for the reconditioning treatment, was similar to washing with potable water. However, one could argue that the higher refreshment that would be achieved when water is being reconditioned to potable water quality could lead to a reduced level of pathogen transfer, and thus lower probability of cross-contamination. Studies measuring the transfer of pathogens when wash water reconditioning is applied are unavailable, therefore the input data was indicated as highly uncertain.

Metric: TTHMs on the end product (µg/kg) ('chemical food safety' sub-criterion)

- López-Gálvez et al. (2019) found concentrations of 5 to 17 µg/kg for TTHM on fresh-cut lettuce and baby leaves after washing with $Ca(ClO)_2$. The mean concentration of the probabilistic distribution for NaOCl disinfection (13 µg/kg, see Table 10), seems a good estimation.

- Information regarding TTHMs concentration when reconditioning with NaOCl were based on simulated wash water experiments performed on laboratory scale, with COD levels ranging from 800 to 1500 mg/L (Addendum 13). However, predicted TTHMs concentration might be an overestimation. It was mentioned by experts, that TTHMs are not considered a relevant public health issue because of the low concentrations found on produce after rinsing.

Metric: chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion)

- Garrido et al. (2019) found chlorate concentrations ranging from 0.1 to 0.6 mg/kg on minimally processed leafy greens washed in water containing NaOCl on laboratory scale and Gil et al. (2019) found a concentration of ± 0.3 mg/kg chlorate on shredded lettuce and baby spinach on pilot-plant scale. While Tudela et al. (2019) found concentrations between 0.05 and 0.07 mg/kg chlorate on leafy greens after processing on industrial scale. The first two examples were on a smaller scale and did not apply a rinsing step, while the last experiment did. It is also known that chlorate uptake tends to increase when the content in the wash water increases, when longer washing times are applied, and if hydration status decreases (Garrido et al. 2019). Additionally, chlorate concentration will be highly dependent on proper storage and handling of NaOCl and proper chlorination management (EFSA 2019).
- The mean concentration of chlorate when disinfecting with NaOCl of 0.478 mg/kg (Table 11) might be an overestimation.
- Results for the reconditioning treatment are highly uncertain, as these are based on one study and no validation data is available. The selected study (Gil et al. 2016) uses artificial process water in a pilot plant. They found a chlorate concentration of 13 mg/L after 6 hours of processing. The minimum value is based on the maximum level of chlorate in potable water (Directive (EU) 2020/2184). The mean concentration (0.203 mg/kg) is lower than for the wash water disinfection with NaOCl. This is in line of expectations, since the reconditioning treatment would require a lower consumption of total added chlorine, as there is no need for continuous dosing to prevent cross-contamination.

Table 20. Uncertainty analysis. Summarising table with main criteria, sub-criteria, metrics and an estimation of the uncertainty related to the input data collection. Issues, assumptions and comments given by experts which explain the uncertainty analysis.

Main criteria	Sub-criteria	Metrics	Intervention option	Uncertainty analysis	Issues, assumptions and comments
Public health impact	Microbiological food safety	Log CFU/g reductions of *E. coli* (O157:H7)	Potable water	+	Issue: probabilistic distribution fit to literature data leads to very high mean reductions
			Wash water disinfection: NaOCl	0	/
			Wash water disinfection: PAA	+++	Issue: reductions are higher than NaOCl Comment: PAA tends to be less effective
			Reconditioning: NaOCl	–	Assumption: comparable reductions to potable water
		% transfer rate (leaf-to-leaf)	Potable water	– – –/+++	Issue: water-to-leaf transfer based on one study
			Wash water disinfection: NaOCl	0	Assumption: no transfer
			Wash water disinfection: PAA	0	Assumption: no transfer
			Reconditioning: NaOCl	– – –/+++	Issue: unknown transfer
		µg/kg TTHMs	Potable water	0	/

	Chemical food safety		Wash water disinfection: NaOCl	+	Issue: high concentrations found in literature. Some experiments did not include a rinsing step
			Wash water disinfection: PAA	0	Assumption: no significant DBPs
			Reconditioning: NaOCl	++	Issue: based on lab scale experiments
		mg/kg chlorate	Potable water	0	/
			Wash water disinfection: NaOCl	+	Issues: based on experiments with and without a rinsing step
			Wash water disinfection: PAA	0	Assumption: no significant DBPs
			Reconditioning: NaOCl	? –/+	Issue: based on study with comparable characteristics to reconditioning (not a reconditioning experiment). No validation data available
	Occupational health and safety	Qualitative: 5-point scale	Potable water	0	/
			Wash water disinfection: NaOCl	0	Comment: disinfection in open tanks could lead to aerosols
			Wash water disinfection: PAA	0	/
			Reconditioning: NaOCl	–/+	Comment: off-line disinfection often in closed tanks

3.2.7.2 Uncertainty analysis: qualitative expert scores

Sub-criterion: occupational health and safety ('human health impact' main criterion)

- The use of peracetic acid and sodium hypochlorite was considered to have an equal impact on workers' safety (Table 20).
- The reconditioning treatment was considered to have less impact on health and safety of workers than in-line disinfection, because the latter is mostly applied in open systems, and as such gas and aerosols could form if the systems malfunctions (e.g. overdosing and pH extremes).

Sub-criterion: ease of implementation ('technological impact' main criterion)

- Variability in the expert scores was low. The experts mentioned that the reconditioning treatment is easier to control. This system will have a larger time frame to treat water with a certain quality (COD, particles, pH, etc.).

Sub-criterion: robustness ('technological impact' main criterion)

- The definition of the robustness sub-criterion was questioned by multiple experts (Table 8). Robustness and effectiveness were said to be very different things. A washing process can be robust in the sense of controlling process parameters but will be less effective in mitigating the potential pathogen cross-contamination, as such not effective for its actual purpose. It was concluded that also the effectiveness in terms of preventing pathogen cross-contamination should be considered here. Therefore, off-line disinfection was scored much lower. It was mentioned that there's no true evidence that this system works and there will always be potential for cross-contamination.

Sub-criterion: wastewater discharge ('environmental impact' main criterion)

- This criterion was not scored by one expert, because it was considered too complicated. It was mentioned that pesticides will be washed of whether or not large volumes of water are being used. The difference is the concentration of pesticides in discharged water. Process water will usually go to a wastewater treatment plant, prior to discharge. These consist of large buffer tanks, where peaks of chemicals are flattened out. Also, the fact that disinfectants could alter the structure of pesticides in the wash water was mentioned, possibly increasing or decreasing the pesticide activity. Direction of uncertainty was therefore indicated as unknown.

Sub-criterion: consumer acceptance ('societal impact' main criterion)

- Scores collected for the 'consumer acceptance' sub-criterion showed more variability and were indicated as an underestimation. One expert explained that it is unknown what the actual perception of consumers towards chemical sanitisers is. Disinfectants are considered processing aids, and don't need to be labelled in the EU, therefore consumers are unaware if disinfectants are being applied or not.

Sub-criterion: pressure from national/international authorities ('societal impact' main criterion)

- The application of sanitisers, both in wash tank and as a reconditioning agent, was scored very low in the 'pressure from national/international authorities' sub-criterion. Experts mentioned that regulations and guidelines related to wash water disinfection is different in EU member states.

Table 21. Uncertainty analysis. Summarising table with main criteria, sub-criteria, metrics and an estimation of the uncertainty related to the input data collection. Issues, assumptions and comments given by experts which explain the uncertainty analysis.

Main criteria	Sub-criteria	Metrics	Intervention option	Uncertainty analysis	Issues, assumptions and comments
Technological impact (operations)	Ease of implementation	Qualitative: 5-point scale	Potable water	0	/
			Wash water disinfection: NaOCl	0	/
			Wash water disinfection: PAA	0	/
			Reconditioning: NaOCl	0	Comment: easier to control, because of larger time range
	Robustness	Qualitative: 5-point scale	Potable water	0	/
			Wash water disinfection: NaOCl	0	/
			Wash water disinfection: PAA	+	Comment: less effective in preventing cross-contamination
			Reconditioning: NaOCl	0	Comment: no evidence for prevention of cross-contamination
Environmental impact	Water use	m^3/ton end product	Potable water	0	Information provided by processing plants
			Wash water disinfection: NaOCl	–/+	Aggregation of information found in literature
			Wash water disinfection: PAA	–/+	Aggregation of information found in literature

			Reconditioning: NaOCl	–/+	Aggregation of information found in literature
	Wastewater discharge	Qualitative	Potable water	– –/++	Comment: difficult to score sub-criterion
			Wash water disinfection: NaOCl	– –/++	Comment: difficult to score sub-criterion
			Wash water disinfection: PAA	– –/++	Comment: difficult to score sub-criterion
			Reconditioning: NaOCl	– –/++	Comment: difficult to score sub-criterion
Societal impact (stakeholders)	Consumer acceptance	Qualitative: 5-point scale	Potable water	0	Comment: generally accepted
			Wash water disinfection: NaOCl	– –	Comment: consumer is unaware of the type of disinfectant
			Wash water disinfection: PAA	–	Comment: consumer is unaware of the type of disinfectant
			Reconditioning: NaOCl	? –/+	Comment: consumer is unaware of the type of disinfectant
	Pressure from national/international authorities	Qualitative: 5-point scale	Potable water	0	/
			Wash water disinfection: NaOCl	0	Comment: no harmonised legislation
			Wash water disinfection: PAA	0	Comment: no harmonised legislation
			Reconditioning: NaOCl	0	Comment: no harmonised legislation

3.2.7.3 Uncertainty analysis: quantitative input data from (fresh-cut) vegetable processing plants

Three vegetable processing plants were contacted and asked to provide information related to the water use, capital costs, operational costs and wastewater discharge costs. Many assumptions had to be made related to in-line/off-line disinfection with NaOCl and PAA. Grey literature related to the use of chemicals was highly variable and ranged over multiple orders.

Sub-criterion: water use ('environmental impact' main criterion)

- The water consumption for disinfection and reconditioning options were based on literature input, thus the calculated mean value might be a slight under- or overestimation (Table 21).

Sub-criterion: capital costs ('economic impact' main criterion)

- It was decided to work proportionately to the information provided by the processing facilities for the measurement of disinfection and reconditioning options. In order to gain more precise information related to storage of chemicals, pumping systems and monitoring and control systems, a collaboration with processing facilities applying the investigated washing methodologies is recommended. The input data is considered highly uncertain.

Sub-criterion: operational costs ('economic impact' main criterion)

- An estimation for the operational costs for all washing methodologies was made in relation to the potable water case. It was assumed that one additional worker will be needed when applying a disinfection methodology. Additional industry information is necessary to confirm this assumption.
- The exact use of chemicals is difficult to predict, since this will depend on multiple factors, such as the type of leafy green and the dosing system. Information was extracted from literature; however, sources might be dated and not a good representation of the Belgian situation.
- It was assumed that 50% less chlorine will be necessary for the off-line disinfection, since longer contact times will be possible using this technique. Actual chlorine dosing will depend on different processing parameters. Ideally, this is informed by a processing facility.

Sub-criterion: wastewater discharge costs ('economic impact' main criterion)

- The costs for potable water were estimated by processing plant B. Wastewater discharge costs for three alternative methods were calculated with an online tool. Input data for the online tool was collected from scientific literature.
- Vegetable processing plants usually will have a wastewater treatment plant, which will assure that discharged water is of proper discharge quality. These costs will depend on the ability of the wastewater treatment plant to provide sufficient effluent quality, and not the applied washing and/or disinfection methodology.

Table 22. Uncertainty analysis. Summarising table with main criteria, sub-criteria, metrics and an estimation of the uncertainty related to the input data collection. Issues, assumptions and comments given by experts which explain the uncertainty analysis.

Main criteria	Sub-criteria	Metrics	Intervention option	Uncertainty analysis	Issues, assumptions and comments
Economic impact (costs)	Capital cost	€	Potable water	0	/
			Wash water disinfection: NaOCl	– – –/+++	Issue: highly uncertain, based on assumptions
			Wash water disinfection: PAA	– – –/+++	Issue: highly uncertain, based on assumptions
			Reconditioning: NaOCl	– –/++	/
	Operational costs	€/ton end product	Potable water	0	/
			Wash water disinfection: NaOCl	– – –/+++	Assumption: 1 additional worker.
			Wash water disinfection: PAA	– – –/+++	Assumption: 1 additional worker.
			Reconditioning: NaOCl	– – –/+++	Assumption: 1 additional worker and 50% less chlorine
	Wastewater discharge costs	€/ton end product	Potable water	0	/
			Wash water disinfection: NaOCl	? +	Issue: calculated with online wizard (VMM), with input found in literature
			Wash water disinfection: PAA	? +	Issue: see wash water disinfection (NaOCl)
			Reconditioning: NaOCl	? +	Issue: see wash water disinfection (NaOCl)

3.2.8 Step 7b: sensitivity analysis

A scenario analysis was used to estimate the sensitivity of MCDA inputs. In scenario 2 to 8 median preference weights (P50) for each stakeholder group are used and input data for criteria evaluation are equal to the baseline scenario. In the remaining scenarios input data for criteria evaluation are varied. Table 23 explains each scenario. Scenarios 9 and 10 take uncertainties related to the 'microbiological food safety' sub-criterion into account. Scenario 11 represents the possible overestimation of the 'chemical food safety' sub-criterion. In scenario 12 the presence of a wastewater treatment plant is taken into account. Uncertainty related to consumer acceptance is included in scenario 13.

Table 23. Sensitivity analysis. Different scenarios with variable preference weights and/or variable input data for criteria evaluation.

Scenario	Weights	Input data for criteria evaluation
Baseline scenario (1a)	Equal weights	Addendum 29
Baseline scenario (1b)	P50 (overall)	Addendum 29
Scenario 2 – 8	P50 stakeholder groups	Equal to the baseline scenario (Addendum 29)
Scenario 9a	Equal weights	Set PAA log CFU/g reductions equal to NaOCl reductions ('microbiological food safety' sub-criterion)
Scenario 9b	P50 (overall)	Set PAA log CFU/g reductions equal to NaOCl reductions ('microbiological food safety' sub-criterion)
Scenario 10a	Equal weights	Exclusion of leaf-to-leaf transfer rate ('microbiological food safety' sub-criterion)
Scenario 10b	P50 (overall)	Exclusion of leaf-to-leaf transfer rate ('microbiological food safety' sub-criterion)
Scenario 11a	Equal weights	P5 for chemical food safety sub-criteria (Table 10) ('chemical food safety' sub-criterion)
Scenario 11b	P50 (overall)	P5 for chemical food safety sub-criteria (Table 10) ('chemical food safety' sub-criterion)
Scenario 12a	Equal weights	Equal wastewater discharge costs and equal scores for 'wastewater discharge' sub-criterion
Scenario 12b	P50 (overall)	Equal wastewater discharge costs and equal scores for 'wastewater discharge' sub-criterion
Scenario 13a	Equal weights	Minimum from collected expert scores for 'consumer acceptance' sub-criterion (Addendum 27)
Scenario 13b	P50 (overall)	Minimum from collected expert scores for 'consumer acceptance' sub-criterion (Addendum 27)

3.2.9 Step 8: examination of ranking

Thirteen scenarios were run in the PROMETHEE decision lab ®. The calculated net outranking phi flows (ϕ) are available in Addendum 34 and Addendum 35. Figure 13 displays the ranking of four intervention options for the baseline scenario in comparison to scenario two to eight. These scenarios represent the preferences indicated by stakeholders for each stakeholder group. The ranking of intervention options did not change, except for the scenario in which preference weights collected from consumer organisation representatives were used. These stakeholders indicated that the human health impact of intervention options is far more important than other main criteria, i.e. P50 of 70% (Addendum 31). This resulted in a greater performance of the wash water disinfection options. Wash water disinfection with peracetic acid received the highest net outranking phi flow (ϕ), and the reconditioning treatment received the lowest.

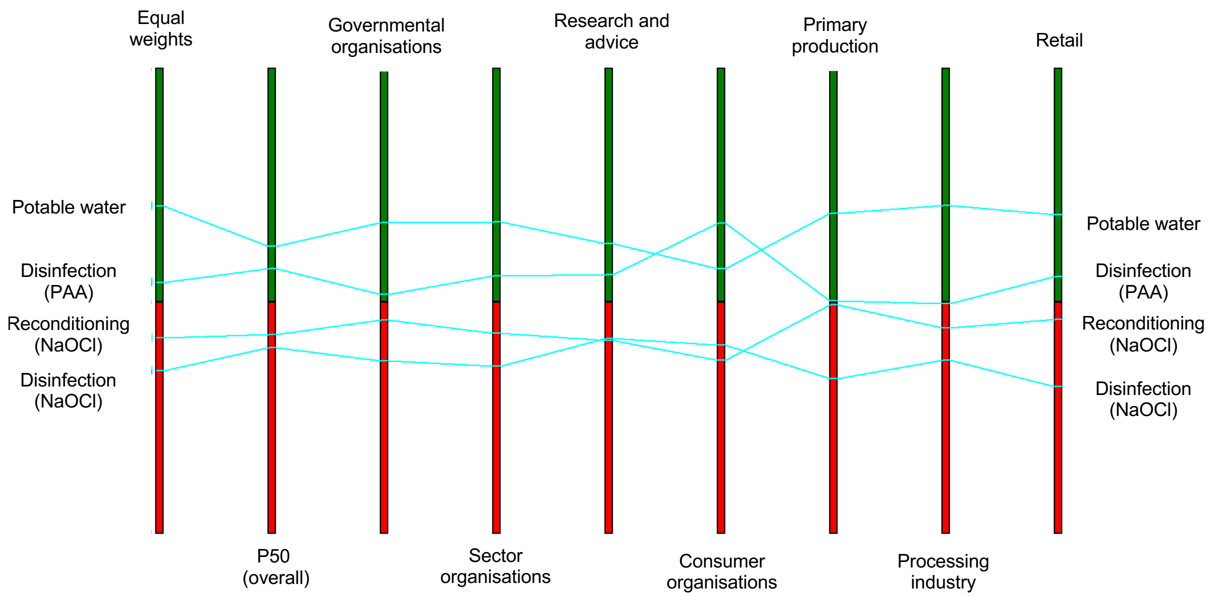

Figure 13. Scenario analysis. Ranking of four intervention options (washing with potable water, wash water disinfection with NaOCl, wash water disinfection with PAA and a reconditioning treatment with NaOCl), according to baseline scenario 1a (equal weights) and 1b (P50 (overall)). In scenario 2 to 8 P50 values of preference weights for each stakeholder group were used.

Ranking of control strategies remained unaltered in scenarios nine, ten, eleven and thirteen in comparison to the baseline scenarios. Exact net outranking flows are given in Addendum 35.

Figure 14 displays the ranking of intervention options for scenario 12 in comparison to the baseline scenarios. In scenario 12b the P50 of overall elicited stakeholder preference weights were used, and wastewater discharge costs ('economic impact' main criterion) were set to € 2 for each intervention option and scores for 'wastewater discharge' sub-criterion ('environmental impact' main criterion) were set to the potable water score of 2 (Table 12). This scenario represents the presence of a wastewater treatment plant, which would equalise water quality of discharged water. In this scenario wash water disinfection with peracetic acid comes out best and the reconditioning treatment with sodium hypochlorite received the lowest net outranking flow using the PROMETHEE II algorithm (Figure 14).

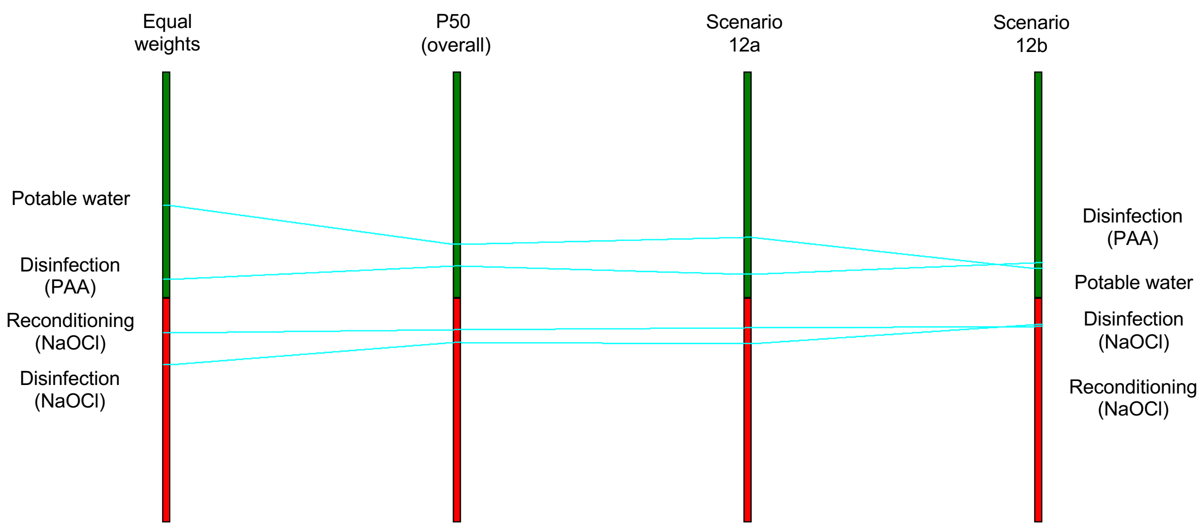

Figure 14. Scenario analysis. Ranking of four intervention options (washing with potable water, wash water disinfection with NaOCl, wash water disinfection with PAA and a reconditioning treatment with NaOCl), according to baseline scenario 1a (equal weights) and 1b (P50 (overall)) In scenario 12 scores for the 'wastewater discharge' sub-criterion and 'wastewater discharge costs' sub-criterion are adjusted, in order to represent the presence of a wastewater treatment plant.

4 DISCUSSION

4.1 Identification of alternative intervention options

The selected interventions options are currently implemented in the industry, which allowed a data informed comparison. More experimental chemical and physical disinfection methodologies, such as chlorine dioxide, ozone, electrolyzed water, essential oils, and cold plasma, were not included (Deng et al. 2020). In terms of the reconditioning treatment, only an off-line disinfection with NaOCl was considered. This will only work towards reducing the microbial load of the process water. It will not have any effect on the particles present in the water, which would require a physical treatment, such as filtration or settling (Manzocco et al. 2015). Gómez-López et al. (2015) found that high power ultrasound combined with residual PAA could be a promising reconditioning treatment for recycled water. Van Haute et al. (2015) also concluded that PAA (+ lactic acid) could act as a reconditioning agent. This would require low dosages of PAA but longer contact times than NaOCl, due to its slower inactivation of *E. coli* O157:H7.

Experts criticised the terminology of intervention options. It was expressed that the term 'washing with potable water', should be replaced by 'washing with process water'. The water cannot be considered of potable water quality, because quality rapidly decreases during the washing procedure. Additionally, it was stated that 'wash water' is restricted to the washing of vegetables, while now more and more flumes are used to 'wash and transport' vegetables within the processing lines, this is why the term 'process water' would be a better alternative. It was suggested to rename the reconditioning treatment to 'reconditioning for water reuse', because terminology related to water reuse in the food industry can be ambiguous and a good clarification is important here (see FAO/WHO 2019).

4.2 Identification of main- and sub-criteria and metrics

Multiple phases led to the final list of evaluation criteria, which were deemed relevant for the leafy greens case study. It was informed by different sources of literature, as well as discussions with academic experts. Evaluation criteria were exhaustive, in the sense that all relevant economic, environmental and social factors were considered. However, the absence of some criteria could be argued for. For example, criteria related to the quality and the impact on shelf-life of minimally processed leafy vegetables were excluded from the MCDA, and only the impact on safety of the intervention options was considered. Yet, product quality might be considered important to vegetable processors and retailers, as this could have economic implications.

The metrics for the 'chemical food safety' sub-criterion were restricted to the concentration of TTHMs (µg/kg) and chlorate (mg/kg) on the end product, which are DBPs related to the use of sodium hypochlorite. Other relevant disinfection by-products, which were not included in the MCDA are haloacetic acids and 3-chlorotyrosine. The production of HAAs in leafy greens washing and presence on minimally processed leafy greens is highly investigated (e.g. Marín et al. 2020; Shen et al. 2016). Tudela et al. (2019a) found concentrations of 52 to 167 µg/L in the wash water of fresh-cut iceberg lettuce and baby leaves, and the legal limit of HAAs in potable water (Directive (EU) 2020/2184) is 60 µg/L. However, it is assumed that concentrations on the product after rinsing would be limited. Cardador and Gallego (2012) found concentrations of approximately 5 to 40 µg/kg total HAAs on store bought minimally processed leafy greens. 3-Chlorotyrosine is less investigated, however Bao Loan et al. (2016) found concentrations 1 to 2.23 µg 3-chlorotyrosine/g vegetable on commercial ready-to-eat iceberg lettuce, and a quantitative exposure assessment for the Belgian and Spanish population demonstrated that 3-chlorotyrosine exposure via lettuce mixes could be considered a public health concern for 17% of Spanish consumers.

The nature of criteria (quantitative or qualitative) and the metrics were highly dependent on the availability of reliable data. If quantitative data was unavailable, a 5- point Likert-type answer scale was used for the qualitative assessment of sub-criteria based on expert judgement. Compared to scales with fewer scale points, 5- to 7- point scales improve reliability and validity of results, yet more finely grading doesn't improve reliability and validity anymore. 5- and 7-point scales tend to produce the same mean (Dawes 2008). An answer form was provided to experts, where experts rated the degree to which they agreed with a statement on an ordinal scale. This implies that the distance between responses cannot be considered equidistant, even though the numbers are. The obtained data should be handled using nonparametric tests, as it cannot be assumed that data is normally distributed. The mean and standard deviation of Likert scale answers have no meaningful meaning and could be an unfair presentation of the data (Sullivan and Artino 2013). Instead, the median and range was used.

Expert judgement was a means to better understand the specifics of washing procedures and obtain additional (technical) information. An inappropriate selection of experts and the framing/wording of the criteria and intervention options could have been a source of bias (Van der Fels-Klerx et al. 2018).

The collection of input data was fully evaluated and discussed in Section 3.2.7: Step 7a: uncertainty analysis. This will not be further elaborated on here.

4.3 Preference weight elicitation

The consideration of stakeholder preferences was incorporated in the MCDA by assigning weights to evaluation criteria. A stakeholder consultation was organised to elicit these preference weights. Comparable methods were applied in multiple MCDA examples (Banach et al. 2021; Mourits, van Asseldonk, and Huirne 2010). This is referred to as the point allocation (PA) method (Bottomley and Doyle 2001) or the use of comparative rating scales. The latter implies that the judgement of each criterion is in direct reference to remaining criteria (Churchill 1995). It also has similar attributes to The Las Vegas Method or Trial Roulette method (Gore 1987), where usually 20 points are divided over a set of 'bins' (e.g. Baert et al. 2012; Cardoen et al. 2009). This direct elicitation technique has been frequently used because of its simplicity. However, it has been critiqued to be time consuming and cognitively demanding, as it could be difficult for individuals to express preferences in numerical values (Bartolini and Viaggi 2010; Cinelli et al. 2020). Other elicitation methods are SMART, SWING weighting, and Tradeoffs. Choosing an appropriate method can be a difficult task, since the results are highly dependent on the method of assessment and are prone to different biases (Riabacke, Danielson, and Ekenberg 2012).

Since weights were obtained from individuals, mathematical aggregation of individual assessments was necessary. Aggregation of individual preferences is not ideal, because it doesn't encourage discussion or sharing of information. Disagreements are mathematically reconciled, without explicitly discussing the cause of these differences. Alternatively, sharing methods aim to obtain input by consensus. The latter entails focus-groups, workshops and the Delphi technique (Henson and Masakure 2012). A Delphi survey is an iterative process designed to transform opinion into group consensus. This consists of a series of questionnaires or 'rounds', alternated with structured feedback (Hasson, Keeney, and McKenna 2000; Powell 2003).

The ambiguity and subjectivity related to the preference weights was dealt with using a sensitivity analysis, to capture the impact of the uncertainty of criteria weights on the final ranking of alternative intervention options (Hyde, Maier, and Colby 2003). Statistical analysis was not possible, and only a qualitative evaluation of the obtained results was performed, due to the small sample of stakeholders included in the consultation.

The stakeholder consultation only addressed Belgian stakeholders. A similar stakeholder survey was performed in the Netherlands (Banach et al. 2021). However, not all respondents were from the Netherlands and cultural impacts of stakeholder interests were ignored.

It might be interesting to organise a stakeholder consultation in different European member states for the elicitation of preference weights, as this could expose discrepancies in beliefs and interests of stakeholders across the European Union. This could explain the variable use of disinfectants in the EU and the lack of harmonised regulations.

4.4 Ranking of alternative options

PROMETHEE methods have been widely used in multi-criteria decision analysis applications (Greco et al. 2016). In this case study, the uncertainty was dealt with by carefully analysing uncertainty related to input data and subsequently running different scenarios to verify the robustness of the MCDA. Alternatively, stochastic methods could be proposed to deal with uncertainty in data and preferences (Greco et al. 2019). Stochastic multi-attribute acceptability analysis (SMAA; Lahdelma, Hokkanen, and Salminen 1998; Lahdelma and Salminen 2001) has become a popular family of MCDA methods. It takes uncertainty into account by considering probability distributions on the space of preference weights and input data. Corrente, Figueira, and Greco (2014) applied the SMAA methodology in combination with the PROMETHEE II method by translating preference information provided by decision-makers using the SMAA methodology. Hyde et al. (2003) incorporated uncertainty in the PROMETHEE method by representing preference weights and input data for the evaluation of criteria by probabilistic distributions and performing a reliability analysis using a Monte Carlo simulation. The leafy greens case study was limited to deterministic methods. The SMAA methodology appears to be an elegant way to include probability-based methods in the PROMETHEE method.

The 'potable water' control strategy resulted in the highest net Phi (ϕ), followed by wash water disinfection with peracetic acid, and reconditioning with NaOCl, while wash water disinfection with NaOCl resulted in the lowest net Phi (ϕ). The 'economic impact' and 'societal impact' main criteria are important contributors towards the position of the 'potable water' control strategy. However, ranking is adjusted when greater importance is given to the human health impact of control strategies. A scenario representing the presence of wastewater treatment plants also led to an altered ranking, with PAA as a disinfectant coming out 'best'.

4.5 MCDA in food safety risk management

Semi-structured interviews revealed that decision support tools are being applied in various domains, such as the RMOA methodology and cost-benefit analyses applied by ECHA. These examples have in common that they provide a structured approach for the gathering of relevant evidence and the consideration of multiple factors. Which is of importance, since decisions are becoming increasingly complex, information-intensive and sophisticated. The EU better regulations toolbox advocates for evidence-based decision-making and recommends using an as broad as possible range of evidence, while ensuring transparency and robustness (European Commission 2017a). This also applies to food safety risk management, where MCDA could provide a tool for sound decision-making. The semi-structured interviews also indicated that multiple opportunities for the application of MCDA in food safety risk management exist. The leafy greens case study provides evidence thereof.

While mainly deterministic methods were applied and many sources of bias and uncertainty were introduced throughout the MCDA development, it had the ability to provide insight into a complex issue in a transparent and accessible manner. If more probabilistic methods would have been applied, such as the SMAA methodology, it could be argued that the final result may be less informative to stakeholders and policymakers. Communicating uncertainty to different audiences can be a difficult task and should always have the aim of increasing acceptance of scientific results (EFSA 2018).

4.6 Opportunistic pathogens

Next to primary foodborne pathogens, the highly diverse microbiomes of vegetables could also serve as a reservoir for opportunistic pathogens. These pathogens cause diseases only in immunocompromised individuals (Berg et al. 2014). It was established that the microbiota of the leafy greens phyllosphere consists of a diverse mixture of bacteria, yeasts and fungi. The access to space, nutrients, the production of antimicrobial compounds and other methods to acquire resources, control the co-existence of different bacterial communities. This means that invading human pathogens must compete and co-exist with an already established bacterial community in order to establish (Mogren et al. 2018). This highlights the importance of the naturally occurring microbiome of leafy vegetables, as it could be more persistent than potential pathogens, and potentially could interact with them (Jackson et al. 2013).

Rosberg et al. (2021) investigated the impact of commercial processing (without the use of sanitisers) on the microbial communities of spinach and rocket. Washing had no reducing effect on the bacterial load, but it did change bacterial compositions. *Pseudomonas* spp. was the most commonly occurring genus in the core microbiome, and abundance increased noticeably after washing. *E. coli* was found on produce after washing, indicating the issues related to cross-contamination via wash water. They concluded that cold storage and washing without the use of sanitisers causes changes in the composition and bacterial diversity, favouring the abundance of spoilage bacteria, namely fast-growing opportunistic microorganisms. Alternatively, the impact of wash water disinfection with chemical sanitisers on the phyllosphere microbiome of leafy greens could be investigated, in order to find out whether significant changes in microbiome occur and whether an environment optimal for (opportunistic) pathogen growth is created.

5 CONCLUSION

Food safety decision-makers are stepping away from a unilateral focus on human health impact and the importance of considering other factors is being recognised. Multi-criteria decision analysis has shown great potential as a decision support tool for risk managers in many other domains, such as environmental risk management. This thesis had the aim to investigate the potential of MCDA in food safety risk management. Therefore, three research questions were formulated.

The MCDA methodology in food safety risk management was investigated by an in-depth literature study of MCDA applications in this domain. A broad range of examples were presented. Some examples had the aim to present a state-of-the-art MCDA application, while others turned to MCDA as a decision support tool and to gain better understanding of complex issues.

Semi-structured interviews with representatives from different domains shed light on the current **risk management decision-making process**. A structured approach towards decision-making at the micro-, meso- or macro level seems to be lacking. The interviews demonstrated the importance of expert input, as a means to fill in knowledge gaps, and the collaboration with stakeholders. The importance of sector associations was emphasised, as they can provide important insights on the public perception of risk management interventions. The application of MCDA, as a tool for structured decision-making, was confirmed by all interviewees.

The leafy greens case study demonstrated that MCDA could be a valuable tool in food safety risk management, to gain better understanding of complex issues, point out knowledge gaps and increase transparency towards stakeholders. A stakeholder consultation pointed that out that the human health impact of intervention options is still considered the most valuable criterion within the decision context. However, importance varied across stakeholder groups. Using the PROMETHEE II algorithm, the intervention option of washing with potable water was ranked first, followed by wash water disinfection with peracetic acid. The final ranking produced by any MCDA algorithm should not be accepted blindly but should be evaluated carefully. Especially since the process leading towards the ranking of intervention options is subject to many sources of bias and uncertainty. An uncertainty analysis pointed out the weaknesses of the case study input data, while a sensitivity analysis of results demonstrated the robustness of the MCDA. The approach towards this case study was to quantify as many (sub-)criteria as possible, supplemented by expert input. This revealed some research opportunities. The degree of process water mediated cross-contamination is still unclear, and consumer perception towards the use of chemical sanitisers in food processing applications remains unknown. Probabilistic methods were applied where possible, however other probabilistic methods, such as the SMAA methodology, are suggested to deal with these uncertainties.

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ADDENDA

Addendum 1. Questions asked in the semi-structured interviews with MCDA practitioners.

When deciding on risk management interventions, multiple factors and the interests of different stakeholders should be taken into account. The goal of this conversation is to determine, whether systematic methods towards decision-making are being applied in your field of expertise.

1. Have you ever contributed to an impact assessment process?
    a. Have you ever contributed to or heard of the specific methods used for the comparison of different options, such as multi-criteria decision analysis, cost-benefit analysis or cost-effectiveness?
2. What criteria would you consider relevant when evaluating potential interventions?
3. How is the performance of an intervention on each criterion determined? (I.e. what key data is required for each criterion?)
    a. What is the nature of the data, would you say mainly qualitative or quantitative?
4. Are experts involved in the decision-making process?
    a. If yes, how exactly does expert consultation happen and how is this information included in the decision-making process?
5. Who are the major stakeholders in your field? (i.e. who should be included/consulted in the decision-making process?)
    a. How exactly does stakeholder consultation happen? In what way are their opinions elicited and included during the decision-making process?
6. Is the relative importance of the criteria determined? Are weights being assigned to the criteria?
    a. If yes, how are these weights determined?
7. Which criteria (if any) are the most important in your opinion? (I.e. which should be given the most weight in the final decision?) Is uncertainty on assumptions that are made during quantification, considered during the decision-making process?
    a. If yes, how is this practically included in the decision-making process?
    b. Is a sensitivity analysis generally used to assess the impact of changes in the assumptions on the final results?
    c. Are probabilistic methods applied? Or are decisions made in a more qualitative or deterministic manner?
8. Are there any practical/feasible ways to improve current decision-making processes (from your perspective)?
9. Is there anyone else within or outside of your organisation/industry who you think I should also talk to?

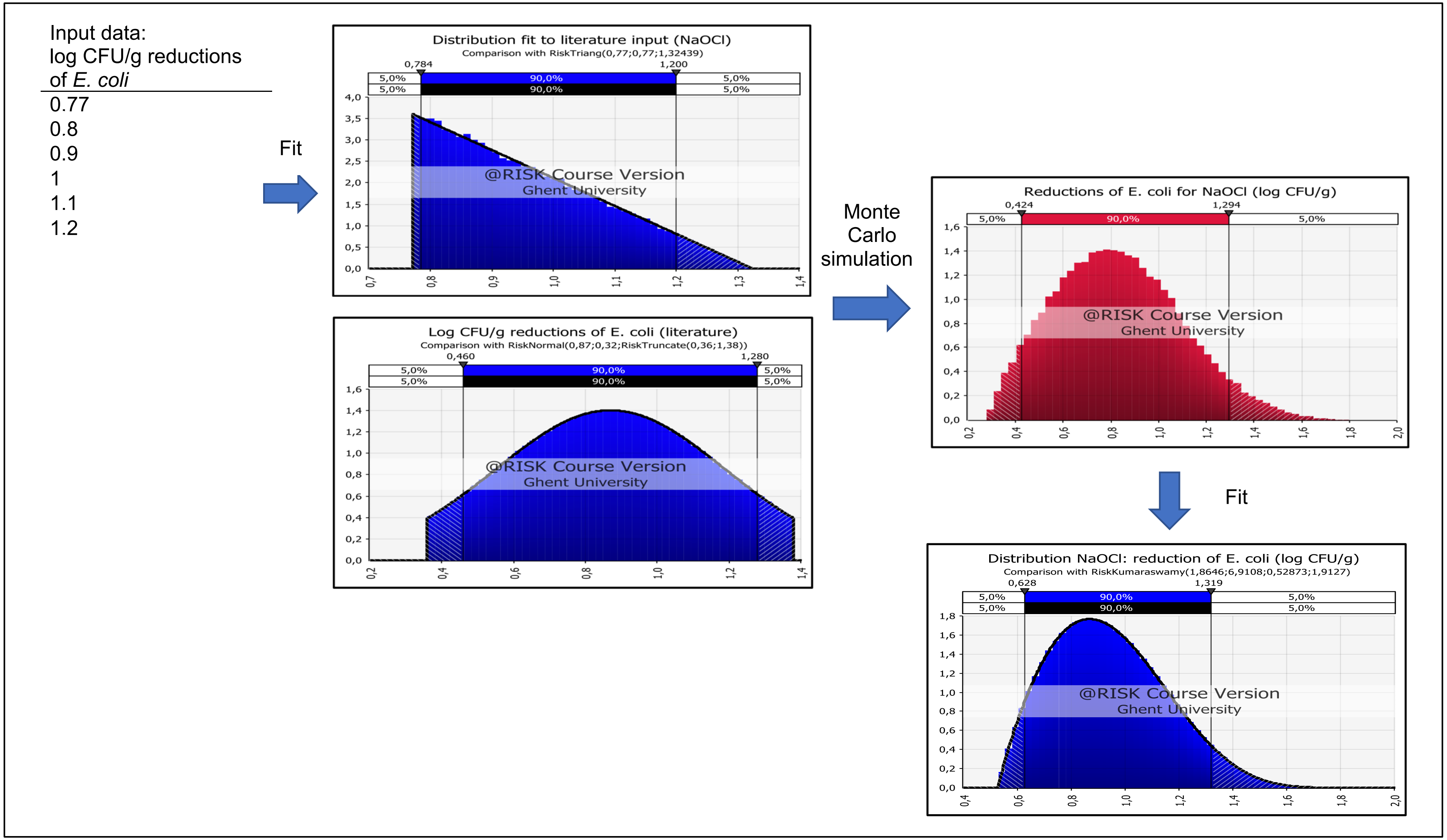
Addendum 2. Input data for the reduction of E.coli (O157:H7) on leafy greens ('microbiological food safety' sub-criterion) when washing with potable water.

Characteristics of study	**Buchholz et al. 2012**	**Davidson, Buchholz, and Ryser 2013**	**Pang et al. 2017**	**Bozkurt et al. 2021**
Microorganism	*E. coli* O157:H7	*E. coli* O157:H7	*E. coli* O157:H7	*E. coli* O157:H7
Leafy green type	Iceberg lettuce, romaine lettuce and spinach	Iceberg lettuce	Romaine lettuce	Fresh-cut cos lettuce
Study dimension	Pilot-plant scale: 890 L water tank, 22.7 kg batches	Small scale commercial processing plant: 890 L water tank, 5.4 kg batches	Probabilistic risk assessment model	Probabilistic risk assessment model
Processing steps	Cutting, shredding, washing, dewatering (centrifuge)	Shredding, conveyed to flume tank, dewatering (shaker table), dewatering (centrifuge)	/	/
Inoculation level and method	Dip inoculation, centrifuging, draining, air drying for 1 h at 22°C. Level: 1E6, 1E4, 1E2 CFU/g	Immersion inoculation. Level: 1E6 CFU/g.	/	/
Water	Sanitiser-free tap water	Potable water	Potable water	Potable water
Reductions of *E. coli* O157:H7 (log cfu/g)	Iceberg: 0.7 – 0.9 Romaine: 1.0 – 1.2 Spinach: 0.9 – 1.3	0.75	= RiskPert(0.6,1,1.4)	= RiskUniform(0.29,0.67)

Addendum 3. Input data for the reduction of E.coli (O157:H7) on leafy greens ('microbiological food safety' sub-criterion) for the wash water disinfection with NaOCl intervention option.

Characteristics of study	**Luo et al. 2012**	**Davidson, Buchholz, and Ryser 2013**	**Davidson et al. 2014**	**Bozkurt et al. 2021**
Microorganism	*E. coli* O157:H7	*E. coli* O157:H7	*E. coli* O157:H7	*E. coli* O157:H7
Leafy green type	Baby spinach and iceberg lettuce	Iceberg lettuce	Iceberg lettuce	Fresh – cut cos lettuce
Study dimension	Semi-commercial scale: 3200 L, 2 wash baths. 540 kg/3200 L	Small scale commercial processing plant: 890 L water tank, 5.4 kg batches	Small scale commercial processing plant: 890 L water tank, 5.4 kg batches	Probabilistic risk assessment model
Processing steps	Shredding, washing (2X)	Shredding, conveyed to flume tank, dewatering (shaker table), dewatering (centrifuge)	Shredding, conveyed to flume tank, dewatering (shaker table), dewatering (centrifuge)	/
Inoculation level and method	Targeted initial contamination of Spinach: 2 x 1E5 CFU/g. Spray inoculation. 0.2% spinach to lettuce ratio	Immersion inoculation. Level: 1E6 CFU/g	Immersion inoculation. Level: 1E6 CFU/g	/
Water	Water + NaOCl: target of 20 mg/L free chlorine	Water + NaOCl: 30 mg/L available chlorine	Water + NaOCl: 65 mg/L available chlorine; 0.31 – 2.15 mg/L FC	Water + NaOCl
Reductions of E. coli O157:H7 (log cfu/g)	Spinach: 0.8 – 0.9	0.77	0.9 – 1.2	= RiskNormal(0.87,0.32, RiskTruncate(0.36,1.38))
Remarks	/	/	Different organic loads: 0, 2.5, 5 or 10 % wt/vol	/

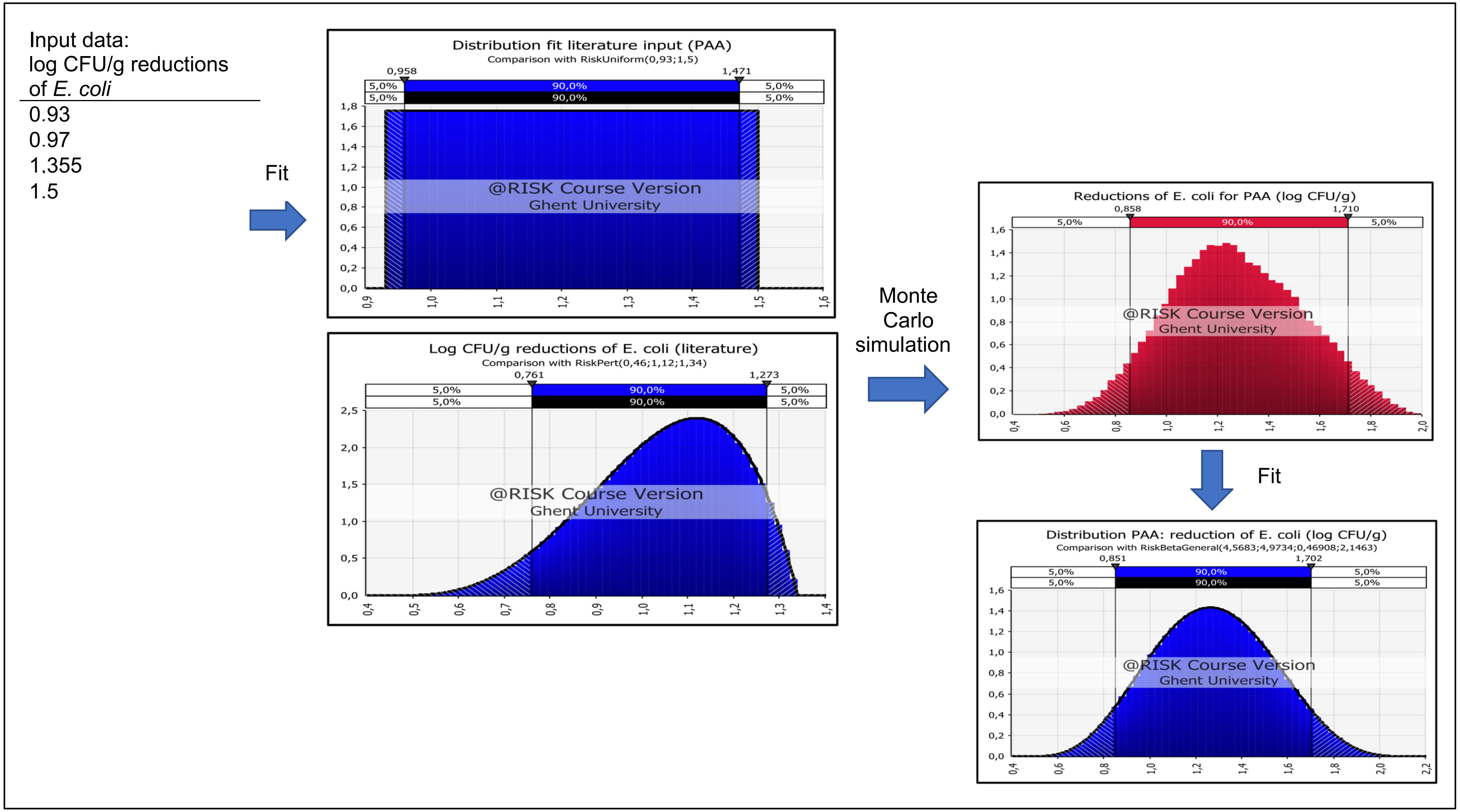
Addendum 4. Schematic overview of steps taken in development of the probabilistic distribution for the log CFU/g reductions of E. coli (O157:H7) ('microbiological food safety' sub-criterion) for the 'disinfection with NaOCl' option.



Addendum 5. Input data for the reduction of E.coli (O157:H7) on leafy greens ('microbiological food safety' sub-criterion) for the wash water disinfection with PAA intervention option.

Characteristics of study	**Davidson et al. 2013**	**Davidson, Kaminski-Davidson, and Ryser 2017**	**Banach et al. 2020**	**Bozkurt et al. 2021**
Microorganism	*E. coli* O157:H7	*E. coli* O157:H7	(generic) *E. coli*	*E. coli* O157:H7
Leafy green type	Iceberg lettuce	Iceberg lettuce	'Batavia' lettuce, endive, 'Lollo Rossa' lettuce	Fresh – cut cos lettuce
Study dimension	Small scale commercial processing plant: 890 L water tank, 5.4 kg batches	Small scale commercial processing plant: 890 L water tank, 5.4 kg batches	Industrial scale**:** 3500 L wash tank, 800 kg batch	Probabilistic risk assessment model
Processing steps	Shredding, conveyed to flume tank, dewatering (shaker table), dewatering (centrifuge)	Shredding, conveyed to flume tank, dewatering (shaker table), dewatering (centrifuge)	Coring and hand pre-trim, shredding, step conveyor, infeed vibrator, washer, rinsing, centrifuge	/
Inoculation level and method	Immersion inoculation. Level: 1E6 CFU/g.	Immersion inoculation. Level: 1E6 cfu/g.	Start suspension: 10^9 cfu/mL was added to the wash water	/
Water	Potable water + PAA: 30 mg/L	Potable water + PAA: 50 mg/L	Potable water + PAA: 75 mg/L	Potable water + PAA
Reductions of E. coli O157:H7 (log cfu/g)	0.93	0.97 – 1.74	~ 1.5	$= \text{RiskPert}(0.46,1.12,1.34)$
Remarks	/	1.74 is considered an outlier. Instead 1.355 (the average of 0.97 and 1.74 is used).	/	/

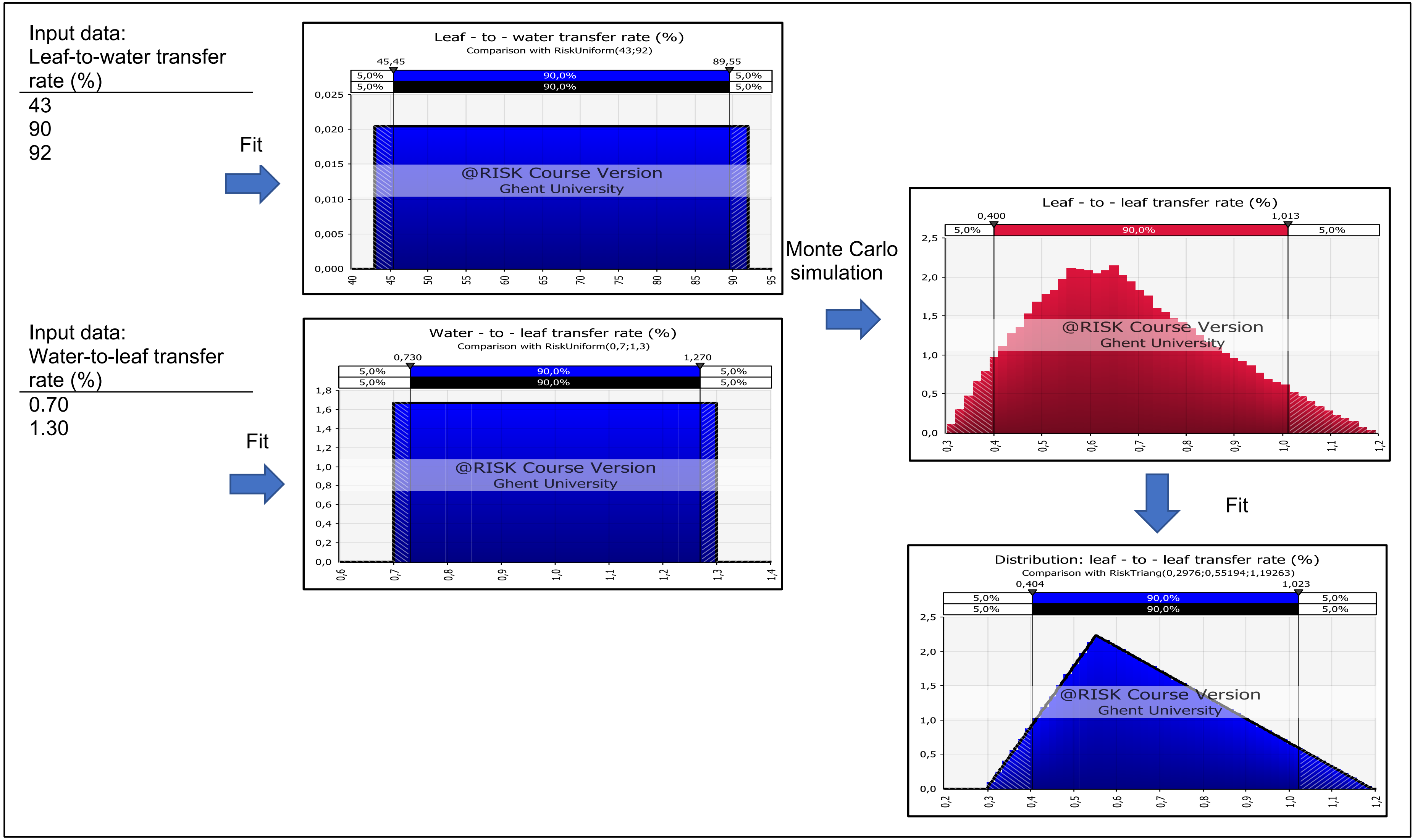
Addendum 6. Schematic overview of steps taken in development of the probabilistic distribution for the log CFU/g reductions of E. coli (O157:H7) ('microbiological food safety' sub-criterion) for the 'disinfection with PAA option.



Addendum 7. Input data for the leaf-to-leaf transfer rate of E. coli (O157:H7) ('microbiological food safety' sub-criterion) for washing with potable water.

Characteristics of study	**Holvoet et al. 2014**	**Deng et al. 2014**	**Buchholz et al. 2012a**
Microorganism	*E. coli, E. coli* O157, MS2 phage, murine Norovirus	*E. coli* 8 O – types and 2 surrogates	*E. coli* O157
Leafy green type	Butter lettuce	Romaine lettuce	Iceberg & romaine lettuce and baby spinach
Study dimension	Laboratory scale: 4 L washing tank; 0.2 kg batch	Laboratory scale: 0.03 L washing volume; 16 cm^2 batch	Pilot plant scale: 890 L water tank, 22.7 kg batches
Processing steps	Cutting, washing (2 WB), dewatering (spinner), rinsing	Cutting, washing	Cutting, washing, dewatering (centrifuge)
Inoculation level and method	Submersion inoculation. Level: 1E4 CFU/g	Submersion inoculation. Level: 1E4 CFU/cm^2	Dip inoculation. Levels: 1E2, 1E4, 1E6 CFU/g
Water	Sanitiser-free water	Deionized water	Sanitiser-free tap water
Transfer rate: from leaf to water (%)	43%	92%	90%
Transfer rate: from water to leaf (%)	1 ± 0.3%	/	/

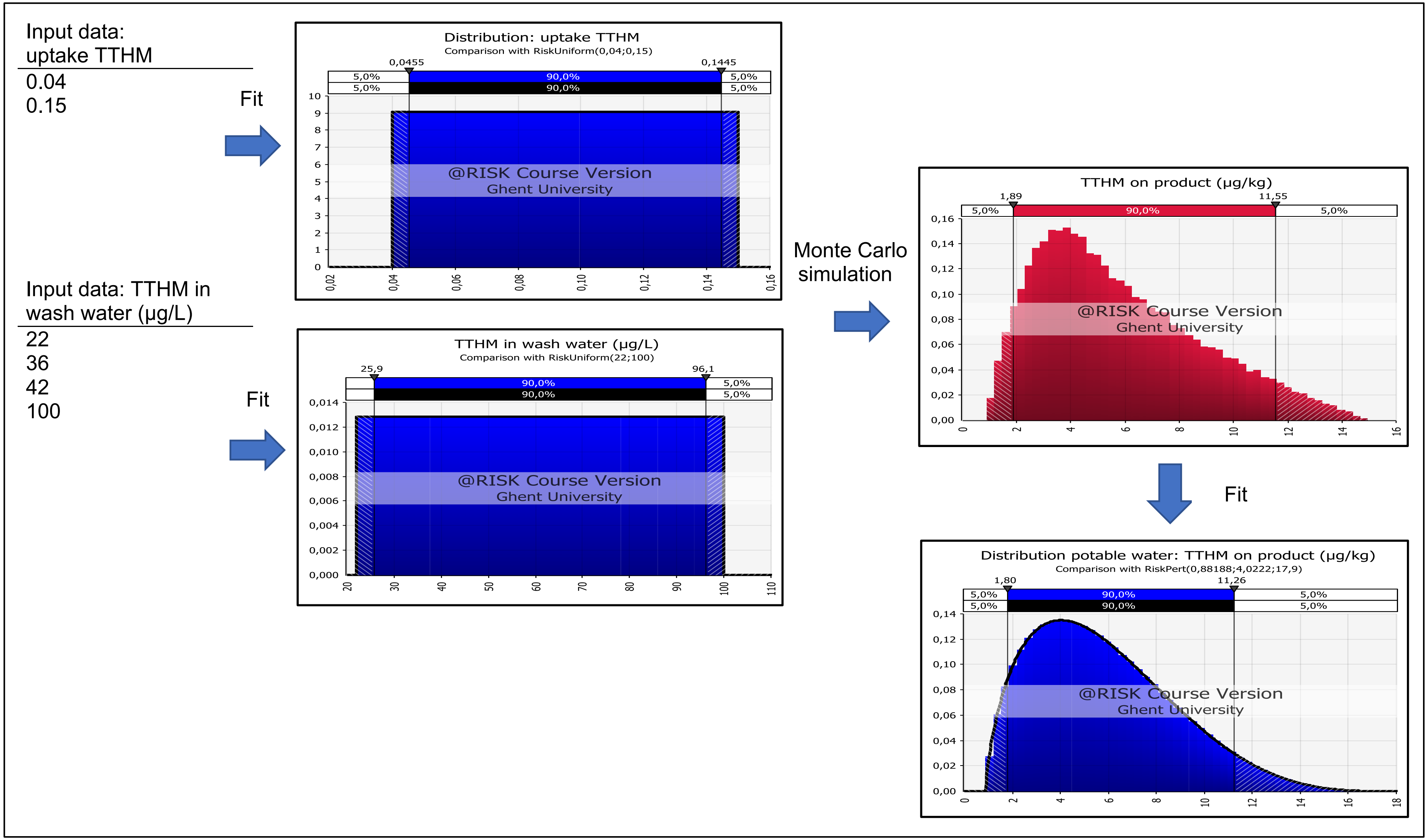
Addendum 8. Schematic overview of steps taken in development of the probabilistic distribution for the leaf-to-leaf transfer rate of E. coli (O157:H7) (%) ('microbiological food safety' sub-criterion) for washing with potable water.



Addendum 9. Input data for concentration of TTHMs on the end product (µg/kg) ('chemical food safety' sub-criterion) for washing with potable water.

Characteristic of study	Gómez-López et al. 2014	Tudela, López-Gálvez, Allende, Hernández, et al. 2019	Potable water: Directive (EU) 2020/2184
DBP	TTHMs	TTHMs	TTHMs
Leafy green type	Baby spinach	Iceberg lettuce & baby leaves	/
Study dimension	Pilot plant: 30 L wash tank Water recirculation: 750 L/h	Pilot plant: 30 L wash tank	/
Processing steps	Artificial process water	Concentrated process water	/
Water	Potable water	Potable water	/
Concentration in water	42 µg/L	Lettuce: 22 µg/L Baby leaves: 36 µg/L	100 µg/L

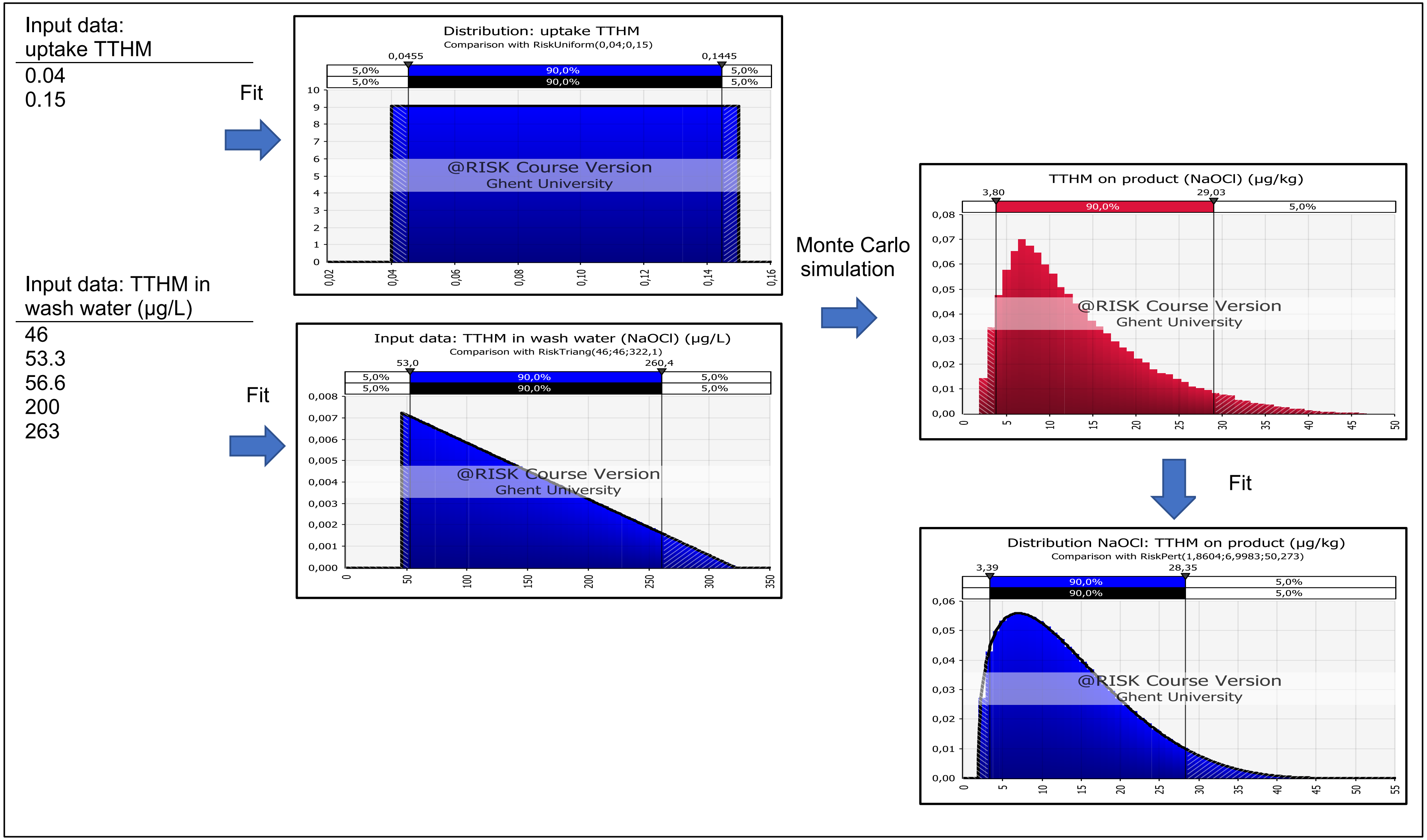
Addendum 10. Schematic overview of steps taken in development of the probabilistic distribution for concentration of TTHMs on the end product (µg/kg) ('chemical food safety' sub-criterion) for washing with potable water.



Addendum 11. Input data for concentration of TTHMs on the end product (µg/kg) ('chemical food safety' sub-criterion) for the wash water disinfection with NaOCl intervention option.

Characteristic of study	**Gil et al. 2019**	**Tudela, López-Gálvez, Allende, Hernández, et al. 2019**
DBP	TTHMs	TTHMs
Leafy green type	Shredded iceberg lettuce	Iceberg lettuce & baby leaves
Study dimension	Pilot plant: 30 L	Pilot plant: 30 L
Processing steps	Cutting, washing in treated wash water, dewatering (spinner)	Concentrated process water
Water	Water + NaOCl NaClO over 70 mg/L to reach a residual FC of 5 mg/L for lettuce Measured concentration of FC: 3 mg/L	Potable water + NaOCl Different FC concentrations: 10, 20, 30 mg/L
Concentration in water (µg/L)	200	Lettuce: 46, 53.3, 56,6 Baby leaves: 263, 309, 348
Concentration on product	2.8 µg/kg	**/**
Remarks	No rinsing	Concentrations over 300 µg/L were considered outliers

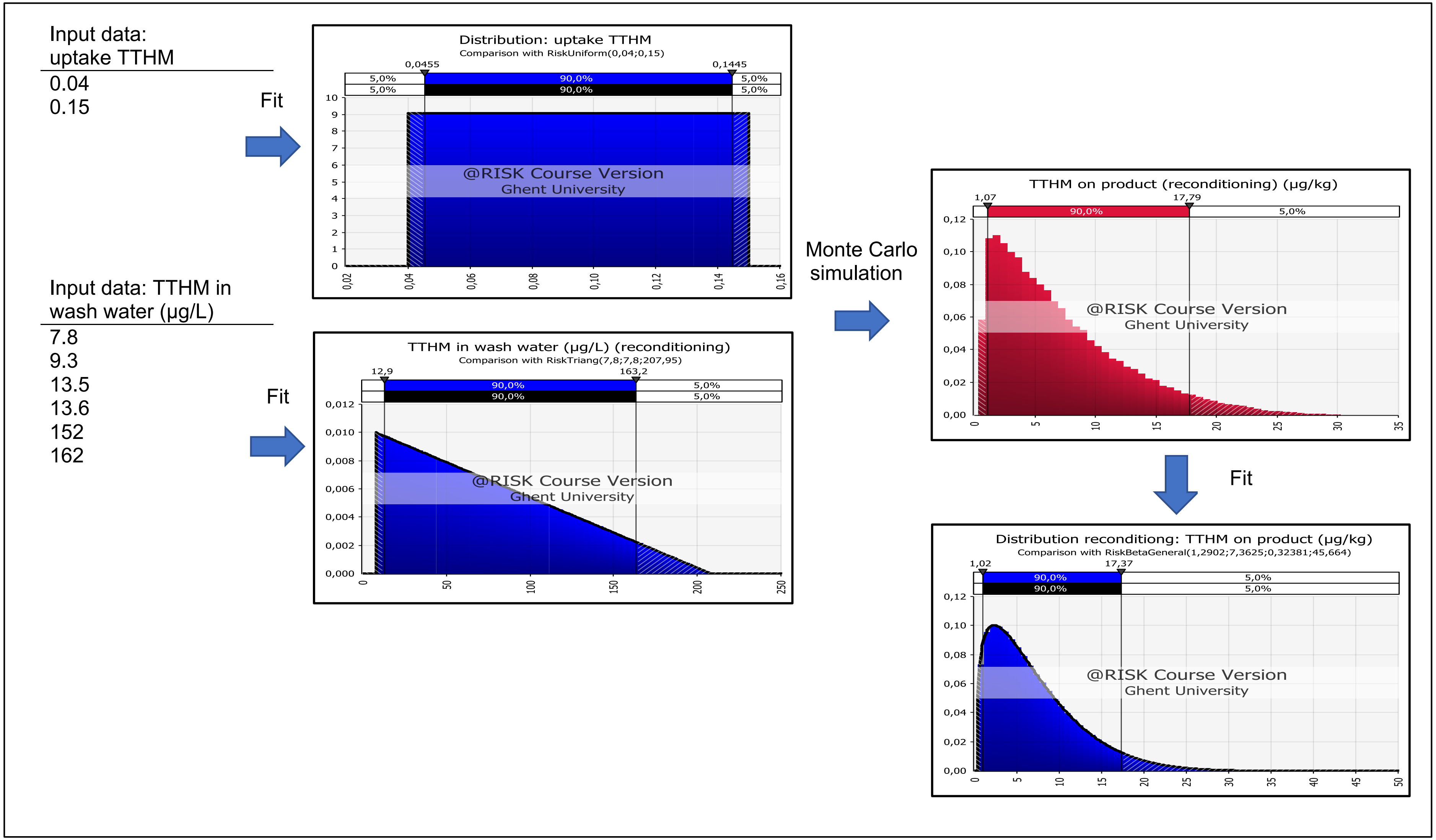
Addendum 12. Schematic overview of steps taken in development of the probabilistic distribution for concentration of TTHMs on the end product (µg/kg) ('chemical food safety' sub-criterion) for the wash water disinfection with NaOCl intervention option.



Addendum 13. Input data for concentration of TTHMs on the end product (µg/kg) ('chemical food safety' sub-criterion) for the reconditioning with NaOCl intervention option.

Characteristic of study	**Van Haute et al. 2013**	**Shen et al. 2016**
DBP	TTHMs	TTHMs
Leafy green type	Lettuce juice	Lettuce juice
Study dimension	Laboratory scale.	Laboratory scale
Processing steps	Disinfection of industrial process water & simulated wash water with NaOCl. Contact time: 30 minutes.	Disinfection of simulated wash water with NaOCl.
Water	Water + NaOCl. Chlorine: 100 & 150 mg/L	Potable water + NaOCl. FC of 80 mg/L at the start. Continuously adding NaOCl, when FC < 2 mg/L
Concentration in water	7.8, 9.3, 13.6, 13.5 µg/L	At a contact time of 6 min: 162.75 µg/L At a contact time of 13 min: 152.3 µg/L

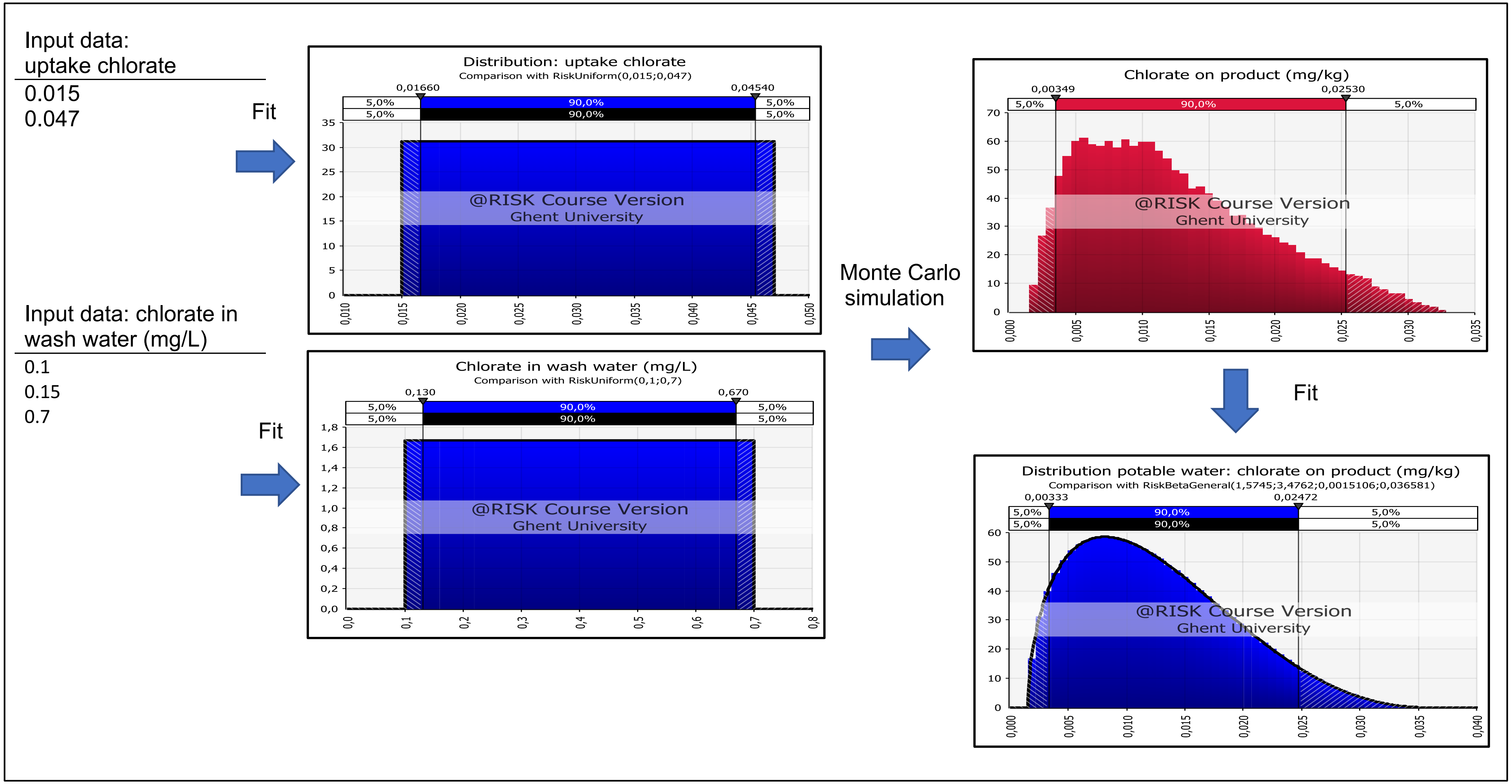
Addendum 14. Schematic overview of steps taken in development of the probabilistic distribution for concentration of TTHMs on the end product (µg/kg) (‘chemical food safety’ sub-criterion) for the reconditioning with NaOCl intervention option.



Addendum 15. Input data for concentration of chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion) for washing with potable water.

Characteristic of study	Tudela, López-Gálvez, Allende, Hernández, et al. 2019	Directive (EU) 2020/2184
DBP	Chlorate	Chlorate
Leafy green type	Iceberg lettuce & baby leaves	/
Study dimension	Pilot plant: 30 L	/
Processing steps	Concentrated process water	/
Water	Potable water	/
Concentration in water	Lettuce: 0.1 mg/L Baby leaves: 0.15 mg/L	0.70 mg/L (if a disinfection method that generates chlorate is applied)

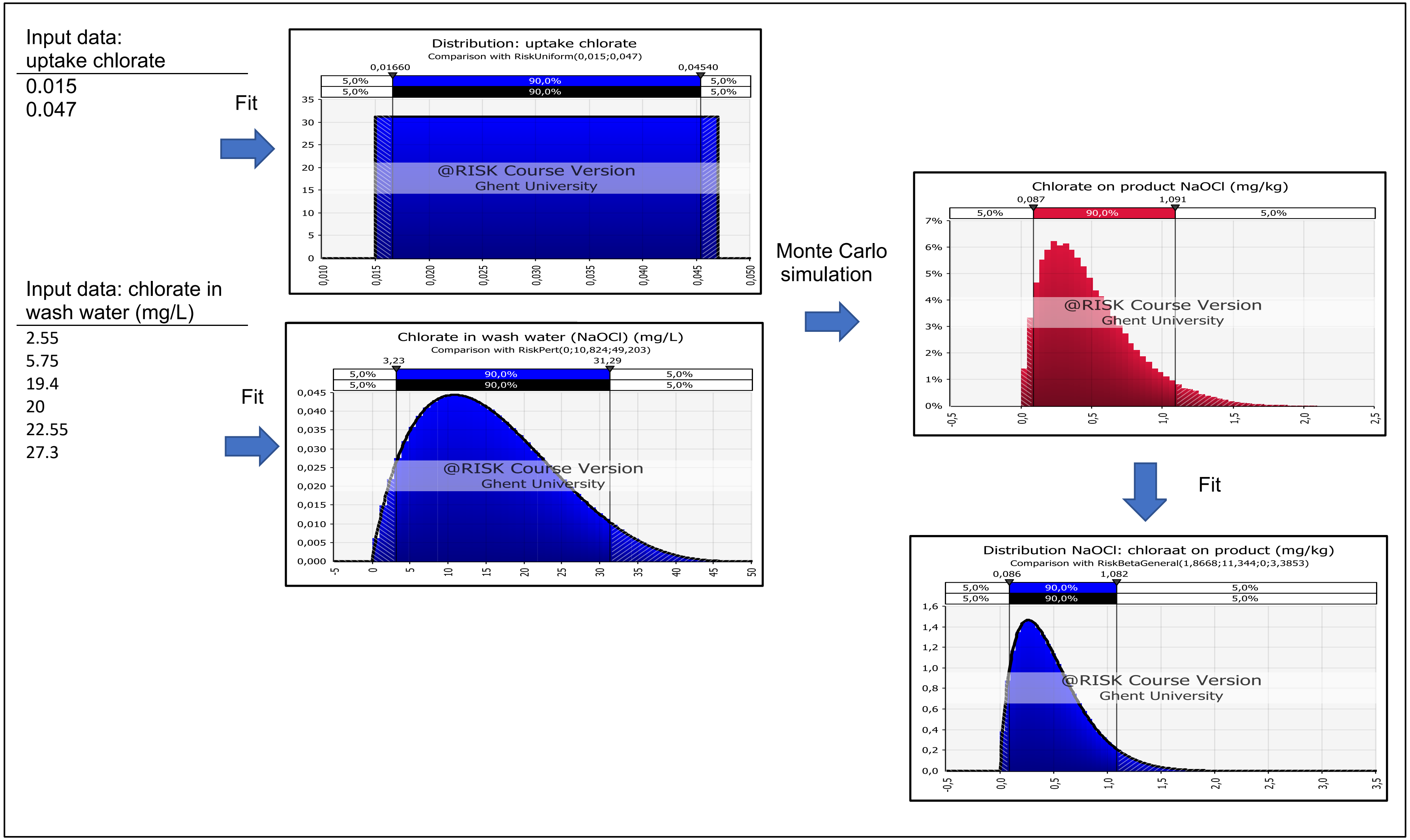
Addendum 16. Schematic overview of steps taken in development of the probabilistic distribution for concentration of chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion) for washing with potable water.



Addendum 17. Input data for concentration of chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion) for the wash water disinfection with NaOCl intervention option.

Characteristic of study	**Gil et al. 2016**	**Tudela, López-Gálvez, Allende, Hernández, et al. 2019**	**Gil et al. 2019**
DBP	Chlorate	Chlorate	Chlorate
Leafy green type	Iceberg lettuce	Iceberg lettuce & baby leaves	Shredded iceberg lettuce en spinach
Study dimension	Commercial processing facility. Tank containing 1000 L water. Water replenishment: 500 – 700 L/h	Pilot plant: 30 L	Pilot plant: 30 L
Processing steps	Shredding, washing, rinsing (shower), dewatering (centrifuge)	Concentrated process water	Cutting, washing in treated wash water, dewatering (spinner)
Water	Water + NaOCl. FC: 1, 5, 80 mg/L	Water + NaOCl. FC: 10, 30 mg/L	Water + NaOCl NaClO over 70 mg/L to reach a residual FC of 5 mg/L for lettuce Measured concentration of FC: 3 mg/L
Concentration in water (mg/L)	After 4 hours of processing: 19.4 After 6 hours of processing: 27.3	FC: 10 mg/L Lettuce: 22.55 Baby leaves: 2.55 FC: 30 mg/L Lettuce: 40.4 (not included) Baby leaves: 5.75	20
Concentration on product (mg/kg)	2.0, 4.5	/	0.30
Remarks	Low replenishment rate	40.4 mg/L was considered an outlier	No rinsing

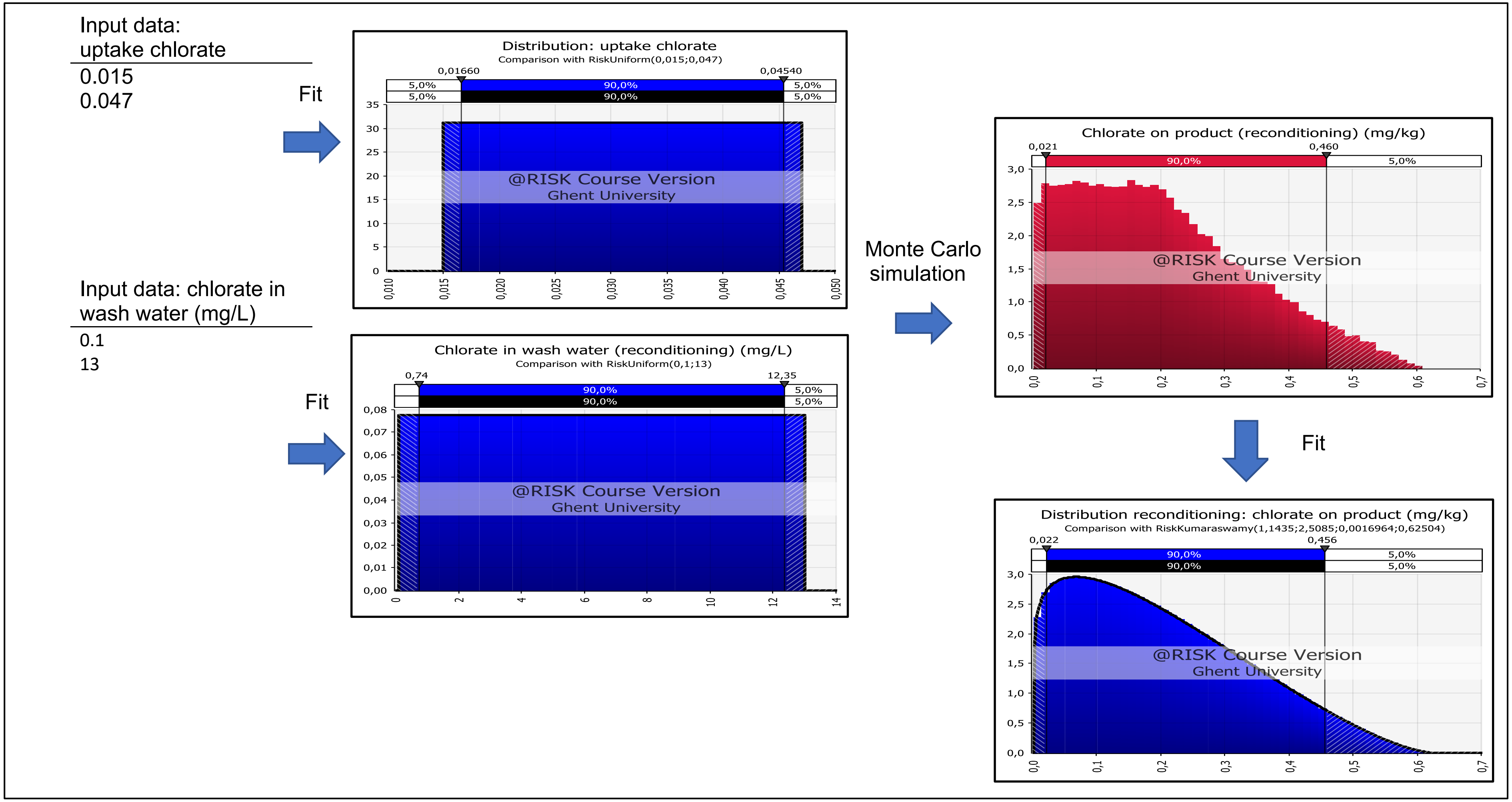
Addendum 18. Schematic overview of steps taken in development of the probabilistic distribution for concentration of chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion) for the wash water disinfection with NaOCl intervention option.



Addendum 19. Input data for concentration of chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion) for the reconditioning with NaOCl intervention option.

Characteristic of study	**Gil et al. 2016**
DBP	Chlorate
Leafy green type	Lettuce juice
Study dimension	Pilot process: 10 L
Processing steps	Artificial process water. Processing time: 6 h
Water	Water + NaOCl FC: 3, 20 – 25
Concentration in water (mg/L)	0 – 13

Addendum 20. Schematic overview of steps taken in development of the probabilistic distribution for concentration of chlorate on the end product (mg/kg) ('chemical food safety' sub-criterion) for the reconditioning with NaOCl intervention option.



Addendum 21. Final probabilistic distributions for the 'microbiological food safety' and 'chemical food safety' criterion.

	Potable water	WW disinfection (NaOCl)	WW disinfection (PAA)	Reconditioning (NaOCl)
Log reductions CFU/g of *E. coli* (O157:H7)	= RiskPert(0.13,0.37,1.22)	= RiskKumaraswamy(1.86,6.91, 0.53,1.91)	= RiskBetaGeneral(4.57,4.97, 0.47,2.15)	= RiskPert(0.13,0.37,1.22)
Leaf – to – leaf transfer rate (%)	= RiskTriang(0.298,0.55,1.19)	0	0	=RiskTriang(0.298,0.55, 1.19)
TTHMs on the end product (µg/kg)	= RiskPert(0.882,4.022,17.9)	= RiskPert(1.86,7.79,70.71)	= RiskPert(0.882,4.022,17.9)	=RiskBetaGeneral(1.29,7. 36, 0.32, 45.66)
Chlorate on the end product (mg/kg)	= RiskBetaGeneral(1.57,3.48, 0.0015,0.037)	= RiskBetaGeneral(1.87,11.34, 0,3.39)	= RiskBetaGeneral(1.57,3.48, 0.0015,0.037)	= RiskKumaraswamy(1.14, 2.51,0.0017,0.63)

Addendum 22. Form provided to experts for the collection of qualitative input data for the 'occupational health and safety' sub-criterion.

	Potable water	**Wash water disinfection (NaOCl)**	**Wash water disinfection (PAA)**	**Reconditioning (NaOCl)**
Elevated ambient concentrations of hazardous chemical compounds?	No	Yes. Possible formation of ambient gaseous chlorine at low pH (Sam Van Haute et al. 2015). Chloramines can be formed, producing irritating vapors (De Corato 2020).	Yes. Besides corrosion and/or irritation of the skin and mucous membranes due to local effects at the site of first contact, peracetic acid causes sensory irritation of the respiratory tract (ECHA 2015).	Yes. Possible formation of ambient gaseous chlorine at low pH (Sam Van Haute et al. 2015). Chloramines can be formed, producing irritating vapors (De Corato 2020).
Special (additional) requirements necessary to protect workers' health and safety?	No	Yes. Where exposure to the concentrated product is possible (i.e. mixing & loading, maintenance of pumping system) personal protective equipment and respiratory protective equipment is necessary (ECHA 2016). Wear protective gloves, protective clothes, eye/face protection. Effective exhaust ventilation system. If necessary, respiratory	Yes. Necessity of personal protective equipment and/or respiratory protective equipment against local effects (irritation and corrosion of skin) dependent on the type of application (closed system or not) (ECHA 2015). **Product as sold:** Protective gloves, eye protection/face protection, skin protection, respiratory protection, hygiene measures. **At use (dilution: 0.0036 % - 0.95 %):** Effective exhaust ventilation system. Maintain air concentrations below occupational exposure standards. No eye protection, hand protection,	Yes. Where exposure to the concentrated product is possible (i.e. mixing & loading, maintenance of pumping system) personal protective equipment and respiratory protective equipment is necessary (ECHA 2016). Wear protective gloves, protective clothes, eye/face protection. Effective exhaust ventilation system. If necessary, respiratory protection (mask type B) (Brenntag 2013)

		protection (mask type B) (Brenntag 2013).	skin protection or respiratory protection needed (Ecolab Inc. 2017).	
Additional safety management actions required for transport, handling and storage of hazardous chemicals?	No	Store locked up, in original packaging, protect from sunlight, store at T < 50°C. Keep in a cool ventilated place, away from combustible material, strong acids and reducing agents (Labaz Hygiene Concept 2016).	Store locked up, in original packaging, protect from sunlight, store at T: - 10°C – 50°C. Keep in a cool ventilated place, away from reducing agents, strong bases and combustible material (SDS Tsunami100). At concentrations of 15% the major concerns are fire and explosion hazards and reactivity issues, as PAA reacts violently with soft metals such as brass, copper, iron, and zinc (BECHTOLD 2016).	Store locked up, in original packaging, protect from sunlight, store at T < 50°C. Keep in a cool ventilated place, away from combustible material, strong acids and reducing agents (Labaz Hygiene Concept 2016).
The washing procedure has the possibility of negatively impacting the health and safety of workers.	**Score**	**Score**	**Score**	**Score**

Addendum 23. Form provided to experts for the collection of qualitative input data for the 'ease of implementation' sub-criterion.

	Potable water	**Wash water disinfection (NaOCl)**	**Wash water disinfection (PAA)**	**Reconditioning (NaOCl)**
The complexity of the technology and required amount of operator training and skills?	Low	Low to moderate. Maintenance and operation are relatively simple to execute (Van Haute et al. 2013). Maintaining an adequate free chlorine concentration is challenging during fresh-cut produce washing. Proper chlorination management for industrial produce washing is still challenging (Luo et al. 2018).	Low. Maintenance and operation are relatively simple to execute (Van Haute et al. 2013). The use of automated chemical monitoring and dosing is possible, since PAA is less sensitive to the presence of organic matter and maintaining residual disinfectant in the wash bath in order to prevent cross-contamination is achieved more easily (Vandekinderen et al. 2009).	Low to moderate. Maintenance and operation are relatively simple to execute A higher degree of automation reduces the needed operator attention (Van Haute et al. 2013). Since the disinfection happens off-line, no specific residual disinfectant concentration in the wash water is necessary in order to prevent cross-contamination.
Degree of structural modifications needed when installing a new system?	Low	Low to moderate	Low to moderate	High. Water recycling requires building and setting up one or more recycling units (Manzocco et al. 2015).
Maintenance of equipment?	NA	Low to moderate. Issues: corrosion of equipment (Van Haute et al. 2013). Corrosiveness is high, particularly on iron and mild steel (De Corato 2020).	Low. No corrosion at levels < 80 mg/L (Ramos et al. 2013). Pure aluminium, stainless steel, and tin-plated iron are resistant to PAA; but plain steel, galvanized iron, copper, brass, and	Low to moderate. Issues: corrosion of equipment (Van Haute et al. 2013). Corrosiveness is high, particularly on iron and mild steel (De Corato 2020).

			bronze are susceptible to reaction and corrosion (Kitis 2004).	
The washing methodology is easy to be implemented in the industry.	**Score**	**Score**	**Score**	**Score**

Addendum 24. Form provided to experts for the collection of qualitative input data for the 'robustness' sub-criterion.

	Potable water	Wash water disinfection (NaOCl)	Wash water disinfection (PAA)	Reconditioning (NaOCl)
Is there a good control of the washing process and is it reliable, meaning that it produces a constant output regardless of water quality, time and/or technological failures?	Efficacy is affected by: - water refreshment rate - product:water volume ratio - temperature (Holvoet et al. 2014)	Efficacy is affected by: - pH - presence of organic matter - temperature - turbidity - concentration of disinfectant - contact time (Gil et al. 2009; Manzocco et al. 2015)	Low sensitivity to: - organic load - pH - temperature (Manzocco et al. 2015) Efficacy is affected by: - concentration of disinfectant - contact time (Gil et al. 2009)	Efficacy is affected by: - pH - presence of organic matter - temperature - turbidity - concentration of disinfectant - contact time (Gil et al. 2009; Manzocco et al. 2015)
Possibility of reliable, real – time monitoring?	NA	- Temperature - pH - Online ORP control system: reflects the concentration of free chlorine and state (Van Haute et al. 2013) Approaches for monitoring the organic load:	- Temperature - PAA (Van Haute et al. 2013) Options for PAA measurement exist as the following: - Color changing test strips	- Temperature - pH - Online ORP control system: reflects the concentration of free chlorine and state (Van Haute et al. 2013) Approaches for monitoring the organic load:

		- COD (= direct measurement of organic load) - TSS - Turbidity Monitoring the free chlorine level: - Color changing test strips - Colorimetric titration methods - N,N-diethyl-p-phenylenediamine (DPD) methods - Manual color wheels - Photometric instruments - Indirect electronic probes - Ion-specific electronic probes (Gombas et al. 2017)	- Colorimetric methods - Titration methods; iodometric method is the most direct and rapid - Photometric instruments - Amperometric sensors (Gombas et al. 2017)	- COD (= direct measurement of organic load) - TSS - Turbidity Monitoring the free chlorine level: - Color changing test strips. - Colorimetric titration methods - N,N-diethyl-p-phenylenediamine (DPD) methods - Manual color wheels - Photometric instruments - Indirect electronic probes - Ion-specific electronic probes (Gombas et al. 2017)
This washing methodology is reliable and allows for adequate monitoring and control.	**Score**	**Score**	**Score**	**Score**

Addendum 25. Form provided to experts for the collection of qualitative input data for the 'wastewater discharge' sub-criterion.

	Potable water	Wash water disinfection (NaOCl)	Wash water disinfection (PAA)	Reconditioning (NaOCl)
Degree of accumulation of chemicals?	Low, due to the high refreshment rates of the wash water.	×	×	High. Recycling of wash water could lead to the accumulation of some commonly used pesticides such as imidacloprid, tebuconazole, chlorpropham and others (Aliste et al. 2020; Camara et al. 2017).
This washing procedure allows for the accumulation of components in the wash water during prolonged water use, and therefore negatively affects subsequent wastewater discharge.	**Score**	**Score**	**Score**	**Score**

'×': insufficient evidence found in literature

Addendum 26. Form provided to experts for the collection of qualitative input data for the 'international/national authorities' sub-criterion.

	Potable water	Wash water disinfection disinfection (NaOCl)	Wash water disinfection disinfection (PAA)	Reconditioning (NaOCl)
Chemical parameters (e.g., disinfection by – products or residues of disinfectants)	**EU:** Directive (EU) 2020/2184: Chlorate: 0.25 mg/L (0.70 mg/L if a disinfection method is applied that generates chlorate, such as ClO_2) Total pesticides: 0.50 µg/L Total THMs: 100 µg/L HAAs: 60 µg/L **BE:** Regulation on potable water quality (KB 14/01/2002): Chemical parameters: Total pesticides 0,50 µg/L Total THMs: 100 µg/L Chemical indicator parameters: free chlorine residues: 250 µg/L	**EU:** EC Regulation (EU) 2020/749:MRL for chlorate on leafy greens: 0.7 mg/kg. **BE:** Belgian autocontrol guide (G – 014): Wash water should be of potable water quality (see chemical requirements for potable water). When processing aids are used, the use should be validated and no (harmful) residues can remain on the vegetables. The use of chlorine should be minimized. The maximum concentration of chlorine in potable water is 250 µg/L. Chlorate and other disinfection byproducts should be measured (Ch. 8 HACCP).	**EU:** No residues are anticipated to be present on foods that were treated with PAA. Residues of acetic acid are expected to remain on treated foods if foods are not further washed or treated (EFSA Panel on Biological Hazards (BIOHAZ) 2014a) **BE:** Belgian autocontrol guide (G – 014): Wash water should be of potable water quality (see chemical requirements for potable water). (SciCom FASFC 2017): No residues of H_20_2 are expected on foods treated with PAA, due to the instability of H_2O_2.	**EU:** EC Regulation (EU) 2020/749: MRL for chlorate on leafy greens: 0.7 mg/kg **BE:** Belgian autocontrol guide (G – 014): Wash water should be of potable water quality (see chemical requirements for potable water). If ClO^- or ClO_2^- are used as disinfectants, the free chlorine levels should not exceed 250 µg/L. If higher concentrations are applied as processing aids, the process should be controlled and validated on the presence of chemical residues (5.8.4).

Water quality: microbiological parameters	**EU:** Revised drinking water Directive (EU) 2020/2184: Intestinal enterococci: 0/100 ml *E. coli:* 0/100 ml **BE:** Regulation on potable water quality (KB 14/01/2002): *E. coli:* 0/100 ml Enterococci: 0/100 ml Pathogenic microorganisms and parasites: absent	**BE:** Belgian autocontrol guide (G – 014): Wash water should be of potable water quality (see microbiological requirements for potable water).	**BE:** Belgian autocontrol guide (G – 014): Wash water should be of potable water quality (see microbiological requirements for potable water).	**BE:** Belgian autocontrol guide (G – 014): Wash water should be of potable water quality (see microbiological requirements for potable water).
Legal status of disinfectants and regulations/guidelines on the use of disinfectants as processing aids	NA	**EU:** European Commission 2017b: The definition of processing aids in fresh fruits and vegetables is harmonised within the EU Regulation (EC Regulation 1333/2008). Disinfecting agents should be approved according to Regulation (EU) 528/2012: Processing aids shall be used under conditions of GMP. **BE:** Belgian autocontrol guide (G – 014): Processing aids can be applied to control the	**EU:** European Commission 2017b: The definition of processing aids in fresh fruits and vegetables is harmonised within the EU (EC Regulation 1333/2008). Disinfecting agents should be approved according to Regulation (EU) 528/2012: Processing aids shall be used under conditions of GMP. **BE:** Belgian autocontrol guide (G – 014): Processing	**EU:** European Commission 2017b: The definition of processing aids in fresh fruits and vegetables is harmonised within the EU (EC Regulation 1333/2008). Disinfecting agents should be approved according to Regulation (EU) 528/2012: Processing aids shall be used under conditions of GMP. **BE:** Belgian autocontrol guide (G – 014):

		microbiological load. Dosing of disinfectants should be measured continuously to prevent the presence of chemical hazards, off - flavours or damage to products. When processing aids are used, the use should be validated and no (harmful) residues can remain on the vegetables. The use of chlorine should be minimized. The maximum concentration of chlorine in potable water is 250 μg/L. Chlorate and other disinfection byproducts should be measured (Ch. 8 HACCP). **FR:** Arreté du 19 octobre 2006: Free chlorine: maximum 80 ppm in the wash bath. AOX < 200 μg/kg. Rinsing is obligated.	aids can be applied to control the microbiological load. Dosing of disinfectants should be measured continuously to prevent the presence of chemical hazards, off - flavours or damage to products. When processing aids are used, the use should be validated and no (harmful) residues can remain on the vegetables (Ch. 8 HACCP). **FR:** Arreté du 19 octobre 2006: Technically unavoidable dose. Rinsing is obligated.	When water is reconditioned to potable water, disinfectants can be applied to adhere to the microbiological requirements of potable water. If ClO^- or ClO_2^- are used as disinfectants, the free chlorine levels should not exceed 250 μg/L. If higher concentrations are applied, as processing aids, the process should be controlled and validated on the presence of chemical residues (5.8.4). **FR:** Arreté du 19 octobre 2006: NaOCl as a reconditioning agent is not mentioned.
Microbiological criteria for leafy greens	**EU: EC Regulation 2073/2005** Food safety criteria: - *Listeria monocytogenes:* absent in 25 g (100 CFU/g during shelf-life) - *Salmonella:* absent in 25 g			

	- Process hygiene criterion: - *E. coli*: 100 – 1000 cfu/g **BE: recommended values FASFC and advise 11-2017 (SciCom FASFC 2017)**: - Process hygiene indicator: - *E. coli:* 100 – 1000 cfu/g - *Campylobacter:* absent in 25 g - Food safety criterion: - *Listeria monocytogenes:* absent in 25 g (m = M = 100 cfu/g during shelf-life) - *Salmonella:* absent in 25 g - Food safety indicator: - Norovirus: absent in 25 g - Hepatitis A virus: absent in 25 g - VTEC: absent in 25 g			
Regulations concerning the washing and potential disinfection (of the wash water) of leafy greens are harmonised on an international, European and Belgian level.	**Score**	**Score**	**Score**	**Score**

Addendum 27. Qualitative input data: expert scores (5-point Likert-type answer scale)

	Potable water	Wash water disinfection (NaOCl)	Wash water disinfection (PAA)	Reconditioning (NaOCl)
Occupational health and safety (min → best)	1	4	4	3
	1	4	4	4
	1	4	4	1
Ease of implementation (max → best)	5	3	3	4
	5	5	4	5
	5	4	4	5
Robustness (max → best)	1	5	5	2
	2	5	5	2
	1	5	3	1
Wastewater discharge (min → best)	3	5	3	4
	NA	NA	NA	NA
	1	5	5	4
Consumer acceptance (max → best)	5	1	2	4
	5	1	3	2
	5	3	3	3
Pressure from national/international authorities (max → best)	4	1	1	3
	5	1	1	1
	4	1	1	1

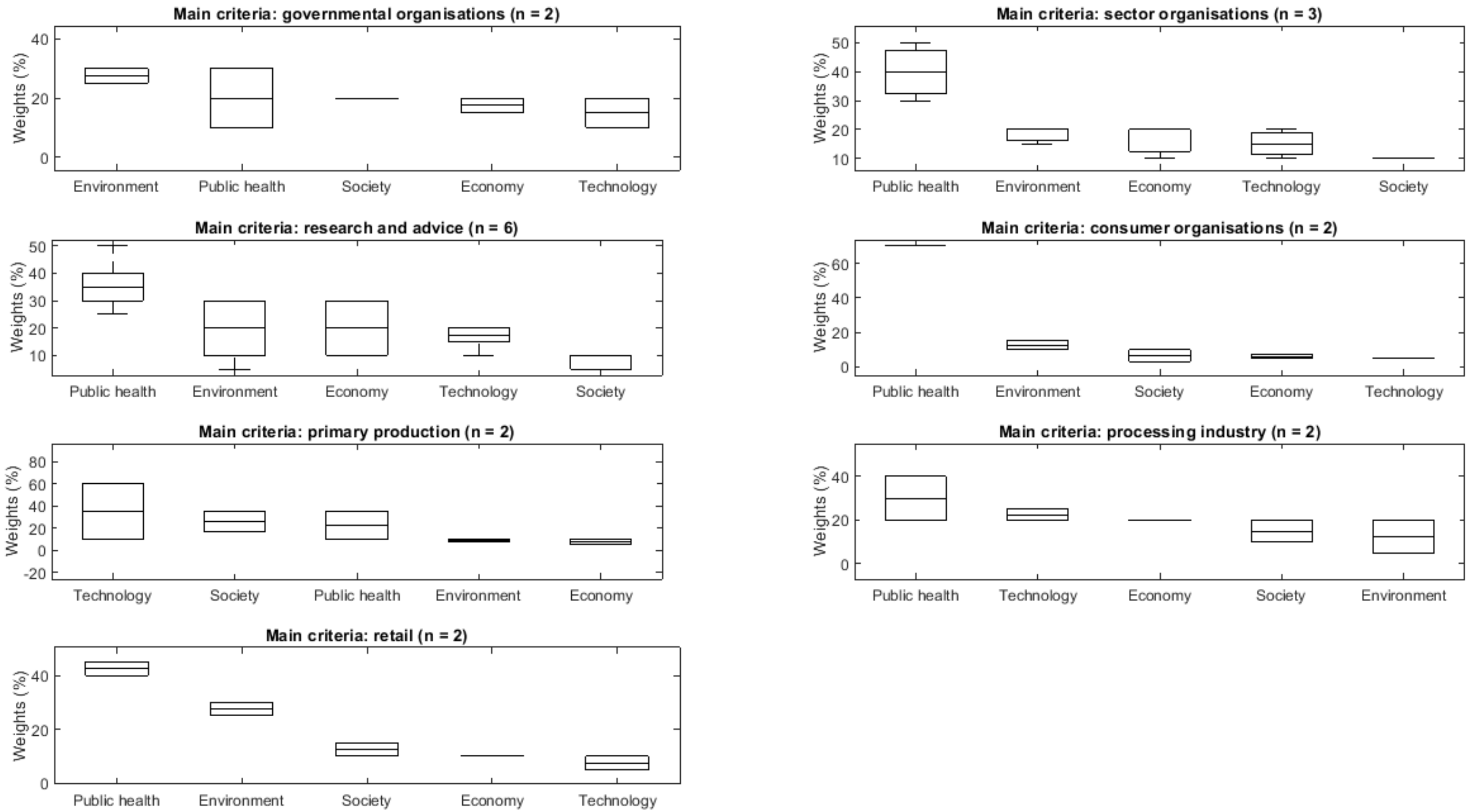
Addendum 28. Quantitative input collected from processors of (fresh-cut) fruits and vegetables. Constituents of main- and sub-criteria requested from processing plants.

Main criteria	Sub-criteria	Constituents
Environmental impact	Water use (m^3)	Vegetable wash water
		Rinsing water
Economic impact (costs)	Capital costs (€)	Investment costs for the installation of a leafy greens washing line
	Operational costs (€)	Personnel costs (~ number of workers/washing line)
		Personnel training
		Maintenance costs
		Chemicals
	Wastewater discharge costs (€)	Costs related to the discharge of wash water

Addendum 29. Input data for baseline scenario. Sub-criterion 1a: ‘microbiological food safety’ (metric: log CFU/g reductions of E. coli (O157:H7)), 1b: ‘microbiological food safety’ (metric: % transfer of E. coli (O157:H7)), 2a: ‘chemical food safety’ (metric: TTHMs concentration on the end product), 2b: ‘chemical food safety’ (metric: chlorate concentration on the end product), 3: ’occupational health and safety’, 4: ’ease of implementation’, 5: ‘robustness’, 6: 'water use', 7: 'wastewater discharge', 8: ‘‘capital costs’, 9: ‘operational costs’, 10: ‘wastewater discharge costs’, 11: ‘consumer acceptance’, 12: ‘pressure from international/national authorities’

	Sub-criteria													
Washing methodology	**Sub-crit. 1a**	**Sub-crit. 1b**	**Sub-crit. 2a**	**Sub-crit. 2b**	**Sub-crit. 3**	**Sub-crit. 4**	**Sub-crit. 5**	**Sub-crit. 6**	**Sub-crit. 7**	**Sub-crit. 8**	**Sub-crit. 9**	**Sub-crit. 10**	**Sub-crit. 11**	**Sub-crit. 12**
Potable water	0.449 log CFU/g	0.655 %.	5.395 µg/kg	0.012 mg/kg	1	5	1	7.5 m^3/ton	2	275 000 €	450 €/ton	2 €/m^3	5	4
Wash water disinfection (NaOCl)	0.921 log CFU/g	0 %	11.891 µg/kg	0.417 mg/kg	4	4	5	5 m^3/ton	5	300 000 €	540 €/ton	4 €/m^3	1	1
Wash water disinfection (PAA)	1.270 log CFU/g	0 %	5.395 µg/kg	0.012 mg/kg	4	4	5	5 m^3/ton	4	300 000 €	550 €/ton	4 €/m^3	3	1
Reconditioning treatment (NaOCl)	0.449 log CFU/g	0.655 %.	5.857 µg/kg	0.182 mg/kg	3	5	2	5 m^3/ton	4	330 000 €	535 €/ton	4 €/m^3	3	1

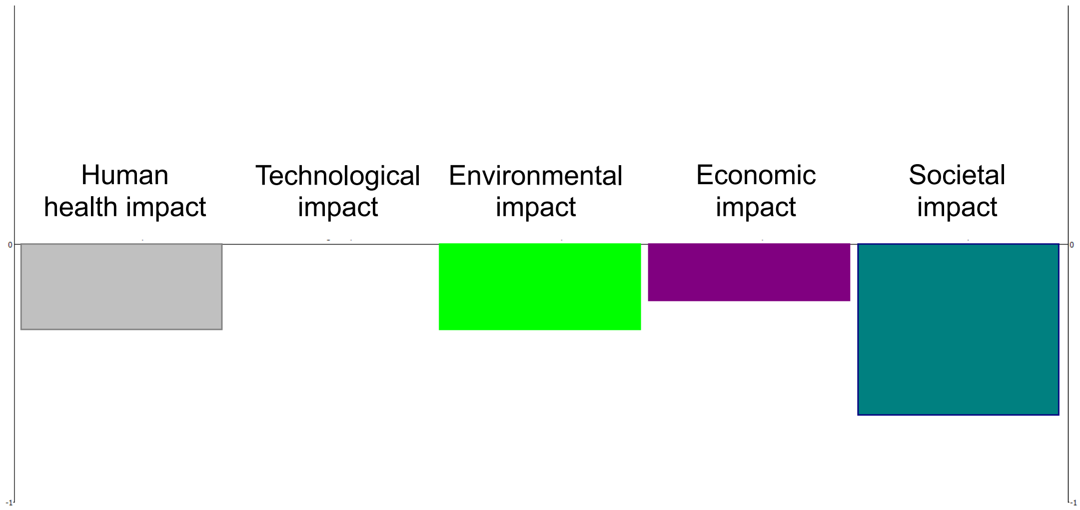
Addendum 30. Boxplots representing preference weights distribution over main criteria for different stakeholder groups.



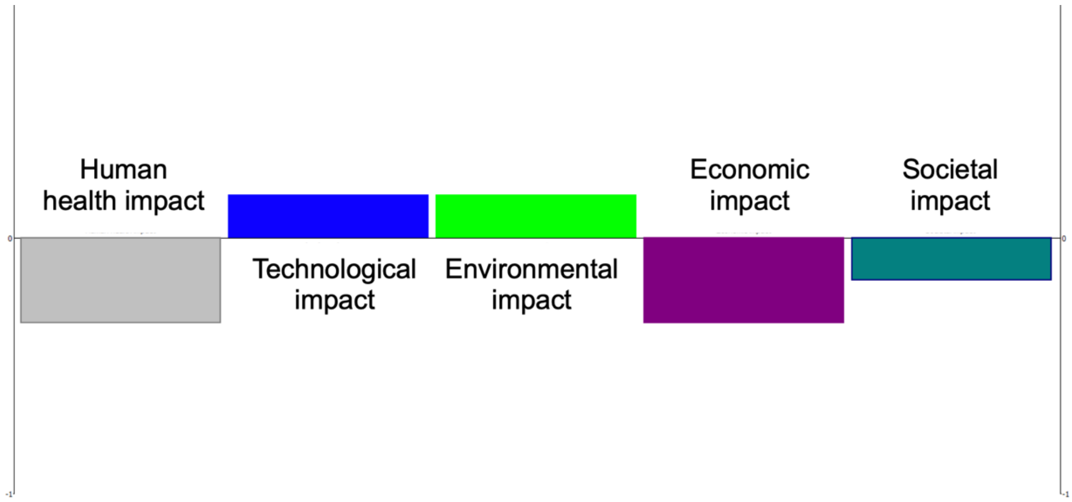
Addendum 31. P50, minimum and maximum of the given preference weights to sub-criteria for each stakeholder group.

Stakeholder group		Sub-criteria											
		Microbio-logical food safety	Chem-ical food safety	Occup. health and safety	Ease of imple-men-tation	Robust-ness	Water use	Waste-water dis-charge	Capital costs	Operat-ional costs	Waste-water discharg e costs	Con-sumer accep-tance	Pres-sure from autho-rities
Governmental organisations	P50	6.5	7.5	6	4	11	15	12,5	5	8	4,5	7	13
	Min	5	3	2	3	7	15	10	5	6	4	7	13
	Max	8	12	10	5	15	15	15	5	10	5	7	13
Sector organisation	P50	14.7	14.7	9.8	5.9	7.8	9.8	9.8	5.9	5.9	5.9	3.9	5.9
	Min	13.5	9	7.5	5	5	9	6	5	3	2	4	4
	Max	20	20	10	7	14	10	10	8	8	6	6	6
Research and advice	P50	16.9	10.6	10.6	5.3	10.6	10.6	5.3	7.9	6.3	6.9	3.2	5.8
	Min	9	5	5	5	5	2	3	2	3	2	1	3
	Max	20	17	16	10	15	20	20	10	10	10	6	7
Consumer organisations	P50	36.5	19	14.5	1.5	3.5	6	6.5	2	2,5	1.5	4	2.5
	Min	23	15	5	1	3	5	5	2	1	1	1	2
	Max	50	23	24	2	4	7	8	2	4	2	7	3
Primary production	P50	9	9	10	3.5	22	13	5.5	3.5	2	3	2.5	12.5
	Min	3	5	2	4	6	5	2	1	2	2	10	7
	Max	15	15	5	40	20	6	5	3	4	3	15	20
Processing industry	P50	9.5	9	11.5	7.5	12.5	6.5	6	7.5	8.5	6.5	6	9
	Min	7	6	7	5	10	3	2	7	7	6	4	6
	Max	12	12	16	10	15	10	10	8	10	7	8	12
Retail	P50	13.5	15	14	2.5	5	12.5	15	2.5	5	2.5	6.5	6
	Min	12	15	13	1	4	10	15	2	5	2	3	5
	Max	15	15	15	4	6	15	15	3	5	3	10	7
Overall	P50	16.3	13.0	10.9	5.4	10.9	10.9	6.5	5.4	5.4	4.3	4.3	6.5
	Min	3	3	2	1	3	2	2	1	1	1	1	2
	Max	50	23	24	40	20	20	20	10	10	10	15	20

Addendum 32. Contribution of main criteria towards net flow of wash water disinfection with NaOCl intervention option for baseline scenario 1a (equal weights).



Addendum 33. Contribution of main criteria towards net flow of the reconditioning with NaOCl intervention option for baseline scenario 1a (equal weights).



Addendum 34. Net outranking phi flows for scenario two to eight, with each scenario representing a set of preference weights collected from stakeholder group representatives.

	Scenario 2: governmental organisations	**Scenario 3: sector Organ-isations**	**Scenario 4: research and advice**	**Scenario 5: consumer organisations**	**Scenario 6: primary production**
Intervention options	**Phi**	**Phi**	**Phi**	**Phi**	**Phi**
Washing with potable water	0.3333	0.3343	0.2413	0.1333*[1]	0.3733
Wash water disinfection (PAA)	0.0225	0.1022	0.1062	0.3292*	-0.0067
Recon-ditioning (NaOCl)	-0.0900	-0.1470	-0.1777*	-0.2650*	-0.0233
Wash water disinfection (NaOCl)	-0.2658	-0.2895	-0.1698*	-0.1975*	-0.3433

	Scenario 7: processing industry	**Scenario 8: retail**
Intervention options	**Phi**	**Phi**
Washing with potable water	0.4067	0.3667
Wash water disinfection (PAA)	-0.0192	0.0992
Reconditioning (NaOCl)	-0.1233	-0.0883
Wash water disinfection (NaOCl)	-0.2642	-0.3775

1 '*' Indicates an adjusted ranking of intervention options in comparison with the baseline scenario

Addendum 35. Net outranking phi flows for scenario nine to thirteen. 'Scenario a' represents an equal weights scenario and in 'scenario b' the P50 value of overall collected weights is applied.

	Scenario 9a: adjusted microbiological reductions	**Scenario 9b: adjusted microbiological reductions**	**Scenario 10a: exclusion leaf-to-leaf transfer**	**Scenario 10b: exclusion leaf-to-leaf transfer**
Intervention options	**Phi**	**Phi**	**Phi**	**Phi**
Washing with potable water	0.4048	0.2295	0.4872	0.2295
Wash water disinfection (PAA)	0.0476	0.1059	0.0256	0.1603
Reconditioning (NaOCl)	-0.1667	-0.1520	-0.1282	-0.1520
Wash water disinfection (NaOCl)	-0.2857	-0.1834	-0.3846	-0.2378

	Scenario 11a: P5 for chemical food safety sub-criteria	**Scenario 11b: P5 for chemical food safety sub-criteria**
Intervention options	**Phi**	**Phi**
Washing with potable water	0.3571	0.1860
Wash water disinfection (PAA)	0.0238	0.0897
Reconditioning (NaOCl)	-0.0714	-0.0651
Wash water disinfection (NaOCl)	-0.3095	-0.2106

	Scenario 12a: adjusted wastewater discharge sub-criteria	Scenario 12b: adjusted wastewater discharge sub-criteria
Intervention options	**Phi**	**Phi**
Washing with potable water	0.2619	0.1212*
Wash water disinfection (PAA)	0.0952	0.1475*
Reconditioning (NaOCl)	-0.1429	-0.1376*
Wash water disinfection (NaOCl)	-0.2143	-0.1311*

	Scenario 13a: adjusted consumer acceptance	Scenario 13b: adjusted consumer acceptance
Intervention options	**Phi**	**Phi**
Washing with potable water	0.4048	0.2295
Wash water disinfection (PAA)	0.0714	0.1331
Reconditioning (NaOCl)	-0.1667	-0.1520
Wash water disinfection (NaOCl)	-0.3095	-0.2106