

# **Generating LCA partitioning factors for sewage sludge management using a Delphi procedure**

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## **ABSTRACT**

In attributional life cycle assessment (ALCA), the goal is to map the environmental impact from the system under study in such a way that it reveals what share of the total global environmental impact that belongs to the product or service investigated. Any process performing multiple functions then gives rise to an allocation problem. It has been recommended that the partitioning in ALCA studies should be based on the drivers of the system. Wastewater collection and treatment facilities are increasingly exploited in different resource recovery attempts and therefore increasingly result in allocation problems. The drivers of present wastewater and sludge management systems is a mix of various ideas and concerns relating to environmental protection, resource recovery, economy, and other interests, that seem to vary among stakeholders, over time and across regions. We developed a two-stage Delphi procedure for finding partitioning factors for use in ALCA studies where multiple drivers and stakeholders are present in relation to multifunctional systems and tested it for a wastewater and sludge management system. The paper reports on the method, on the experiences from applying the method and implications for ALCA studies.

## **KEYWORDS**

Allocation, environmental assessment, life cycle assessment, multifunctional system, stakeholder, wastewater treatment

## **INTRODUCTION**

The second half of the 20<sup>th</sup> century was characterized by a rapid increase in pressures on human health and the environment related to human activities. Concerns simultaneously increased for the resulting impacts on human well-being and ecosystem functioning. This led to the launch of various environmental assessment efforts, amongst others, environmental life cycle assessments (LCAs) that aim to capture the environmental impact related to the life cycle of a product or service. This means that resource use, emissions, and waste generation along the life cycle, from resource extraction to waste management, is inventoried and recalculated into an environmental impact per a certain functional unit that reflects the function of interest in the study.

In so-called attributional life cycle assessment (ALCA), the goal is to map the environmental impact from the system under study in such a way that it reveals what share of the total global environmental impact that belongs to the product or service investigated. Any process

performing multiple functions then, unless the studied system is enlarged to encompass all functions, gives rise to an allocation problem. The environmental impact related to the process then needs to be partitioned between the functions. How this should be done has been a recurring issue of debate in the LCA community. In an early consensus process, it was concluded that partitioning should be based on causal relationships [1]. Expected revenues from the products or services are often the most important drivers behind the construction and operation of a system; consequently, the economic value of the products or services has been advocated as a partitioning basis [2, 3]. However, when the construction and operation of the system are not driven by economic profit, another basis for partitioning has to be found. This is the case for waste management processes and other societal services that are not driven by commercial interests.

It should be mentioned that there is no consensus in the LCA community on precisely what ALCA is and how multifunctionality issues should be handled in such studies. We base the present work on the idea that it is meaningful to do either ALCA or consequential LCA (CLCA) depending on whether you are interested in the share of the global impact that should be connected to the life cycle under study and to its subsystems, or whether you want to know how the global impact changes as a consequence of the introduction of or a change in the system under study [cf. 2]. We focus in this work on partitioning as a means to handle multifunctionality issues rather than a substitution approach where functions other than the main function are handled by subtracting environmental impacts that correspond to an alternative way of generating the same function. Our main argument for this, other than that it has been stated by others to be the typical/usual way to handle allocation in ALCA [4, 5] is that partitioning is more in line with the philosophy of ALCA as it avoids the introduction of elements that belong to the life cycle of another function. Often, market effects would have to be taken into account, which introduce consequential notions into the study. We therefore focus here on partitioning based on causal relationships as suggested already in early discussions within the LCA community [1]. Today, substitution is the predominant method used for avoiding allocation in ALCA for wastewater and sludge management systems and our aim is to develop and test a new approach to allocation that is more in line with the philosophy underpinning ALCA.

Wastewater collection and treatment facilities were originally built to address problems associated with odour, the spreading of diseases, and eutrophication. Today, however, such systems are increasingly exploited in different resource recovery attempts. Various options exist or have been suggested for the recovery of carbon (e.g., as methane in biogas or as the biopolymer PHA), nutrients (e.g., by direct use of hygienised sludge on arable land or by extraction of phosphorus from sludge incineration ash), and even reuse of the water itself after purification. In the transition towards a circular economy, such recovery is expected to be increasingly emphasized and increasingly common in practice. Consequently, as wastewater and sludge management systems are to an increasing extent multifunctional, they more often present allocation problems when any of their products or services is to be part of an LCA. It is important to remember that as the roles of and thereby also the drivers of wastewater and sludge management systems change over time and vary between locations, the appropriate allocation bases might also vary with time and place and so could the appropriate partitioning factors.

The Delphi method is a structured, interactive method that generates results based on expert judgements [e.g., 6]. Typically, involved experts answer questionnaires in two or more rounds. In between each round, a facilitator generates an anonymised summary of the experts'

judgements as well as the reasons for their judgements, which is shown to all participants. The idea is that the answers will eventually converge towards a “correct” answer. We propose that various stakeholders in wastewater and sludge management could be used as “experts” in a Delphi procedure for generating partitioning factors for these processes in LCA. The judgements they would be asked to provide would be related to how important a driver each function generated by the studied system is for the construction and operation of the system as a whole, i.e., the causal relationships between the functions and the multifunctional processes.

We have developed and tested a two-stage Delphi procedure for finding partitioning factors for use in ALCA studies where multiple drivers and stakeholders are present in relation to multifunctional systems\*. We have applied the procedure for a wastewater and sludge management system where the sludge management simultaneously provides three functions: (1) management of the sludge from the wastewater treatment, (2) biogas production for use in vehicles, and (3) fertilisation of agricultural soil. Various actors with a strong connection to sludge management in Sweden were involved in the procedure. The paper reports on the method, on the experiences from applying the Delphi procedure, and on the results and their implications for ALCA studies.

## **METHOD – THE DELPHI PROCEDURE AND THE STUDIED SYSTEM**

### **The Delphi technique**

The Delphi technique for gathering information was developed by Dalkey and Helmer in the 1950s [7]. It is primarily a method for consensus-building among an expert panel by means of a series of questionnaires. The multiple iterations is what particularly distinguishes the Delphi technique from other methods for gathering data as this allows for convergence within the expert panel. Three key features of the Delphi technique are multiple iterations, subject anonymity and controlled feedback [6]. Anonymity reduces the risk of dominant individuals or group pressure influencing the process. By carefully controlling feedback, the effect of noise (that data is distorted by a focus on group and/or individual interests rather than on the task) can be minimised. The multiple iterations not only allow for convergence but also set the participants in a problem-solving mode in which they typically provide their opinions more elaborately.

In the project described in this paper, we developed a Delphi procedure for finding partitioning factors for modelling, in ALCA, of a multifunctional system that is not driven by commercial interest.

### **The studied sludge management system**

The particular system that we decided to focus on is a wastewater and sludge management system in Sweden where the sludge management simultaneously provides three different functions: (1) management of the sludge from the treatment of municipal wastewater, (2) biogas production for use in vehicles, and (3) fertilisation of agricultural soil. The allocation problem cannot in this case be avoided by means of subdivision as has been exhaustively discussed in another paper [8]. Management of sludge resulting from wastewater treatment is mandated by law. It would not be an option to just leave the sludge where it arises, nor to simply transport it elsewhere. In Sweden, landfilling of organic waste is not allowed and any

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disposal route for sewage sludge has to be safe for human health and the environment. Sludge volume reduction and water removal is often desirable in order to avoid high transportation costs. Overall costs need to be minimised to keep water fees at an acceptable level for households. Biogas production is often employed as a sludge management method as it provides some hygienisation of the sludge and makes it easier to dewater and also less odorous. Further, the biogas that is generated can be utilised to either reduce the external energy input to the wastewater treatment plant, or it can be sold for energy generation or as a transportation fuel. In Sweden, there has for some time been strong political pressure to increase the availability of vehicle gas for both passenger cars and for buses and other heavy vehicles. This is one important reason behind the increasing total capacity of anaerobic digestion facilities for organic waste, including for sewage sludge, in Sweden over the past two decades. These facilities are often run either by municipal companies or by entrepreneurs and are not purely commercially driven. The recycling of phosphorus in sludge to productive land has been pushed by the Swedish government but, there has been strong opposition against such practice from some organisations (e.g., the Ren åker Ren mat (Clean soil Clean food) initiative). Proponents of spreading of sludge on arable land emphasize its content of nutrients (primarily nitrogen and phosphorus) and organic material, while the opposition claims that there are large (or at least unknown) risks associated with pathogens, heavy metals, various organic chemicals including medicines and hormones, micro-plastics, and other content in the sludge. Currently, about 25 percent of the sewage sludge in Sweden ends up on arable land.

Consequently, there are several drivers of the described sludge management system. The extent to which each function is a reason for the system's existence and operation is not easily quantified. For an LCA of one of the functions of a system, it may have a tremendous impact on the results if a large or a small share of the total environmental impact is attributed to that function. For such partitioning to reflect each function's importance as a driver in the context described, we suggest the use of a Delphi procedure among a mix of experts relevant for the particular system under study.

The studied system not only served as the case for which partitioning factors were generated but it was also used to illustrate the impact of the results. A detailed description and inventory data are available elsewhere [8, 9]. This paper displays life cycle impact assessment results at midpoint level for climate change (global warming potential, in carbon dioxide equivalents) and acidification (acidification potential, in mole H<sup>+</sup>-equivalents) for the functional unit of operation of the system over one year.

### **The employed Delphi procedure**

A critical issue is to select and get access to relevant experts to include in the Delphi procedure. In fact, the selection of participants has been described as the most important step in the entire procedure as it will determine the quality of the generated results [e.g., 6]. The study described in this paper serves two purposes: (1) to test the feasibility of a Delphi procedure for finding LCA partitioning factors in a wastewater and sludge management context and (2) to provide one or a few sets of partitioning factors for a particular wastewater and sludge management system. The selection of participants is critical for the second purpose and the achieved partitioning factors therefore need to be discussed in relation to which the participants are. Participants should of course be knowledgeable concerning the target issue and the number of participants should allow for "a representative pooling of judgments and the information summarizing capability of the research team" [10].

For this study, a special opportunity arose as one of the authors of this paper was conveniently invited to give a presentation on LCA of sludge management at an annually recurring event called “Sludge days” for actors, typically about 80 participants, in Swedish wastewater and sludge management. The event typically includes one day of study visits to various relevant sludge related activities and one day of presentations and discussions on various sludge related topics. We decided to use this opportunity to find volunteers to our study. We believed that the type and breadth of expertise represented at this event was in line with what we sought and we hoped that a relevant selection would volunteer. We did not know beforehand exactly which the participants at the event would be and which and how many would eventually volunteer to participate in the follow-up Delphi procedure, which was planned to be carried out via email during the following weeks. We hoped that the volunteers would together represent a relevant pool of experts. We decided to ask the volunteers to also describe their role in relation to sludge management to allow for an analysis of the group, and, if consensus was not reached in the Delphi procedure, to allow for generation of several sets of partitioning factors that reflect different stakeholder groups. In fact, we expected a variation in opinion amongst the participants in this heavily debated topic.

We used part of the time slot for the presentation at the Sludge days to introduce the topic so that volunteers would know what they signed up for and also would have gotten most of the necessary information already before the first questionnaire was sent out. We also made an effort to get a first preliminary judgment on partitioning factors from all the participants at the presentation (using electronic voting on cell phones) so that this would provide some of the starting material for the Delphi procedure. We decided to use two iterations after the event. This can therefore be described either as a two-stage Delphi procedure with a small group of experts or a three-stage Delphi procedure but with a larger group participating in the first stage. The type of information that would be sent out in between iterations would be an anonymised compilation and analysis of answers.

The procedure that was employed thus had the following steps:

1. Day 0: After a 15-minute presentation on an LCA study on sludge management, the participants were given a brief background to the current study and were asked to log into a Mentimeter ([www.mentimeter.com](http://www.mentimeter.com)) webpage on their cell phones and to provide a relative rating for the three function's importance as drivers for the particular system. Results were presented on the screen in the front of the room and the generated partitioning factors were also entered into an Excel sheet that had been prepared to calculate the impact of this set of factors for the results in an actual LCA. The results were shown on the screen as bar graphs to the participants.
2. Day 1: A description of the study and the studied system as well as the results of the electronic voting was sent out to all participants after the event. The participants were also asked to volunteer for the subsequent two-stage Delphi procedure. If they agreed to participate, they were asked to complete a questionnaire (see Appendix 1) and send it back within six days. The questionnaire contained questions about their role in relation to the sludge management, and on which partitioning factors that they wanted to give the three functions of the system and why.
3. The submitted questionnaires were analysed and the results were compiled. The compilation contained the partitioning factors (low, high and average for each function), a digested list of arguments, other comments from the facilitator, and (as an appendix) an anonymised list of all complete argumentations with the corresponding partitioning factors.

4. Day 12: A new and slightly modified questionnaire was sent out to those who had volunteered (see Appendix 1), together with the compilation of results from the first stage. Participants were asked to review the results and send in a new assessment within three days that reflected their standpoint in light of the new information. As vacation times were starting, several reminders were sent out and the actual deadline was postponed by more than a month.
5. Results were summarised and this paper was written. Upon submission, the paper was sent to all participants as documentation and feedback.

## RESULTS

### Sludge event

The sludge event gathered 90 participants of which 70 participated in the electronic voting. Results from the voting on each function's importance as a driver of the system are displayed in Figure 1 in the same way as it was shown to the participants at the conference (but translated from Swedish to English). They responded to the question: "How strong reasons to the existence and operation of the system are each of the three functions? Distribute 10p among the three functions (treatment of wastewater and resulting sludge, production and use of biogas in vehicles, and fertilization of agricultural soil)". Correcting for the fact that some participants had provided too many points at the sludge event as the sum was over 10.0, we end up with the partitioning factors 5.7, 1.6 and 2.7 for the three functions.

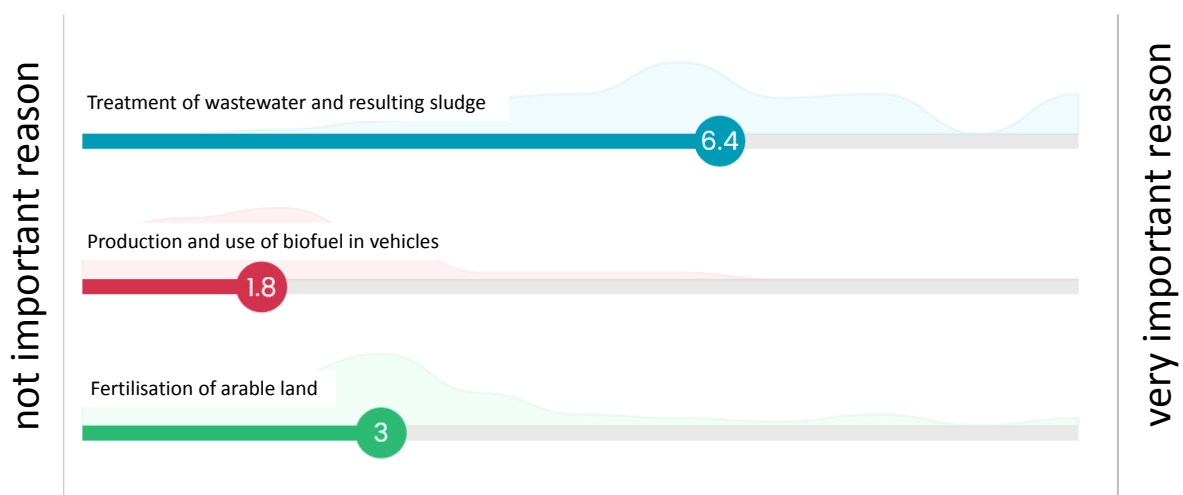


Figure 1. Results from the electronic voting at the sludge event. Note that the total sum is over 10.0.

### First and second questionnaire

The first questionnaire received 26 responses. Of the 15 persons that responded also to the second questionnaire, only one person changed its response, but only in terms of the argumentation and not the partitioning factors. The partitioning factors are provided in Table 1. It is clear that no consensus was reached in terms of partitioning factors. However, the wastewater treatment and sludge management function was always seen as the main driver of the system by the respondents which means that there was consensus in this sense (with the exception of one respondent that gave equal importance to the soil fertilization function). The most even set of partitioning factors that was provided was 4, 3, 3. Other sets that contained

extremes for each function were 10, 0, 0; 6, 3, 1 and 5, 0, 5. It was not possible based solely on the partitioning factors to distinguish any grouping of answers.

Table 1. Results from the questionnaire on the relative importance of each function as a driver of the system.

Function	Lowest	Highest	Average
Wastewater treatment and sludge management	5	10	6.8
Production and use of biogas in vehicles	0	3	1.3
Fertilization of agricultural soil	0	5	1.9

We can see that compared to the results from the sludge event, the importance of the first function has increased while it has decreased for the other two, most notably for the third. Whether this is a result of the more narrow selection of respondents in the questionnaire or of changed opinions cannot be seen from this study. However, we believe that the questionnaire provided more relevant results than the electronic voting as the respondents had more information available, more time to do the task and likely, as participation required some effort, both interest in the results and commitment to the procedure.

Two rounds were not enough to obtain consensus. However, as there was almost no difference between the answers in the first and the second questionnaires, it is unlikely that more similar rounds would help to converge results. The conclusion is that there are either differences in opinion that will not converge and thereby, different sets or ranges of partitioning factors must be employed to reflect reality, or, the set-up of the study was not appropriate for finding consensus. We expected that results might not converge or that they might even diverge as participants could take sides as arguments became clearer and therefore we think it is more likely that consensus cannot be found (which is not the same as that a compromise cannot be negotiated).

When it comes to the argumentation that each respondent provided for their set of partitioning factors, a complete list cannot be given in this paper, but a selection is presented here. Arguments behind a high importance of the *wastewater and sludge management function* (and low of the others) included:

- Wastewater treatment plants were built to avoid negative local health and environmental impacts related to the content in wastewater
- Municipalities have the responsibility to protect the local environment, not to produce fertilizer or a vehicle fuel
- Wastewater treatment plant operators have as their primary task to treat wastewater
- The wastewater treatment is the reason that its waste exists
- Digestion is primarily done to stabilise the waste of the wastewater treatment

Arguments behind a high importance for the *production and use of biogas in vehicles* included:

- It is the task of wastewater treatment plant operator to optimise the whole system
- Political targets to generate biogas, in order to, e.g., increase fossil-free transportation
- There is a high demand for biogas

Arguments behind a high importance for the *fertilization of agricultural soil* included:

- There are clear benefits related to sludge application on soil, e.g., related to nutrients and organic carbon

- The function of sludge on soil is less easily substituted than the function of biogas as a vehicle fuel
- Sludge is at present cheaper for the farmer than other fertilizers and therefore attractive
- Political targets related to a circular economy
- The mission for the companies operating wastewater treatment plants have in some cases been expanded to include the generation of “clean” resources
- Phosphorus is seen as a critical resource
- Use of sludge in agriculture creates a secondary driver to engage in upstream activities to reduce the content of toxic substances in wastewater, which is also a political target

In terms of the roles of the respondents, they varied and can be sorted into three major groups. Most (18 out of 26) were employed by a municipality, either in the municipality itself, in a municipal company, or in an association formed by municipalities. These were mostly engineers, working with environmental issues, processes, operation, quality, in the laboratory or with investigations or development, mostly within wastewater treatment and sludge management but some more broadly within the whole sector of water and waste. Two of the 18 stated specifically that they work with Revaq certification, which focuses on the quality of sludge with the aim of making it suitable for use in agriculture (see e.g. <http://www.svensktvatten.se/vattentjanster/avlopp-och-miljo/kretslopp-och-uppstomsarbete/revaq-certifiering/>). Two of the 18 were managers of treatment plants. No particular patterns could be seen in the responses in terms of the different roles in municipal organisations or in terms of geographical position in Sweden from north to south or east to west. Five people from four different companies in the water, wastewater and waste treatment sector also participated. These companies develop and deliver technologies or treatment services to treatment plant operators, primarily within sludge management. Finally, three people worked either in research institutes or in consultancies, typically providing knowledge generation services to treatment plant or sludge management operators. Table 2 provides partitioning factors for these three major groups.

Table 2. Results from the questionnaire on the relative importance of each function as a driver of the system – divided into three major participant groups.

Function	Municipal organisations (n=18)			Private companies (n=5)			Consultancies and institutes (n=3)		
	Low	High	Ave	Low	High	Ave	Low	High	Ave
Wastewater treatment and sludge management	5	10	6.9	6	10	7.2	6	6	6.0
Production and use of biogas in vehicles	0	3	1.2	0	2	1.0	1	3	2.0
Fertilization of agricultural soil	0	5	1.9	0	3	1.8	1	3	2.0

The only thing that stands out in the results shown in Table 2 is that people in consultancies and institutes all gave relatively low importance to the wastewater and sludge management function. One possible reason is that they do not see it as their main task to perform these services. If this is the case, the perceived role of the participant may have a large influence on the results, which could be expected for an issue as complex as this. However, with the fairly low number of respondents in this group, we cannot know whether these results are



representative for the whole group. It is therefore not possible based on these results to say that certain groups of participants are well represented by different sets of partitioning factors. However, to test the importance of varying the partitioning factors, some extreme combinations can be tested in a sensitivity analysis, e.g., 10, 0, 0; 6, 3, 1; 5, 0, 5 and 4, 3, 3, besides the total average of 6.8, 1.3, 1.9. Which combinations that should be tested may vary depending on the context of the study.

### LCA case study

To illustrate the impact of the various sets of partitioning factors on actual LCA results, two different sets of graphs will be shown. The first set of graphs, Figure 2, provides the total LCA results for the studied system as well as the shares that belong to each function for the average set of partitioning factors from the Delphi study, for climate impact and acidification, respectively. Note that for the system under study, the impact from the wastewater treatment process is fully allocated to the function “Wastewater and sludge treatment” and the use of the biogas is completely allocated to the function “Biogas production and use”.

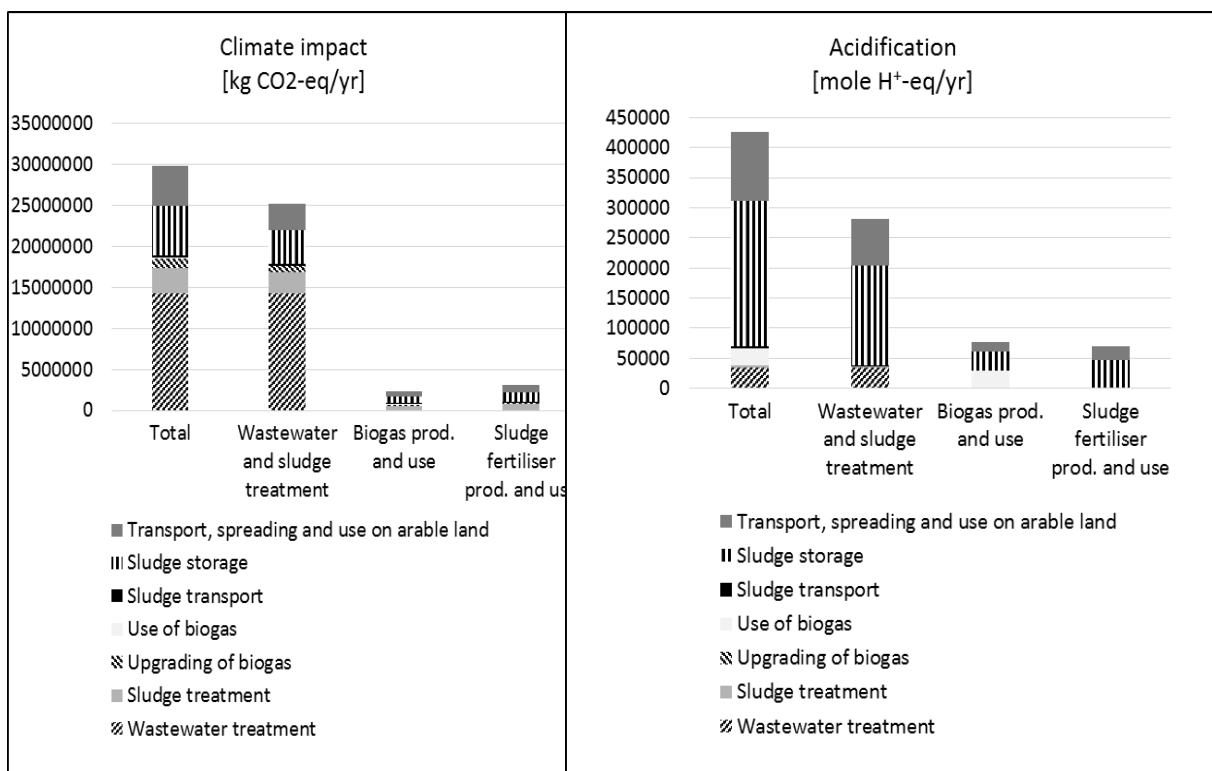


Figure 2. LCA results (climate impact on the left and acidification on the right) for the studied wastewater and sludge management system and the effect of using the average set of partitioning factors generated in the Delphi procedure (0.68, 0.13 and 0.19, respectively, to the three functions).

For an ALCA that focuses on either of these three functions, only the share of the total that is allocated to that function by means of the partitioning factor is counted. The rest is considered to belong to the other functions. Examples of ALCAs that study either of these three functions are:

- A study that aims to compare different wastewater and sludge management options but where each option generates different by-products, with the functional unit of 1 cubic metre of wastewater
- A study that compares different vehicle fuels, with the functional unit of 1 km driven

- A study that compares the use of different fertilizers on agricultural land, with the functional unit of x kg of P and y kg of N applied.

The second set of graphs, Figure 3, aims to show such comparisons to an alternative, comparable product for two of the functions. For the vehicle fuel, natural gas was selected as the comparable product and for P and N, a combination of common mineral fertilisers. As this study is not an LCA case study per se, we are not providing any details on these systems here; details can be found elsewhere [8]. It should be noted that allocation principles may not be consistent across all data sets, but as this serves as an illustration rather than a quantitative comparison we deem such inconsistencies to be of low relevance.

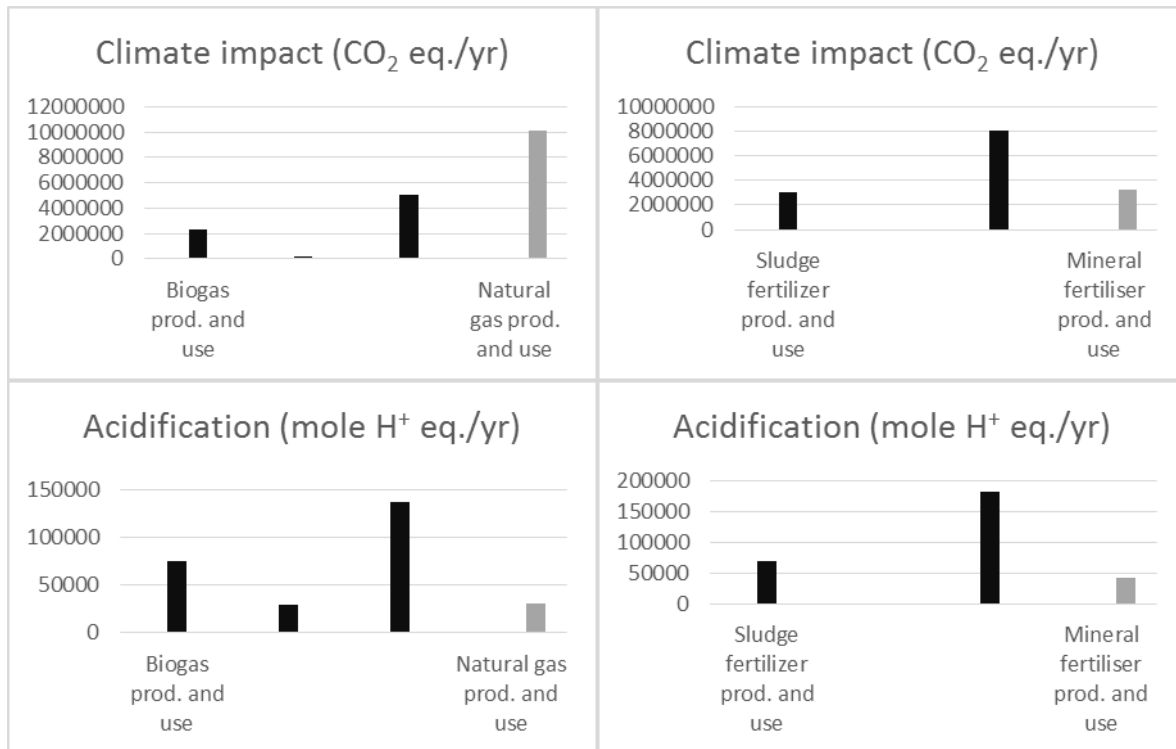


Figure 3. Effect of applying different partitioning factors from the Delphi study (average, low and and high) for each function in comparative LCA. The two graphs on the left show a comparison between biogas (black bars; average, low and high, respectively) and natural gas (grey bar), while the two graphs to the right show a comparison between sludge fertiliser (black bars; average, low and high, respectively) and mineral fertilizer (grey bar), for climate change (upper graphs) and acidification (lower graphs), respectively.

It can be seen in Figure 3 that the LCA comparison to another comparable product that fulfils a similar function is strongly affected by the partitioning factor. Natural gas performs worse than biogas in terms of the climate impact but outperforms biogas in terms of acidification unless a very low partitioning factor is applied. The ranking order of sludge and mineral fertilizers is determined by the partitioning factor for both climate impact and acidification. Clearly, which set of partitioning factors is selected can potentially be important for the conclusion from such comparisons.

Graphs like the ones presented here were also shown at the sludge event and also sent out after the event together with the invitation to participate in the Delphi procedure, but then based on the normalised average partitioning factors generated at the event.

## DISCUSSION

The Delphi technique was developed for finding consensus among a group of experts. As earlier mentioned, we suspected that it might be difficult to find consensus on the partitioning factors as opinions in relation to sludge management tend to vary widely between individuals and be strong; also, there is no way to objectively evaluate all aspects that may come into play. There was not even consensus on the partitioning factors within any of the subgroups of participants identified in this study. However, there was consensus in the view that the wastewater and sludge treatment function is important for the system. All participants considered this function at least as important as any of the other functions; almost all considered it more important than the other functions together. Based on this study, we find it well motivated to allocate at least half of the impact from the sludge management processes to the treatment of wastewater and its waste. For the other two functions, the results indicate a comparable importance but with some more weight to the use of sludge as a fertilizer.

As no consensus was found, the potential of the Delphi technique in developing consensus could not be fully exploited. As a matter of fact, not a single participant changed their partitioning factors in the second iteration. One may ask whether the feedback that was sent out after the first round was not ideally designed to trigger reflection among the participants. Or is this a business sector where people have developed strong opinions that do not easily change? A third potential explanation is that the feedback was sent out at the same time as some people started their summer vacation and that participants therefore did not put much (or any) time into understanding the feedback and reconsidering their judgments. Only 15 out of the 26 that responded to the first questionnaire replied in any way to the second questionnaire despite multiple reminders. Careful consideration should be put into how the procedure and the feedback are designed so that participants are encouraged or even forced to react on the feedback. This could, for example, have been emphasized more in the first presentation of the study and in the information that was sent out together with or after the first questionnaire.

We cannot be sure that all participants understood the system that we presented in the same way or that they even strictly considered the specific system. Their viewpoints may have been colored by experiences of other similar systems (leading to ‘noise’ – irrelevant information - in the study), e.g., systems where wastewater and resulting sludge are not as clean or systems that are configured in a different way. Actually, some comments from participants in emails and questionnaires indicated that there might be differences in how the system is understood. Some of the feedback to the participants after the first iteration was actually that they should carefully think through which system they were considering when they filled in the second questionnaire and report any potential deviations from the system that we presented (we wanted to see if subgroups could be distinguished based on this information). However, no participant reported any such deviation. Further, the limited experience of LCA of the participants and, consequently, the challenges posed in finding allocation factors in LCA, may also have played an important role as the task could have been misunderstood (also leading to noise in the results). It might be wise to follow up a study like the one we have presented here with an interview study in which participants are asked about their understanding of the system and of the task, both to learn how to provide better description in the future and to understand how results could potentially be corrected for noise. An effort should always be made to carefully explain the system and the task, without being too lengthy as this might decrease the participation rate.

Following from the discussion in the earlier paragraph on the importance of correctly understanding the task and the system is that the results from this study are valid primarily for this specific task and this specific system. Had another type of system been studied, for example a system in which also the biopolymer PHA (polyhydroxyalkanoate) was generated in the wastewater treatment process, different allocation problems would arise and the outcomes of a similar procedure would be different. We do not expect the achieved partitioning factors to be valid outside the context of this specific type of system, outside Sweden or beyond the present time. However, even if there are limitations to how results achieved in this study can be used, we expect it to be meaningful to use similar Delphi procedures for generation of ALCA partitioning factors also in other contexts. It could even be used in a future-oriented study for generating partitioning factors for prospective ALCA. Expert judgments in a Delphi study could be a useful way to manage the uncertainties that would be introduced when circumstances distant in time (or in place) are to be considered.

A fundament of the Delphi procedure is that involved experts are relevant to the specific question at hand. During the procedure, the more relevant of the involved experts could be identified and their judgments could be given higher value or be the only viewpoints included. However, in our case, the participants can be seen as experts on their own different perspectives and in this sense, they are all equally important. However, certain viewpoints may be overrepresented and some viewpoints may be completely missing. We did not expect that a consensus would form as there are many possible standpoints in relation to sludge management and therefore hoped that the procedure would eventually include many different types of participants and that the whole breadth of considerations would become explicit in their argumentation. Clearly, many different arguments appeared and the spread in partitioning factors was fairly large. When considering which actors that likely came to the sludge event that was the basis for our selection of experts, we can imagine viewpoints that were likely not represented, e.g., high-level policy-makers and organisations highly critical to the spreading of sludge in agriculture. It could therefore be interesting to do the selection of participants in a more directed way to ensure an even broader coverage. Whether it is reasonable or not to give each participant's vote the same weight, we cannot say. But it is important to keep in mind that when averaging judgments without weighting, the mix of participants can potentially be important. The context of a specific study will have to determine which experts are involved and which may be seen as more relevant.

Once relevant experts have been identified, the next challenge is to get them on board and committed to the whole procedure. We chose the easy way of working only with volunteers that had been listening to an introduction to the study, which obviously made some of them interested in participating as they volunteered for an additional effort afterwards. An alternative could have been to send similar information to a targeted group of people. We cannot say if this would have gathered a more relevant group that was even more committed to the procedure but this is a possibility.

## **CONCLUSIONS**

We have described a Delphi procedure for generating partitioning factors for ALCA. The procedure was successfully used for finding partitioning factors for three functions that the sludge management activities of a particular wastewater and sludge management system performs. The generated partitioning factors are case-specific. There was more or less consensus in terms of which is the most important function but not in the numerical partitioning factors of the different functions.

Particular challenges that were identified during the work was to get relevant experts involved and committed to all steps of the procedure, to describe the task and the system in an understandable way, to generate relevant feedback that could trigger reconsideration, and interpreting results when consensus is not achieved.

It was shown by using the partitioning factors in an LCA comparison that it can determine the outcome of such a comparison which numbers are used. Therefore, it is important to find appropriate partitioning factors and, if ranges or several sets of partitioning factors seem relevant, that the sensitivity to this is checked.

We believe that the suggested Delphi procedure can be useful in many different situations where expert or stakeholder judgments could be a way to meaningfully describe the drivers of a system. The suggested procedure is not specific to the system investigated in this study and it is also adaptable in various ways.

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## APPENDIX 1: DELPHI QUESTIONNAIRE

Below, an English translation (original language Swedish) of the questionnaire that was sent out to the participants is provided. When the text in the second questionnaire deviates from the first questionnaire, this is shown in brackets [like this].

### Questionnaire 1 [2]: Delphi procedure on partitioning factors in life cycle assessment on sludge management.

Fill in the white cells in the table:

Date:	
Name:	
Company/organisation:	
[Your] role:	
1. How strong reasons to the system's (see appendix for description) existence and operation are the following functions? Distribute a total of 10.0 points between the three functions:	
Wastewater treatment including management of the residual sludge:	
Production and use of biofuel for vehicles:	
Sludge fertilization in agriculture:	
[2. If the system you think of is different in any way from the system that has been described (e.g. if biogas for vehicles or sludge fertilization in agriculture are not applicable) you describe this here:]	
2. [3.] What are your most important arguments behind the distribution of points that you entered in question 1? Feel free to provide a list of several arguments.	