Life cycle analysis of horticultural products: Memo on capital goods modelling

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Introduction

This memo has been prepared to address modelling capital goods of plant protection products (PPP) in the context of the development of a methodology for calculating the environmental footprints of horticultural products, the HortiFootprint category rules (HFCR, see Helmes et al., 2020a). The goal of this HFCR is to provide a harmonised methodology after which consistent LCA studies can be performed for the European horticultural sector. The development of the methodology is following as much as possible the most recent guidance for developing product environmental category rules (PEFCR) published by the European Commission (Zampori and Pant, 2019).

The development of the HFCR was initiated by Royal FloraHolland, Fresh Produce Centre and Wageningen Economic Research, with co-financing from the Dutch Fund for Horticulture & Propagation Materials, ABN AMRO Bank N.V., the Dutch sector organisation for greenhouse horticulture (Glastuinbouw Nederland), MPS, Rabobank, Foundation Benefits of Nature and in co-production with experts from Blonk Consultants and PRé Sustainability.

At the start of the project, several topics were identified where additional guidance was needed for the horticulture sector as well as the guidance currently available in the Product Environmental Footprint (PEF). The following methodological challenges were identified:

- modelling of capital goods;
- modelling nitrogen and phosphorus emissions;
- modelling pesticides emissions and
- handling multifunctionality of combined heat and power systems used during cultivation.

This memo is one of the four memos elaborating on methodological challenges.

The aim of this memo is to assess the relevance of capital goods in the environmental footprint of horticultural products, decide which capital goods to include in the analysis and propose a default way to model included capital goods in case primary data is not available.

In the latest update of the PEF method, the following rule is formulated to decide whether capital goods should be included in the system boundaries: 'Capital goods (including infrastructures) and their end of life should be excluded, unless there is evidence from previous studies that they are relevant' (Zampori and Pant, 2019). This is different from the rule defined in the previous version of the Guidelines (version 6.3, European Commission, 2018) where capital goods had to be included unless they could be excluded based on the 1.0% cut-off rule.

The burden of proof now lies with those who want to include capital goods, because the default option is not to include them. This document describes whether there is any evidence of the relevance of capital goods in the environmental footprint of horticultural products.

The development of a HFCR for horticultural products started in 2018. The aim of this project is to produce a widely accepted standard for implementing and communicating environmental footprints of horticultural products, so that everyone assesses an environmental footprint in the same way, regardless of the software tools used, and that the results can be interpreted unambiguously. The technical requirements of the Product Environmental Footprint Guide (European Commission, 2013), the previous version of the Product Environmental Footprint Pilot Guidance (version 6.3, European Commission, 2018) and the most recent Guidelines for updating the Product Environmental Footprint (Zampori and Pant, 2019) are followed.

In the first part of this document, a definition of capital goods is provided. This is followed by a description of handling of capital goods in the following LCA standards (this list is not exhaustive but these are the most widely used standards in LCA):

- ISO 14040/14044: Environmental Management: Life Cycle Assessment
- ISO 14067: Carbon Footprint of Product
- International Reference Life Cycle Data System (ILCD)
- Product Environmental Footprint (PEF)
- GHG protocol
- PAS 2050
- Ecological footprint
- BPX 30-323
- WBCSD (Life Cycle Metrics for Chemical Products)

In the second section, the contribution of capital goods in the representative product studies (RP-studies) is evaluated. In the third part, the relevant literature is summarised, before a conclusion with recommendations on which capital goods to include is presented. Finally, recommendation are made on how to include capital goods in the life cycle analysis of horticultural products.

Definition of capital goods

There is no clear definition of capital goods in the LCA standards or in literature on the inclusion of capital goods in LCA studies. In a report by Guinée et al. (2001), the authors argue that there is a definition problem, because a capital good in one LCA study might be the object of investigation in another study. Imagine an LCA study on food crops, where agricultural machinery is a capital good needed to produce one unit of output. Now imagine a study issued by John Deere where the company wants to know the environmental impact of their tractors. This example shows that the classification of a capital good is dependent on the subject of the study. In search of generic definitions, most LCA-related literature turns to dictionary descriptions such as in Frischknecht et al. (2007) where they state that 'most online dictionaries define capital goods as "goods", such as machineries, used in the production of commodities (articles of trade or commerce); producer goods.'

For the purpose of this memo we use the definition from the Cambridge dictionary that describes capital goods as the buildings, machines and equipment that are used to produce products or provide services.

The different standards examined in this document do not offer additional guidance or specific definitions regarding the use of capital goods in LCA. Some standards provide examples of capital goods, for instance the PEF standard lists the following examples; machinery used in production processes; buildings; office equipment; transport vehicles; transportation infrastructure. The GHG protocol lists machinery, trucks and infrastructure as examples of capital goods.

Capital goods in horticulture
In this section, a list of capital goods that could be used for the production of horticultural products is presented. This list is not exhaustive and not all horticultural products will require all capital goods on the list. The list is used as a starting point to find the most relevant capital goods.

Cultivation phase
The following categories of capital goods used in the cultivation phase are described in the HFCR for horticultural products.

- Primary production structures
  - Greenhouse
  - Shading/energy sheet
  - Tunnel
  - Soil covering (pavements, etc.)
  - Lighting systems
  - Irrigation system
  - Air circulation system / Climate control system
  - Growing benches
  - Soil mixer
  - Plant filler
  - Transplanter
- Secondary production structures
  - Cooling cells
  - Processing barn
  - Storage buildings (cooled, ventilated)
  - Conveyor belts
  - Packaging machinery
- Supporting structures
  - Office
  - Canteen
- Energy production units
  - CHP unit
  - Boilers
  - Geothermal installation
  - Ground-source heat pump
  - Solar system
  - Heat buffers
- On-site vehicles/equipment
  - Vehicles
  - Tractor
  - Forklift
  - All-terrain vehicles (ATV)
- Soil cultivation
  - Cultivator
  - Cultipacker
  - Chisel plough
  - Harrow
  - Plough
  - Subsoiler
  - Rotator
  - Roller
  - Strip tiller
- Planting
  - Trowel
  - Seed drill
- Fertilising and pest control
  - Liquid manure fertiliser
  - Dry manure spreader
  - Sprayer
- Irrigation
  - Drip
  - Sprinkler
  - Centre pivot
- Produce sorter
  - Many types
- Harvest and post-harvest machinery
  - Many types depending on the crop
- Small equipment
  - Strimmers
  - Lawnmowers
  - Brush cutters
  - Chainsaws
  - Harvesting tools
  - Etc.

Other capital goods
The default data for distribution centres is provided in the PEFCR Guidance 6.3 (European Commission (2018), see 7.15.1. Distribution centre (DC)). This is to be used if no site-specific data is available.

Water use might differ substantially from an average distribution centre, but this might also differ significantly per product.
The default data for retail space is provided in the PEFCR Guidance 6.3 (7.15.2. Retail space). This is to be used if no site-specific data is available. For agricultural products, the default storage time should be adapted to make it product specific. Default storage time for ambient products can be 4 weeks, but this is not very realistic for bananas for instance. If we decide to use the data from the PEFCR Guidance, the default storage times have to be revised to match the product of the study.

The default data for fridges is provided in the PEFCR Guidance 6.3 (7.15.3. Fridge). This is to be used if no site-specific data is available.

The default data for small equipment that can be used during the use phase is provided in the PEFCR Guidance 6.3 (7.15.4. Small equipment to be considered). This is to be used if no site-specific data is available.

Overall, these 'other capital goods' are less critical compared to capital goods used in the cultivation phase as we will see in the following sections. These cover the environmental impact of capital goods in the RP-studies that have been conducted during the development of the HFCR for horticultural products.

Comparison of standards

The following table provides an overview of the treatment of capital goods in the LCA standards. A more detailed description of the content of the guidelines can be found below.

Table 1 *Summary of the treatment of capital goods in LCA guidance documents*

LCA Standard	Modelling of Capital Goods
ISO 14040/14044: Environmental Management: Life Cycle Assessment	Capital goods should be taken into account
ISO 14067: Carbon Footprint of Product	Capital goods can be excluded
International Reference Life Cycle Data System (ILCD)	No specific guidelines
Product Environmental Footprint (PEF)	Capital goods (including infrastructures) and their end of life should be excluded, unless there is evidence from previous studies that they are relevant. Linear depreciation shall be used. The expected service life of the capital goods shall be taken into account.
GHG protocol	Not required to include, unless it cannot be excluded from the process data of if the capital goods are relevant. Relevance may be based on many different factors including business goals and reduction potentials, product rules or sector guidance, and relative impact.
PAS 2050	Excluded
Ecological footprint	May be included
BPX 30-323	No specific guidelines. There is a 5% cut-off rule, based on mass, energy and environmental impact.
WBCSD (Life Cycle Metrics for Chemical Products)	No specific guidelines

During the goal and scope of an LCA study, the system boundaries shall be clearly defined.
ISO 14040 states that the 'manufacture, maintenance and decommissioning of capital equipment' should be taken into account when setting the system boundary. Specifics on how they should be taken into account are not provided.

In **ISO 14067** (carbon footprint of product), capital goods are only mentioned as an example. It states that they can be excluded in accordance with the goal and scope if their exclusion is not expected to significantly alter the conclusions.

In the **International Reference Life Cycle Data System** (ILCD) guidance, capital goods are not mentioned.

In the **Product Environmental Footprint** (PEF) methodology, capital goods are generally not taken into account. Capital goods (including infrastructures) and their end of life should be excluded, unless there is evidence from previous studies that they are relevant. If capital goods are included, the PEF report shall include a clear and extensive explanation, reporting all assumptions made. 'Linear depreciation shall be used for the capital goods. The expected service life of the capital goods shall be taken into account (and not the time to evolve to an economic book value of 0)' (European Commission, 2013).

PAS 2050 sets certain specific inclusions and exclusions for the system boundary as a default unless provided for in supplementary requirements. Capital goods are excluded from the analysis.

In the **GHG protocol***, c*apital goods (e.g. machinery, trucks and infrastructure) are listed as non-attributable processes. Non-attributable processes are not directly connected to the studied product during its lifecycle because they do not become the product, make the product or directly carry the product through its life cycle. Therefore, according to the GHG protocol, capital goods are not included. It is allowed to include them, as long as this is clearly documented. An exception is made for non-attributable processes that cannot be separated from attributable process data, or if the company determines that the process is relevant to the studied product. In that case, the non-attributable processes should be included. Relevance is determined by the company and may be based on many different factors including business goals and reduction potentials, product rules or sector guidance, and relative impact in relation to the rest of the inventory.

The **Ecological Footprint Standard** doesn't provide rules for definition of system boundaries. It is required to report all activities included within system boundaries. Most product EF analyses define the life cycle boundaries as including activities from cradle to point of purchase. Other possibilities include (i) purchase plus disposal, (ii) purchase plus consumer activities that use the product (iii) the EF of the societal infrastructure created as a result of consumers using the products (e.g. including the footprint of road construction in the footprint of a car). Capital goods may be included.

In the French LCA standard **BP X30-323**, no specific guidance is offered on the inclusion or exclusion of capital goods. As a general cut-off rule in the standard to developing sector-specific guides, total cumulated flows of less than 5% of the reference flow can be excluded. Exclusion criteria are mass, energy and environmental impact.

In the **WBCSD (Life Cycle Metrics for Chemical Products)**, nothing is mentioned on capital goods. The cut-off section is focused on dealing with the distribution of benefits and burdens of recycling.

Relevance of capital goods for horticultural products in previous LCA studies

Representative product studies
Multiple representative product (RP) studies were conducted during the development of the HFCR for horticultural products (see Goglio, 2020; Helmes et al., 2020b, c; Kan et al., 2020; and Ponsioen and Helmes, 2020a, b). The following sections describe which capital goods were taken into account, and their impact on the final results is reported.

Apples
In this study, the following capital goods used in the cultivation phase are taken into account in the inventory data.
- Field sprayer (application of plant protection)
- Broadcaster (fertilising)
- Tractor and trailer
- Trellis system
- Establishing the orchard

The following processes were identified as most relevant in the final results.
- Broadcaster (fertilising)
- Trellis system
- Establishing the orchard

Bananas
In this study, the following capital goods used in the cultivation phase are taken into account in the inventory data.
- Broadcaster (fertilising)
- Irrigation system
- Tractor and trailer
- Spraying aircraft (application of plant protection)
- Establishing the orchard
- Agricultural machinery

The following processes were identified as most relevant in the final results.
- Irrigation system
- Agricultural machinery

Phalaenopsis
In this study, a CHP unit, a geothermal heat production system and the greenhouse are incorporated in the capital goods. The greenhouse is modelled using data from ecoinvent, and from literature (Montero et al., 2011). Capital goods are listed as relevant life cycle stages for the following relevant impact categories:
- Climate change (8%)
- Resource use, energy carriers (8%)
- Resource use, mineral and metals (81%)
- Acidification terrestrial and fresh water (23%)

Roses
In this study, the CHP and the greenhouse are included using ecoinvent data. A hoeing rotavator is also included. The greenhouse is reported as one of the most relevant processes, but only in one of the five most relevant impact categories (3% contribution in acidification).

Tomatoes
In this study, a CHP unit, a geothermal heat production system and the greenhouse are incorporated in the capital goods. The greenhouse is modelled using data from ecoinvent, and from literature (Montero et al., 2011). Capital goods are listed as relevant life cycle stages for the following relevant impact categories:

Heat from CHP:
- Climate change (4%)
- Resource use, energy carriers (3%)
- Resource use, mineral and metals (75%)
- Acidification terrestrial and freshwater (12%)
- Respiratory inorganics (25%)
- Ecotoxicity fresh water (24%)

Heat from geothermal installation:
- Climate change (7%)
- Resource use, energy carriers (6%)
- Resource use, mineral and metals (69%)
- Acidification terrestrial and freshwater (13%)
- Respiratory inorganics (26%)
- Ecotoxicity fresh water (22%)

The following parts of the greenhouse are identified as most relevant processes:
- zinc
- aluminium
- electronics for control units
- steel
- glass

If these materials are used for the greenhouse, the CHP or the geothermal installations is not reported separately. For glass, it is clear that it is for the greenhouse, but some of the metals could be for the CHP or the geothermal installation as well.

Conclusion

In the RP-studies, we see that some capital goods are included in the inventory data and in some cases they are also identified as most relevant processes. For the horticultural products grown in greenhouses, the RP-studies show that the greenhouse structures are important as their components are among the most relevant processes in all RP-studies.

For the banana and the apple studies, the broadcaster (for fertilising), the trellis system and the establishment of the orchard, the irrigation system and agricultural machinery can be among the most relevant processes. However, for the irrigation and for the agricultural machinery, there is no distinction in the results of the study between the production of the capital goods, and the inputs and emissions in the use phase of the capital good. For fertilising by broadcaster for instance, the dataset consists of both production of the capital good and the emissions from fuel use. Therefore, these results do not show that these capital goods themselves are most relevant, but it is more likely that the fuel, electricity or water use during operation are most relevant.

We can conclude from the RP-studies that the greenhouse is a relevant capital good that should be included in the HFCR for horticultural products.

Literature review
As we were only able to conduct a limited number of case studies, we have also analysed relevant publications of LCA studies on horticultural products. The literature review is not exhaustive, but most relevant publications for this topic are covered. Since no specific standard was needed to be included in the literature review, there is a variety of environmental issues covered using different background data and impact assessment models. The aim of the literature review is to ensure we did not miss any capital goods not included in the RP-studies. The following paragraphs focus on studies that (partially) include capital goods. We found that many studies do not take capital goods into account (Soode et al., 2015; Gunady et al., 2012). This exclusion does not come as a surprise as we saw that generic standards such as the GHG protocol do not require the modelling of capital goods, but also specific studies for horticultural products exclude capital goods (Blonk et al., 2010). In this case the authors chose to be compliant with PAS 2050. Specific research on the impact of capital goods in agricultural products shows that in cases that included the capital goods, the environmental impact of capital goods exceeded the cut-off criteria for at least one impact category (van Paassen, 2016). This conclusion supports the inclusion of capital goods in LCA on agricultural products.

Greenhouse systems
In an LCA study on tomatoes grown in a multi-tunnel greenhouse in Almeria (Torrellas et al., 2012), the greenhouse structure accounted for 30%–48% of the impacts, depending on the impact category. The most important impacts in auxiliary equipment is substrate and electricity use. In the conclusion, the authors criticise the PAS-2050 carbon footprint method because this method prescribes excluding the capital goods, but since the impact from the greenhouse structure accounts for one-third to half of the impact (depending on the impact category), excluding the capital goods would neglect a significant share of the impacts.

More detailed results on the contribution of greenhouses can be found in a study from Montero et al. (2011). In this research, the environmental performance of different greenhouse production systems in different countries was compared. Several scenarios with different types of greenhouses in different locations were studied. Included in the study are: a tomato crop in a multi-tunnel greenhouse in Spain; a tomato crop in a glass greenhouse in Hungary; a tomato crop in a Venlo greenhouse in the Netherlands; a rose crop in a Venlo greenhouse in the Netherlands.

For tomato production in Spain, the results show that the structure of the greenhouse contributes a substantial amount to the overall impact in all impact categories and in all scenarios (between 30.4% and 47.8%). The auxiliary equipment also contributes a substantial amount to the impact in all impact categories and in all scenarios (between 30.4% and 49.2%). The contribution of the climate control system is negligible.

For tomato production in Hungary, the results show that the structure of the greenhouse contributes a substantial amount to the overall impact in all impact categories and in all scenarios (between 20.7% and 40.7%). The climate control also contributes a substantial amount to the impact in all impact categories and in all scenarios (between 21.9% and 42.7%). The contribution of the auxiliary systems is low (between 1.8 and 10%).

For tomato production in the Netherlands, the climate control system was by far the largest contributor to the overall impact (between 81.1% and 96.1%). Structure was the second burden for all impact categories (between 2.3% and 13.5%).
For the production of roses in the Netherlands, similar results were reported as for tomatoes in the Netherlands. The impact of the climate control system was the highest (between 95.4% and 98.9%). Structure was the second contributor, but the values were very low (between 0.53% and 2.43%).

The research from van Paassen (2016) also shows the contribution of capital goods is significant for almost all impact categories. Greenhouses in strawberry production have an especially important contribution to the total impact of the product.

We can conclude from the studies by Montero et al. (2011), Torrellas et al. (2012) and van Paassen (2016), that structure can be a relevant capital good to take into account. For the studies on the roses and the tomatoes from the Netherlands, the climate control system was also important. However the main contributions in this part of the life cycle does not come from the capital goods, but from the energy use (gas and electricity).

Lighting
Lighting systems are an important part of greenhouse production systems. Zhang, Burr and Zhao (2017) have conducted a comparison between the two dominant technologies used in greenhouse crop production – high-intensity discharge (HID) lighting and light-emitting diode (LED) systems. The authors conclude that the use phase dominates the total environmental impacts (approximately 74%–97% for HPS lighting systems and 78%–100% for LEDs).

These results show that if even if the lighting system is a relevant contributor to the environmental impact we can still exclude the capital goods, as long as we take the energy use of the system into account.

Horticultural products grown in orchards
The PEFCR on horticultural products does not aim to be applied solely to products grown in greenhouses, but also to products grown in orchards. Examples of this type of products can be mushrooms, lettuce or strawberries as studied by Gunady et al. (2012). In their research, the environmental impacts of these crops grown in Western Australia were compared.

Unfortunately, the manufacture and construction of buildings and infrastructure was not included in this study. However, all farm machinery was included because of the short lifespan and high maintenance needs. The authors used input–output data to include this contribution. In the results we see a high contribution of farm machinery operation for strawberries (58% of the total) and lettuce (52% of the total), but not for mushrooms (not reported). In the hotspot analysis however, the authors write that these contributions could be lowered by switching fuel type. This means that the contribution is not only from the capital goods, but (mostly) from the fuel combustion.

Fuel use and production of equipment is reported separately in a research on apple production in New Zealand (Milà i Canals et al., 2006). In this study the farm buildings and infrastructure production was taken into account, but did not show up in the results. The machinery production and maintenance was also included. The impacts from machinery production ranges from 7–12% in energy use, 5–11% in climate change and acidification, but the contribution is much higher for ecotoxicity (30%). The authors do confirm however, that more than 50% of most impact categories results arise from energy-related emissions. This confirms that energy use of capital goods is much more important than the production of the capital goods.

The importance of collecting site-specific data on fuel use is described in a study from Tassielli et al. (2018). The authors identified the variability in fuel use for 20 agricultural operations such as tillage, cultivation, planting, harvesting and post-harvest operations. The fuel use for tillage operations for instance ranges between 12.6 L and 76.0 L per ha, depending on tractor type and power, field conditions, operation depth and soil conditions.

Capital goods to include

There is no specific definition for capital goods in the context of the LCA or the horticultural sector. Therefore, we use a more general definition provided by the Cambridge dictionary: ‘The buildings, machines and equipment that are used to produce products or provide services.’

The commonly used LCA standards differ widely in terms of treatment of capital goods. For some standards, inclusion is mandatory. Some guidelines allow exclusion if they are not relevant, while others allow exclusion without any assessment of the relevance. As this could lead to exclusion of relevant impacts, it is worthwhile to look at previous studies in order to ensure this automatic exclusion does not lead to incomplete results.

Using the RP-studies and other relevant literature on horticultural products, we can conclude that the greenhouse structure is a relevant contributor to the overall results of LCA studies in this sector. The use of substrate can also significantly add to the overall environmental impact.

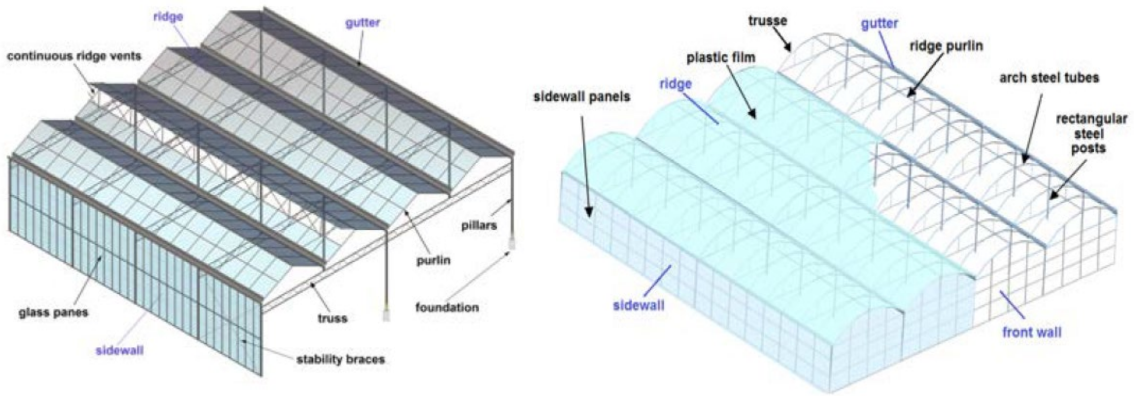
Often, other capital goods also appear to have a relevant impact, but a more thorough examination of these studies shows that not only the production of capital goods, but also the fuel, electricity or water use is included in the results. We saw this in the case of auxiliary systems, and climate control systems in greenhouses, but also in irrigation systems and agricultural machinery in orchards. The energy or water use is most often the major cause of the environmental impact, outweighing the production of the capital good itself.

This leads to the following recommendations for the PEFCR on horticultural products:

- The supporting studies should include capital goods to explore to what extent capital goods are relevant for the environmental performance of the life cycle of horticultural products.
- The materials used to build the greenhouse (aluminium, steel, glass, plastics) should be taken into account when modelling the life cycle of horticultural products. The inclusion of the light bulbs needs to be explored.
- Substrate production and use should be included.
- For other systems in greenhouses (lighting, irrigation, climate control), the energy and water use should be taken into account, but the production of these capital goods is less relevant.
- The production of capital goods used in orchards and greenhouses (both heavy machinery and small equipment) does not have to be taken into account, but the energy and the water use has to be included in the inventory data.

How to model greenhouses

If the company conducting the study does not have access to the company-specific information on greenhouses, the following background data can be used for two types of greenhouses: the (glass) Venlo greenhouse or the (plastic) multi-tunnel type shown in the following figure. The lifetime of both types of greenhouse is assumed to be 15 years (Montero et al., 2011).



(a) *(b)*

Figure 1 *Venlo type (a) greenhouse and the multi-tunnel (b) greenhouse (Valera et al., 2017)*

A standard Venlo type greenhouse has the following characteristics (described in Table 2). The inventory data is based on an area of 4 ha which corresponds to a volume of 225 200 m^3 (Montero et al., 2011). For the standard Venlo type greenhouse the default material requirements, transport, and processing inputs from Table 3 can be used.

Table 2 *Characteristics of a standard Venlo type greenhouse of 4 ha (Montero et al., 2011)*

Element	Size	Units
Greenhouse spans	25	u
Bays per span	2	u
Module width	8	m
Module length	5	m
Span width	8	m
Span length	200	m
Greenhouse width	200	m
Greenhouse length	200	m
Greenhouse perimeter	800	m
Greenhouse surface	**40,000**	m^2
Gutter height	6	m
Ridge height	6.76	m
Gutter to ridge distance	0.76	m
Greenhouse volume	**255,200**	m^3
Roof slope length	2.14	m
Roof slope angle	23	º
Roof surface	42,791	m^2
Front walls surface	2,552	m^2
Side walls surface	2,400	m^2
Number of ventilator windows	2,000	u
Ventilator dimensions	1.325 × 1.425	m
Ventilator surface	3,776	m^2

Table 3 *Materials and processes considered in the Venlo greenhouse structure inventory (adapted from Montero et al., 2011)*

Type	Venlo or similar	Amount per greenhouse	Unit
Area		4	ha
Lifetime (expected)		15	yr
Material	**Element**	**Amount per greenhouse**	**Unit**
Aluminium	Gutters, ridges, bars, ventilator opening mechanism, energy screens	112,439	kg
Concrete	Foundations and main path	182	m^3
Glass	Glass covering and walls	475,709	kg
Polyester	Polyester floor material and screens	5,810	kg
Steel	Roof bars, girders, stability braces, rails, posts, tie beams, foundations reinforcements, ventilator opening mechanism, high-wire system	439,315	kg
Processes			
Aluminium	Manufacturing processes	112,439	kg
Aluminium	Powder coating	10,071	m^2
Glass	Manufacturing processes	475,709	kg
Polyester	Extrusion plastic film	5,810	kg
Steel	Manufacturing processes	439,315	kg
Steel	Zinc (steel coating)	25,845	m^2
Transport	Lorry, 200 km*	206,654	tkm

* Distance of 55 km is adjusted to 200 km to align with the default transport distance of the multi-tunnel greenhouse

A standard multi-tunnel type greenhouse has the following characteristics (shown in Table 4). The inventory data is based on a surface of 1.94 ha which corresponds to a volume of 104,679 m^3 (Montero et al., 2011). For the standard type greenhouse the default material requirements, transport and processing inputs from Table 5 can be used.

Table 4 *Characteristics of a standard multi-tunnel type greenhouse of 1.94 ha (Montero et al., 2011)*

Element	Size	Units
Greenhouse spans	18	u
Span width	8	m
Span length	135	m
Greenhouse width	144	m
Greenhouse length	135	m
Greenhouse perimeter	558	m
Greenhouse surface	19,440	m^2
Gutter height	4.5	m
Ridge height	5.8	m
Gutter to ridge distance	1.3	m
Greenhouse volume	104,679	m^3
Roof arch	8.55	m
Roof angle to vertical	36	º
Roof surface	20,781	m^2
Front walls surface	1,550	m^2
Side walls surface	1,215	m^2
Number of roof ventilators	2 × 18	u
Ventilator dimensions	1.6 × 135	m
Ventilator surface	7,776	m^2
Insect-proof screening	8,009	m^2

Table 5 *Materials and processes considered in the multi-tunnel greenhouse structure inventory (adapted from Montero et al., 2011)*

Type	Multi-tunnel or similar	Amount per greenhouse	Unit
Area		1.94	ha
Lifetime (expected)		15	yr
Material	**Element**	**Amount per greenhouse**	**Unit**
Concrete	Foundations and main path	213	m^3
LDPE	Covering and floor	7,361	kg
PC	Walls	3,319	kg
PE	Insect-proof screens and plant gutter system	3,176	kg
PP	Raffia plant gutter system	206	kg
PVC	Clips and wedges	2,385	kg
Steel	Posts, frame reinforcements, gutters, axes, profiles, ventilators arches, high-wire system	149,675	kg
Wire	Plant gutter system	2,188	kg
Processes			
LDPE	Extrusion, plastic film	7,361	kg
PC	Extrusion, plastic film	3,319	kg
PE	Extrusion, plastic pipes	3,175	kg
PP	Extrusion, plastic film	206	kg
PVC	Injection moulding	2,385	kg
Steel	Manufacturing processes	149,675	kg
Steel	Zinc (steel coating)	9,043	m^2
Transport	Lorry, 200 km*	33,662	tkm
Wire	Wire drawing, steel	2,188	kg

* Distance of 605 km is adjusted to 200 km to align with the default transport distance of the Venlo greenhouse

Company-specific greenhouse inventory data

The data points to collect for modelling a company-specific dataset for a Venlo type glass greenhouse are the following:

Table 6 *The data points to collect for modelling a company-specific dataset for a glass (Venlo type) greenhouse*

Type (specify)	Venlo or similar	Amount per greenhouse	Unit
Area			ha
Lifetime (expected)			yr
Material	**Element**	**Amount per greenhouse**	**Unit**
Aluminium	Gutters, ridges, bars, ventilators opening mechanism, energy screens		kg
Concrete	Foundations and main path		m^3
Glass	Glass covering and walls		kg
Polyester	Polyester floor material and screens		kg
Steel	Roof bars, girders, stability braces, rails, posts, tie beams, foundations reinforcements, ventilators opening mechanism, high-wire system		kg
Processes			
Aluminium	Manufacturing processes	Amount of processing based on the material inputs listed above	kg
Aluminium	Powder coating		m^2
Glass	Manufacturing processes		kg
Polyester	Extrusion plastic film		kg
Steel	Manufacturing processes		kg
Steel	Zinc (steel coating)		m^2
Transport	Lorry, distance between the farm and the warehouse of the greenhouse manufacturer (a default value of 200 km can be used if this information is not available)	Distance (in km) is multiplied by the weight of the materials (in tonnes)	tkm

By combining the material bill of the greenhouse, the total size and the expected lifetime of the greenhouse, the material use in number of greenhouses is established. If there is no specific information on the lifetime of the greenhouse, the default lifetime of 15 years (Montero et al., 2011) will be assumed. To calculate the input of greenhouse per unit of product (in mass), the total yield is divided by the size of the greenhouse, the expected lifetime of the greenhouse and, in the case of different crops grown after each other, the share of cropping time it takes to grow the product. For a multi-tunnel greenhouse, the same calculation is used.

The greenhouse per mass of crop (GH_p in greenhouse per tonne) can be calculated as:

$$GH_p = 1 / (AGH_T * CT_p / CT_T) / (LTGH * YGH)$$

where AGH_T is the total area of the greenhouse (ha), CT_p is the cropping time (length of the cropping period) of crop p (weeks), CT_T is the total cropping time (weeks), LTGH is the lifetime of the greenhouse (yr), and YGH is the yield of the product for the entire greenhouse (t/yr).

For instance, in a greenhouse of 5 ha (AGH_T) that has an expected lifetime of 15 years (LTGH), 1,500 tonnes of tomatoes are grown (YGH) and the cropping period is 52 weeks (CT_p) out of 52 weeks total cropping period (CT_T). In that case, the amount of greenhouse per tonne of tomatoes is:

$$GH_{tomatoes} = 1 / (5 * 52 / 52) / (15 * 1500) = 8.9 \times 10^{-6} \text{ GH/t}$$

For instance, in a greenhouse of 1 ha that has an expected lifetime of 15 years, 200 tonnes of tomatoes and 50 tonnes of lettuce are grown, and the cropping period of tomatoes is 36 weeks out of a total cropping period of 48 weeks. In that case, the area of greenhouse per tonne of tomatoes is:

$$GH_{tomatoes} = 1 / (1 * 36 / 52) / (15 * 200) = 1.8 \times 10^{-7} \text{ GH/t}$$

For a multi-tunnel greenhouse, the same calculation can be used. The data collection Table 7 can be used to gather company-specific data.

Table 7 *The data points to collect for modelling a company-specific dataset for a plastic (multi-tunnel type) greenhouse*

Type (specify)	Multi-tunnel or similar	Amount per greenhouse	Unit
Area			ha
Lifetime (expected)			yr
Material	**Element**	**Amount per greenhouse**	**Unit**
Concrete	Foundations and main path		m^3
LDPE	Covering and floor		kg
PC	Walls		kg
PE	Insect-proof screens and plant gutter system		kg
PP	Raffia plant gutter system		kg
PVC	Clips and wedges		kg
Steel	Posts, frame reinforcements, gutters, axes, profiles, ventilators arches, high-wire system		kg
Wire	Plant gutter system		kg
Processes			
LDPE	Extrusion, plastic film	Amount of processing based on the material inputs listed above	kg
PC	Extrusion, plastic film		kg
PE	Extrusion, plastic pipes		kg
PP	Extrusion, plastic film		kg
PVC	Injection moulding		kg
Steel	Manufacturing processes		kg
Steel	Zinc (steel coating)		m^2
Wire	Wire drawing, steel		kg
Transport	Lorry, distance between the farm and the warehouse of the greenhouse manufacturer (a default value of 200 km can be used if this information is not available)	Distance (in km) multiplied by the weight of the materials (in tonnes)	tkm

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