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NEW PARADIGM IN URBAN DEVELOPMENT: LIFE CYCLE THINKING AND SUSTAINABILITY

Development of LCA Calculator to support community infrastructure co-design

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Abstract

Purpose LCA tools are increasingly used to support decision making. However, the current generation of tools is mainly targeted at users with significant background in industrial and environmental processes. This paper presents a novel process of developing the LCA Calculator with inputs from community members embedded in a co-design process. It demonstrates how engineering tools can be developed by considering end-user perspectives and used to communicate systems thinking in infrastructure co-design.

Methods The process of the LCA Calculator development was informed by the outcomes of community engagement through the co-design process. The method consists of four parts including horizon scanning of suitable technology options, LCA modelling, development of the LCA Calculator and pilot testing of the Calculator with residents from the selected case study community. The case study community are residents of a social housing estate in central London. The estate has a total of 123 flats arranged in three low-rise blocks with shared gardens and courtyards. Three technology options—wormery composting, rainwater harvesting and urban food growing—were used to illustrate the LCA methods and test the Calculator development.

Results and discussion The Calculator developed in this project pushes the boundaries beyond expert users to develop a new generation of LCA tools for a wider range of decision makers. The LCA results were communicated using the LCA Calculator in a workshop as part of the co-design process. The communication process was supported by the visual language of the Calculator, information sheets of the technology options and community members' involvement in the process of the Calculator development. The Calculator provided a solid base on which sustainable design discussions could happen. It provided to the participants valuable insights into the scale of material flow given different design choices—such as the amount of waste generated over a month or the irrigation requirements of a raised bed—and environmental impacts of these options.

Conclusions A prototype version of an LCA Calculator software tool has been developed to enable rapid assessment of conceptual design of engineering systems. The LCA Calculator was successfully tested at a community workshop, enabling clear engagement between engineering design choices and resource and environmental impacts. The Calculator facilitated a two-way exchange between community members and infrastructure designers that embeds end-user perspectives in the design and implementation of the infrastructure they use, taking into account lifecycle impacts of technology and material options.

Keywords Community engagement · Community infrastructure · Co-design · LCA Calculator · Life cycle assessment (LCA) · Sustainability

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1 Introduction

Decentralised infrastructure systems are likely to be important in building urban resilience and sustainability (van Vliet et al. 2005). Community-scale infrastructures, particularly community energy and green infrastructure systems, have an important role to play in adapting cities to environmental, social and economic change. Decentralised systems provide new opportunities for community and local economic development that have not been seen with conventional centralised infrastructure

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provision. Stronger engagement between local communities and infrastructure engineers and designers can enable positive co-evolution of engineered systems and society in response to environmental and climate change.

However, new tools are needed to enable stronger engagement between infrastructure engineers and designers and local communities.

Life cycle assessment (LCA) has evolved into a major decision support tool for sustainable design and management. The quality of the decision support that LCA provides is determined in terms of its relevance to the type of questions to be answered. Originally, the starting point in LCA was with its application to relatively simple choices, for instance, in making technical changes to a product or choosing one material over another in relation to packaging. The outcomes of LCA have then been used to influence consumer choices. Over time, there has been a shift in LCA thinking to more encompassing questions, such as the benefits of biofuels and biochemicals compared to the fossil-based materials that they are replacing (McManus et al. 2015).

LCA tools are increasingly used to support decision makers with quantitative evaluations of the decisions they make throughout the lifecycle of their products, systems or services. However, the current generation of tools is mainly targeted at experts or users with a significant background in industrial and environmental processes. There is considerable interest from the LCA community in pushing the boundaries beyond expert users (e.g. Brezet et al. 1999; Sinclair et al. 2007) and being able to develop the next generation of LCA tools that can help a wider range of decision makers such as industry managers, developers, urban designers, infrastructure planners, estate managers, product users and local residents or community representatives.

Engineering Comes Home was a research project based in London, funded by the UK Engineering and Physics Science Research Council (EPSRC). The project supports system-level sustainable design by engaging local communities and system users to co-design technology and infrastructure to improve well-being and reduce resource and environmental impacts in delivering water, energy, food and waste services (Bell et al. 2017). The project aims to develop a prototype design toolkit of potential technical options for meeting household needs and their lifecycle resource and environmental impacts. As part of toolkit development, an open-source life cycle assessment (LCA) Calculator has been developed to create a two-way exchange between community members and infrastructure designers that will embed end-user perspectives in the design and implementation of the infrastructure they use, taking into account lifecycle impacts of technology and material options. The LCA Calculator enables quick estimation of the impacts of new systems and technology to deliver water, energy and food (WEF) and manage waste at the household and neighbourhood scale, in a way that makes the information easy to understand and relevant to the community, while allowing infrastructure designers to better understand needs and use cases in the community.

This paper presents a novel process of developing the LCA Calculator with inputs from community members to support community infrastructure co-design. It demonstrates how engineering tools can be developed by considering end-user perspectives and used to communicate the systems thinking to local community in designing more sustainable and resilient infrastructure. Three technology options—wormery composting, rainwater harvesting and urban food growing—were used to illustrate the LCA methods and test the Calculator development.

2 Methods

The process of the LCA Calculator development must be understood in context of the co-design process, from which end-user requirements were ascertained, and which have directed content and design choices for the Calculator. Hereafter, the process of developing LCA Calculator consists of four stages including horizon scanning of suitable technology options (i.e. systems of interest), LCA following the requirement and guidelines of ISO 144004: 2006, development of the LCA Calculator and pilot testing of the LCA Calculator with residents from the selected case study community. The case study community are residents of a social housing estate in central London. The estate has a total of 123 flats ranging from one to four bedrooms arranged in three low-rise blocks with shared gardens and courtyards.

The project began when a joint management board of a social housing provider expressed interest in piloting the co-design process with residents of one of their estates to address sustainability in their properties (Bell et al. 2017). We then carried out qualitative research on people's use of water, energy and food in their homes (Johnson et al. 2017). This information helped form the basis for the choice of systems to include in the horizon scan, LCA and design choices for the tools used in subsequent engagement with the community. This engagement was primarily through three co-design workshops that were intended to develop new infrastructure systems and technologies that might better meet those needs with lower resource and environmental impacts and in line with the community's shared priorities and governance structures. In the first workshop, residents described existing systems and opportunities and ideas for change. From these initial ideas, based on feasibility, desirability and practicality, we shortlisted wormery composting, waste compaction, food growing, rainwater harvesting and food sharing as systems to evaluate in more detail with the community. In the second co-design workshop, the LCA Calculator was used to support this evaluation and the community selected rainwater harvesting as the technology to be developed further through the design process. A prototype of the chosen option, in this case, smart rainwater harvesting system from a small company called Over The Air (OTA) Analytics, was installed on the estate, and the final co-design workshop developed options for larger-scale implementation. The overall co-design approach is shown in Fig. 1.

The development of the LCA Calculator to support the selection of options in co-design workshop 2 was a central element of the work, which has potential for wider application in other participatory processes involving non-expert users. The method for developing the LCA Calculator involved horizon scanning of potential technologies, definition of the LCA framework and data gathering, creation of a visual language accessible to the community, software design and engineering and field testing of the tool.

2.1 Horizon scanning

Horizon scanning is carried out through desk based research with an aim to systematically examine the technology options that are suitable for neighbourhood and home scales. Desk research involves a wide variety of sources, such as the Internet, government ministries and agencies, non-governmental organisations, international organisations and companies, research communities and on-line and off-line databases and journals.

A structural systematic review relating to water, energy, food and waste technologies that are suitable for home and neighbourhood scales is conducted as detailed in Fig. 2.

2.2 LCA

The LCA employed in the Calculator follows the standard LCA framework (ISO 14040:2006). The first steps in a typical LCA study involve defining its goal and scope of analysis. This is followed by the development of a Life Cycle Inventory (LCI) that forms the basis for a life cycle impact assessment (LCIA) and results interpretation. The definition of the system being assessed and the function of the system are crucial elements of a LCA study. This involves describing the system that is being analysed, such as an individual product, a production process, the provision of a service or some other human activity, both quantitatively and qualitatively. What distinguishes the LCA and the subsequent LCA Calculator in this study is the input, from the start of the research process, from the community through the initial contact and qualitative research and co-design workshops, to create tool that not only facilitates the communication of systems thinking (via result interpretation) to the infrastructure co-design process with the community but also encodes within the different stages of LCA development, thus shaping the potential co-designed engineering solutions so that they have a higher likelihood of positively impacting resource use and sustainability in the design of community infrastructure.

2.2.1 Goal and scope

The goal of the study, informed by the outcome of initial contact and qualitative research, is to quantify the environmental impacts of the decentralised technology options from the horizon scanning, which are suitable for home and neighbourhood scales. The selection of technologies was part of the Engineering Comes Home co-design process and was initially informed by the horizon scanning and then iterated following the outcomes of co-design workshop 1. Residents participated in co-design workshop 1 to develop alternative technology ideas and intervention options leading a short list of five technologies for LCA, three of which are discussed here. For each technology, a baseline reference is established for comparison purpose. System boundaries for the three case study technology options were also determined using input derived from the first co-design workshop, where the community was facilitated to create systems of interest where they saw the possibility to intervene. The workshop participants presented their systems of interest to the group during the first

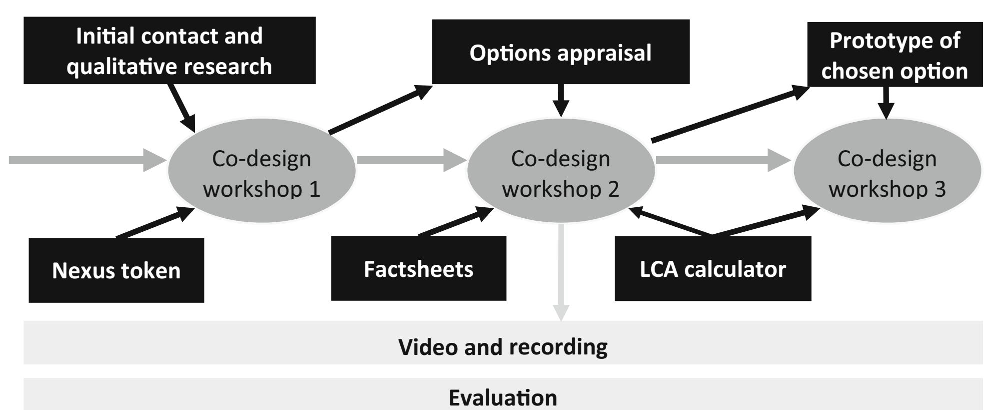

Fig. 1 Overall co-design approach

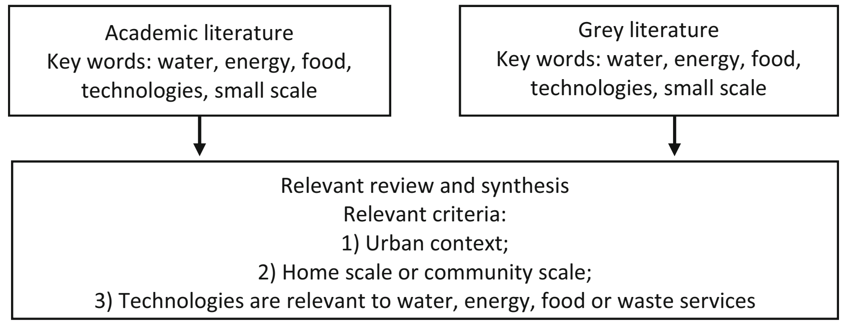

Fig. 2 Systematic review of technologies for home and neighbourhood scale

workshop, and these systems and the discussions around them were used to determine:

- Systems of interest to the participants
- System boundaries from the participant perspectives
- Explicit requirements—from the discussions at the start of the first co-design workshop
- Implicit requirements—from the systems of interest and from line-by-line analysis of workshop transcripts

These factors were used to decide upon the scenarios to be implemented in the Calculator (see Section 2.3).

The system boundaries are shown in Fig. 3, with detailed explanations below.

The system boundary of the wormery (Fig. 3a) includes wormery composter, water required for composting, direct emissions from composting process and compost for fertiliser substitution. It is assumed that food waste collection is conducted manually; hence, no associate impacts was included. The wormeries are placed in the common area of the case study community. Landfill of the compostable waste is used as a reference baseline for comparison purpose.

The system boundary of rainwater harvesting (Fig. 3b) consists of gutters and pipes, storage tank and pump. It was assumed that the rainwater harvested was used for watering gardens for plants and food growing by replacing tap water. Drinking tap water is selected as a reference baseline.

The system boundary of food growing (Fig. 3c) starts from obtaining of suitable seeds and includes all the chemical and associated fuel consumption and use of machineries including water, fertiliser, pesticide and fuel use. Direct emissions from the fertiliser are also included in the system boundary. Tomato growing is used as a case study, and it was assumed that all tomatoes harvested are for consumption within the case study community. Scenarios on growing food with conventional chemical fertiliser and drinking water as well as with composting fertiliser and rainwater harvested were developed for comparison purpose.

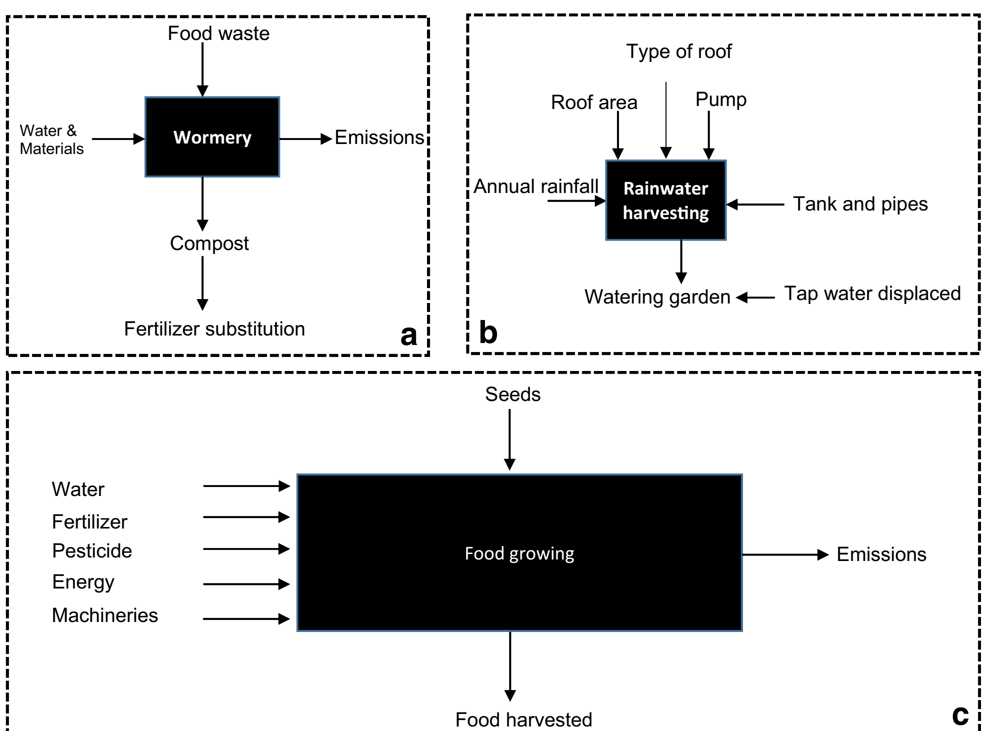

Fig. 3 System boundaries for wormery (**a**), rainwater harvesting (**b**) and food growing (**c**)

Data collected for this study comes from publicly available source with reliable reference as detailed in Section 2.2.2 and specific parameters to the case study community. The LCA results are then fed into the Calculator which was used in co-design workshops enabling community residents to engage in decision making in infrastructure design. Different functional units are used for different scenarios and scales. For example, for wormeries, functional units includes per tonne of food waste and the amount of food waste produced by a household and the case study community within 1 year.

From the initial contact, the joint management board (JMB) of the case study community expressed interest in the sustainability of their housing estate. Greenhouse gas (GHG) emissions and energy use were two issues they were concerned about but felt uncertain how to address these in the existing stock they manage, which have unmetered supplies of energy. The qualitative research with residents showed that they were particularly concerned about wasting energy and water. In workshop 1, residents expressed interest in generating electricity for communal use and in reducing all forms of waste on the estate and opportunities for recycling or repurposing waste. Because of these diverse concerns and interests, this prototype version of Calculator included two layers of information: (1) material flow relating to the amount of garden space, amount of water saved, amount of waste reduced, amount of food produced and the number of flats/residents participated and (2) GHG emissions and energy consumption as overall impact categories.

2.2.2 Data source and inventory

Building on the horizon scanning of technologies that are suitable for community scale, data were then collected and processed in an excel table before an inventory was developed. The development of the inventory followed an iterative process embedded in the co-design process. Generic data of systems of interest were first gathered through literature to develop an inventory. Further iterations were then applied to the inventory using specific data linking to the case study community through qualitative research and co-design workshop 1, as detailed in Section 2.3.2. Using the three scenarios of food growing, rainwater harvesting and wormery composting, the sections below provide details of data source and data gathered for each of the selected technology options.

Wormeries are used for composting unavoidable food waste generated from the case study community. It was assumed that the amount of food waste generated per person per week (pppw) was 2.14 kg, and unavoidable food waste accounted for 40% of the food waste generated including water required, direct emissions generated from composting and the amount (Waste and Resource Action Programme (WRAP), 2015). Among the food waste, 70% of food waste was compostable. Data on emissions from composting process and the amount of fertiliser that compost can substitute were gathered from literature (Andersen et al., 2010). Table 1 shows the detailed material flow of the wormery composting process and sources of data collected. It was assumed that wormeries were made of polyethylene (PE) plastic with 4 kg PE for a 100 L wormery.

The amount of rainwater harvested is calculated using Eq. (1) (Environment Agency, 2012):

$$\text{The amount of rainwater harvested } \left(\mathrm{m}^3\right) = \text{Roof area } \left(\mathrm{m}^2\right) \times \text{Hydraulic coefficient} \times \text{Annual rainfall (mm)}/1000 \quad (1)$$

The roof area was obtained from Google Maps. Hydraulic coefficient was obtained according to the type of roof (Environment Agency 2012). Annual rainfall was obtained from a meteorological observation site located in Hampstead of North London called NW3 Weather using average rainfall in London (NW3 weather 2017). The tank size was calculated using Eq. (2) (Santos and Taveira-Pinto 2013):

$$\text{Tank size} = \text{the amount of rainwater harvested } \left(\mathrm{m}^3\right) \times 0.06 \quad (2)$$

Information on gutters and pipes including length and type of material was obtained from literature (Ghimire et al. 2014). Table 2 shows the detailed material flow of rainwater harvesting systems and corresponding data sources. The material flow was collected based on a domestic rainwater harvesting systems with a volume of 6.2 m^3.

Data for tomato growing in an urban environment was collected with detailed inputs (i.e. fertiliser, irrigation, pesticides) from the UK Department for Environment, Food and Rural Affairs annual farming statistics (Department for Environment, Food, and Rural Affairs (DEFRA), 2015). Fuel use for growing tomato was obtained from agricultural LCA model (Williams et al. 2010). The crop yield for small-scale growing was obtained from literature (Rabin et al. 2012). Table 3 summarises the material flow and their data sources.

2.2.3 LCIA

ReCiPe Midpoint methodology (Goedkoop et al. 2008) was used to calculate GHG emissions and energy depletion. The primary objective of the impact assessment stage is to transform the long list of Life Cycle Inventory results into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. These indicators are then classified into categories according to their potential long-term damage. A midpoint approach was taken; midpoint methods convert the emissions of hazardous substances and extractions of natural resources into impact

Table 1 Material flow for composting one tonnes of food waste

Wormery composting	Material flow	Unit	Data source
Water	89	L per ton organic waste	Andersen et al. (2010)
Annual CO_2 emissions	73	kg CO_2 per ton organic waste (wet)	Andersen et al. (2010)
Annual CH_4 emissions	0.8	kg CH_4 per ton organic waste (wet)	Andersen et al. (2010)
Annual N_2O emission	0.36	kg N_2O per ton organic waste (wet)	Andersen et al. (2010)
Substitution of fertiliser	200	kg chemical fertiliser	Andersen et al. (2010)

category indicators. Detailed explanations of these impact categories can be found in the Section 3. Only classification and characterisation are applied; weighting and normalisation are not considered in this paper.

2.2.4 Result interpretation

Result interpretation is an important process aimed at assessing the LCIA results and interpreting the results to reach a conclusion. As per ISO 14044 (2006), interpretation needs to include identification of significant issues and evaluation of the study and conclusions, recommendations and reporting.

The identification of the significant issues was achieved through the comparative results of the two selected indicators (GHG and energy consumption) by allowing users to choose different technology options and compare them with reference systems embedded in the LCA Calculator, as detailed in Sections 2.3.2 and 2.3.3.

The evaluation of the study was achieved with the modelling techniques used in the LCA Calculator as detailed in Section 2.3.3, allowing users to vary the input parameters to identify how sensitive the results might be.

The results were contextualised and discussed in the second co-design workshop (Fig. 1) with the aid of the visual language developed in the Calculator (Section 2.3.4). The results were interpreted in conjunction with additional information sheets and exercises that provided context to the technological options and anchored the scenarios in the participants' real lives, respectively, enabling users to understand the trade-off of different technology options to make informed decisions.

2.3 Development of the LCA Calculator

The Calculator development consists of three stages: (1) defining the scope for scenarios pertinent to the community; (2) implementing the system's model as a backend for the Calculator; and (3) implementing a user friendly frontend allowing model interaction and presentation. Figure 4 shows the novel process of the LCA Calculator development, which was informed by the outcomes of community engagement (through initial contact and qualitative research and co-design workshops) and conventional iterative LCA approach.

2.3.1 Incorporating the community user into the Calculator

The first co-design workshop allowed us to identify implicit and explicit requirements with the community members. The activities were designed to produce explicit choices, for example the group decided to focus on reducing waste, rather than generating low carbon energy. The workshop structure encouraged open debate for participants to express their hopes and concerns. We analysed these recorded discussions to generate a set of implicit requirements for our design brief. The four key requirements that emerged were the need for any technical interventions to be "human-focused" (e.g. community-building, enabling resilience) "practical" (e.g. easy to use), "reduce concerns" (e.g. not be open to theft or manipulation from non-residents) and to be aesthetic. We used these requirements to select from the horizon scanning three main technology options and contextualise which aspects of these systems would be of most interest to the community to be shown through the Calculator design. The co-design workshops also demonstrated the kinds of questions that the

Table 2 Material flow for residential building rainwater harvesting systems

RWH system	Volume/length	Mass (kg)	Data source
Storage, tank, polyethylene (m^3)	6.2	5.8	Ghimire et al. (2014)
Collection 1, gutter, 101.6 mm diameter PVC	30	89.3	Ghimire et al. (2014)
Collection 2, 101.6 diameter PVC	6.4	19.1	Ghimire et al. (2014)
Distribution pipe, 19 mm diameter CPVC	23.7	10.6	Ghimire et al. (2014)
Pump (unit)	1	NA	Ghimire et al. (2014)
Electricity, pumping to the point of use (kwh)	0.49	NA	Ghimire et al. (2014)

Table 3 Material flow for urban food growing

Urban food growing	Tomato	Broccoli	Lettuce	Potatoes	Data source
N fertiliser (kg/ha)	59	152	56	103	Department for Environment, Food, and Rural Affairs (DEFRA) (2015)
P fertiliser kg/ha)	80	0	0	92	Department for Environment, Food, and Rural Affairs (DEFRA) (2015)
K fertiliser (kg/ha)	78	0	0	233	Department for Environment, Food, and Rural Affairs (DEFRA) (2015)
Pesticide (kg/ha)	0.96	0.25	0.35	0.42	Department for Environment, Food, and Rural Affairs (DEFRA) (2015)
Primary energy use (GJ/ton)	1.40	1.40	1.40	1.40	Williams et al. (2010)
Field diesel	0.45	0.45	0.45	0.45	Williams et al. (2010)
Machinery manu.	0.14	0.14	0.14	0.14	Williams et al. (2010)
Crop cooling, drying and storage	0.42	0.42	0.42	0.42	Williams et al. (2010)
Pesticide manufacture	0.08	0.08	0.08	0.08	Williams et al. (2010)
Fertiliser manufacture	0.31	0.31	0.31	0.31	Williams et al. (2010)
Irrigation (m^3/ha)	304.14	304.14	304.14	1128.47	Department for Environment, Food, and Rural Affairs (DEFRA) (2015)

community would be likely to ask subsequently of the Calculator. In order to answer these questions, it was necessary to reframe the data in the LCA to incorporate a user's perspective. For instance, we began to map LCA data to user-generated questions such as "how much water will I need for my garden?", "how much space will the water tank take up?" and "will there be enough room in the bins?" Moving forward from this, we designed a usable and engaging front end for use in subsequent workshops (see Fig. 5 and Section 2.3.4).

The result was the detailed implementation of five scenarios focused on three main technology options: wormery composting, rainwater harvesting and food growing. An introductory food waste management scenario was developed for presentation purposes, as well as a food sharing scenario.

Detailed methods for the three stages development are presented in the section below.

2.3.2 Modelling parameters

For wormery composting, the amount of food waste is the key factor affecting the number of wormeries required and the amount of compost produced. Based on the statistics

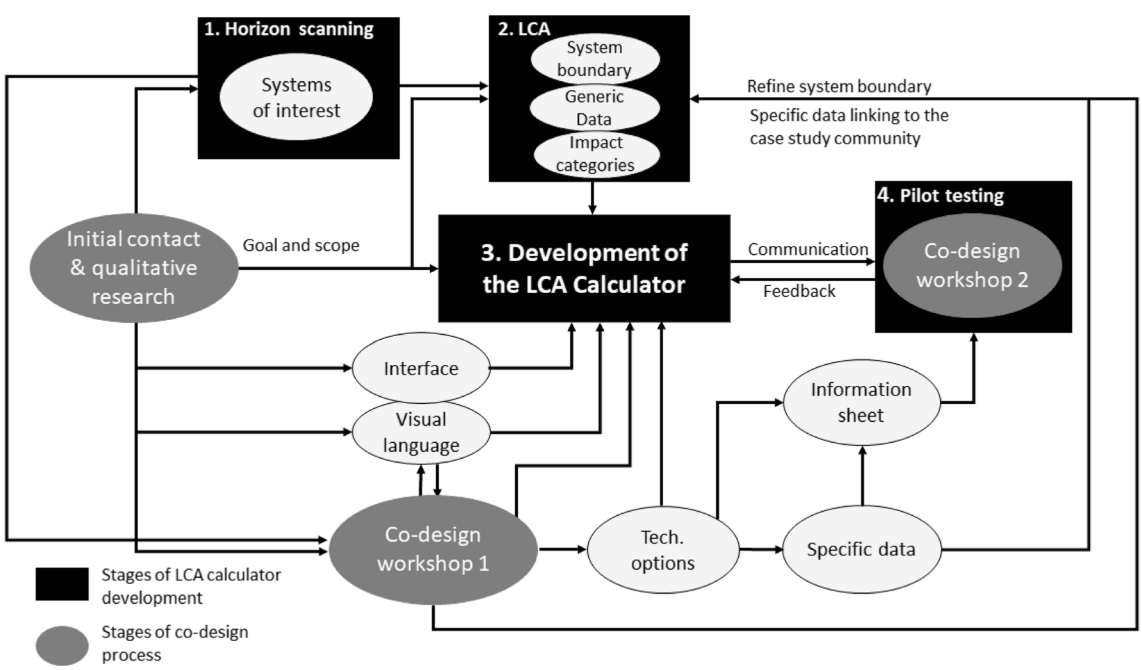

Fig. 4 Process of LCA Calculator development embedded in the co-design process

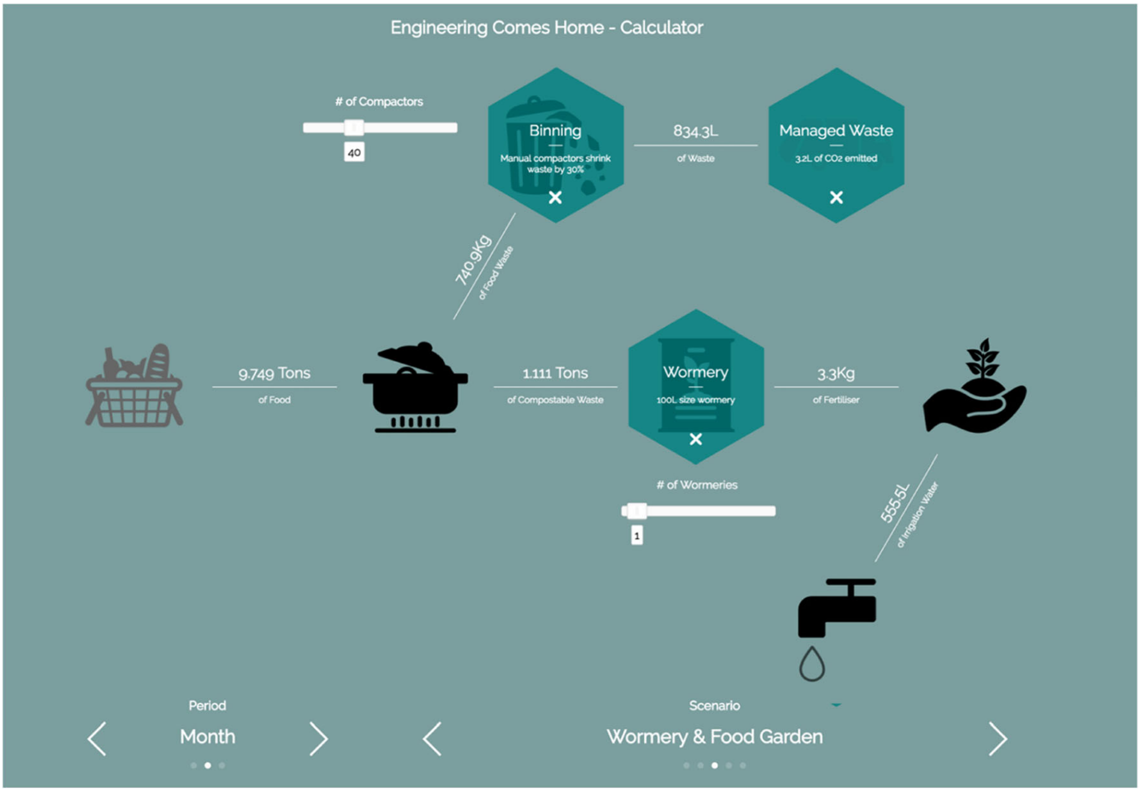

Fig. 5 LCA Calculator interface (iilab, 2017)

data from WRAP (2015) on average food waste produced (i.e. 2.14 kg pppw), the number of residents is used as an input to calculate the amount of food waste. Depending on the amount of food waste, average water required is calculated automatically. With the assumption of food waste generated per person per week, the LCA model uses the number of residents as an input and generates outputs such as amount of compost generated as well as the amount of fertiliser that it can substitute. Depending on the volume of wormery composter and the amount of food waste each wormery can take, the number of wormeries is calculated using the amount of food waste generated by the number of residents.

For rainwater harvesting system, the area of roof available and the type of roof are used as inputs, giving the amount of rainwater harvest and the total tank size. As the rainwater was mainly used for watering garden in the case study, water loss during the watering process was assumed to be 40%. A material flow for rainwater harvesting for watering garden is then established as shown in Table 4.

Key inputs for food growing were growing area and the type of food (i.e. tomato in this case study). With this information, the amount of material and energy inputs as well as the amount of food harvested were then calculated as shown in Table 4.

Once the key inputs for the modelling parameters are identified. A material flow balance sheet was created (Table 4) and used as a basis for the Calculator development. Building on the material flow as shown in Table 4, environmental impacts (i.e. (GHG emissions and energy consumption) using the methods in Section 2 are then calculated and displayed in the Calculator.

2.3.3 Model implementation

The first modelling approach implemented used a simplified stock and flow approach with linear relationships and present intervals. The modelling parameters were used as constant flow ratios, and a selection of dynamic input parameters was surfaced to the frontend including an interval parameter.

In the following iteration of the model, used when developing a more detailed rainwater harvesting module, time was added to the model and time series provided as inputs (specifically for rainfall data) enabling a simplified systems dynamic model with linear relationships. Additional types where also added in order to surface specific anomalous conditions to the user (such as the lack of water in a rainwater harvesting tank).

Each process was modelled as monadic functions, over a state monad keeping a record of the models stock, taking model constants and user input parameters as arguments and calculating the new state as a side effect. In the second iteration of the model, process functions and the system state are indexed by time intervals. Material flows are modelled as typed quantities, enabling some basic consistency guarantees via the purescript compiler's type checker.

Table 4 Modelling parameters, inputs and outputs of studied systems for LCA Calculator

Process	Parameters						Input					Output					
Home boundary	No. of occupants	No. of bedrooms	Garden surface (m^2)	Garden type	Roof area (m^2)	Roof type	Food (kg)	Food waste (kg)	Compostable food waste	Rain water (m^3/year)	Fertiliser (kg)	Waste weight (kg)	Edible food waste ratio	Inedible food waste ratio	Waste weight (kg)	Fertiliser (kg)	Food (kg)
Food	1						585						11.40%	7.60%			
Waste generated		1										100					
Technology options	No. of occupants	No. of bedrooms					Food (kg)	Food waste (kg)					Edible food waste ratio	Inedible food waste ratio	Waste	Fertiliser (kg)	Food (kg)
Wormery								1	70%						8892	1111.5	
Rainwater collection					2738	Pitched roof tiles				1464							
Food garden			100	Tomato							217						244

Scenarios were implemented as compile-time sequences of process functions. This allows reuse and composition of processes in a specific sequence to create scenarios.

2.3.4 Interface implementation of the Calculator

In designing the Calculator for public use, it was important to ensure not only usability of the interface, but that the Calculator would be able to answer questions relevant to its users in their lived experience. To meet this need, it was necessary to take a user perspective; to define the questions users might pose of the Calculator about a system, translate them as input parameters to the model and to determine how to interact with models and present answers. The initial focus for the Calculator was interdependent water and food systems, including food growing and food waste (including composting versus anaerobic digestion).

The interface consists of process nodes connected by flow arrows. Nodes can be boundary objects (system inputs and outputs such as food shopping, waste disposal trucks), transformative processes (such as cooking, composting) or productive processes (such as solar panels, rainwater harvesting). Each node can be clicked or tapped on to reveal input parameters when they exist or more detailed information (for instance environmental impact data on waste management processes). Flow arrows display quantities with their units.

Scenarios are presented in a sequence of increasing complexity (with more nodes and arrows) in order to allow users to be progressively introduced to additional parameters and richer systems.

The choice of scenario, data presentation and input parameters was informed by the input from the pilot community. Care was taken to ensure that the naming of nodes was accessible and accurate. A simple visual language was developed based on existing icons which were introduced as token objects and used in the first workshop's preparation activities with the pilot community.

2.4 Pilot testing of the LCA Calculator

The Calculator was installed in tablets and piloted in two community workshops as part of the Engineering Comes Home co-design approach (Fig. 5). The Calculator enables community residents participating the workshop to understand (1) the material flow of water and food in the technology options and (2) selected environmental impacts of the technology options. Its design visually conveys the interconnected nature of the WEF nexus systems being explored and focusses on questions of sustainability in terms of resource use and environmental impact of choices. The Calculator was introduced with a simple example of food-consumption-waste, with instructions of the interface and sliding scales. Once the participants were familiar with the material flow, more complex systems and environmental impacts of the technologies options were then introduced.

Participants were able to vary the number of flats consuming food to determine the overall amounts of food and waste flowing through the system over time periods of days, months or years. The system was further elaborated to include alternatives for food waste including waste compaction, and a wormery plus gardening, and introducing the option of rainwater collection for irrigation of the garden (Fig. 5). These scenarios increase in complexity in order to introduce first the interface to the community participants and then to facilitate discovery of systemic connections within the nexus, leading users to discover material flows and implications of design choices of technology options.

In a second set of scenarios, rainwater collection was explored. Time frame options were given for daily, weekly, monthly, yearly and seasonal variation, and various uses for rainwater were explored.

The Calculator was used in conjunction with additional information sheets and exercises that provided context to the technological options and anchored the scenarios in the participants' real lives, respectively.

3 Results and discussion

Horizon scanning of technologies were selected and included in the Calculator. The following criteria were used to make the following selections: (1) technologies for water, energy or food sectors, (2) decentralised options, (3) suitable for deployment for home or a small community, (4) input from the social housing management team and (5) input from the qualitative research. Initial technology options for the prototype Calculator database include composting, anaerobic digestion (AD), solar panels, urban food growing, hydroponics, grey water reuse at home and at community level and rainwater harvesting. These technology selections were iterated after using feedback from the first co-design workshop with community members. The further criterion of waste compaction was added, and solar panels, hydroponics and anaerobic digestion were removed from the technology options. Inventory data for LCA were then gathered using a similar approach to those technology options presented in Section 2.

3.1 LCA contextualisation

Results of the three technology options on rainwater harvesting, wormery composting and urban food growing (tomato plants) are shown in Table 5. Reference cases were used for comparison purpose. For rainwater harvesting, the reference case is mains water in the UK; for wormery composting, the reference case is landfill of unavoidable food waste without energy recovery; and for urban food growing, the reference case is food growing without the use of rainwater or compost produced. Two indicators were used including GHG emissions and energy consumed. All impacts presented in this section are based on annual cumulative impacts on the case study community in London as described in Section 2. Different functional units are used for different scales (i.e. person, household and community) when the results of environmental impacts are shown in the Calculator.

Based on the climate conditions and the roof space available in the case study community, a total 1464 m^3 of rainwater can be harvested over 1 year, which requires a tank size or several tanks with the total size of just over 110 m^3. Rainwater harvesting systems at the community scale can save GHG emissions (reducing from 527 kg GHG from mains water to 82 kg GHG per year). There is also a slight saving of energy consumed. This is because rainwater harvesting requires pumping energy of 0.49 kwh.

Based on the population of the case study community and statistics of food waste generated in the UK household, the case study community could generate over one ton of compost which requires about 15 composting bins. A 60% of annual cumulative GHG savings can be achieved if all unavoidable food waste (40% of total food waste) are composted, instead of going to landfill. Nearly 50% of energy savings can be achieved by switching from landfill to composting. This is because wormery composting does not require any direct energy input and the embodied energy input for composting bin is about 90 MJ with over 95% from embodied energy required for PE plastics materials used. In contrast, the landfill reference case requires transportation of food waste to landfill site, site operation and landfill gas treatment.

Based on the area of garden available, the UK growing conditions and the type of food grown (i.e. tomatoes), a total of 224 kg of tomato can be harvested during one season of growth. Tomato growing in the case study community with rainwater harvested and compost produced can save just over one third of GHG emissions, compared with traditional tomato growing with mains water and chemical fertiliser. More than half of energy consumed can also be saved. This is due to the energy required to produce chemical fertiliser in comparison to compost from food waste.

The material flow data collected for LCA and LCA results formed the basis of the LCA Calculator. GHG emissions and energy consumption are calculated using the scenarios of technology options, time duration and scale (i.e. personal, household level, or estate level) using the methods presented in Section 2.1. The LCA results were communicated using the LCA Calculator in the second co-design workshop, as shown in Fig. 2. The Calculator interface was walked through by the Engineering Comes Home team using simple systems to allow the community to become familiar with systems thinking before moving onto more creative use of the Calculator to answer questions such as the following: What impact do our

Table 5 Annual cumulative life cycle GHG emissions and energy consumption of the case study technology options

Technology option	GHG (kg CO_2 eq)		Energy consumed (MJ)	
	Cumulative[a]	Reference[b]	Cumulative[a]	Reference[b]
Rainwater harvesting	82	527	4025	5416
Wormery composting	1759	4073	90	176
Urban food growing	317	1001	3800	7474

[a] Annual cumulative impacts are based on the cases study community as mentioned in Section 2

[b] For rainwater harvesting, the reference case is mains water in the UK; for wormery composting, the reference case is landfill of unavoidable food waste without energy recovery; and for urban food growing, the reference case is food growing without the use of rainwater or compost produced

design decisions have on resource use? What is practical to implement in this physical location? What compromises might we have to make when implementing our design solution?

The communication process was supported by the visual language of the Calculator and information sheets of the technology options and community members' involvement in the process of tool development embedded in the co-design process. To this end, the choices determining the system boundaries in the Calculator were explained and contextualised openly with the workshop participants. Further discussions on the communication of LCA outcomes through the Calculator were presented in Section 3.3 (pilot testing of LCA Calculator).

3.2 LCA Calculator and its interface

The LCA Calculator (Fig. 5) developed has a browser based interface enabling enables quick estimation of the impacts of new systems and technology to deliver water, energy and food and manage waste at the household and neighbourhood scale. The Calculator consists of two layers of information: (1) material flow and (2) environmental impacts. For each technology option and their reference system, the tool calculates material flow of resource consumption and waste generation at individual, household and community level.

Further iterations of the backend will focus on improving the correctness and flexibility of the model, for instance via improving the interface with LCA experts to enable checking calculation results against test input parameters and datasets, as well as defining a DSL (domain specific language) which LCA experts can use to describe scenarios and model parameters.

Other software engineering aspects which will benefit the LCA Calculator correctness include a better use of the type system to statically check scenario dimensions, enable graphs of processes clarifying the semantics of cycles and allow non-linear relationships to implement systems dynamic models, implementing process functions as arrows in order to modify scenario graphs at runtime, specifying process graphs as an algebra and implementing various modelling approaches as interpreters.

With regard to the frontend, sliders were used to allow users to choose the time scale (day, month and year), number of occupants (within the community) and the different technology scenarios (e.g. combination of wormery and food garden). In a chosen scenario, sliders are used to select the parameters. For example, in the wormery and food garden scenario, users were able to select the number of wormeries that they would like to have, by clicking on the icon of wormery. By sliding the number of the wormeries, the amount of fertiliser and food waste to be managed will be automatically updated. Within each scenario, users can select to display information about environmental impacts (e.g. GHG emissions within the time period and scenarios selected).

Further work on the interface will focus on representing quantities visually, allowing to switch between various information layers that will display quantities relevant to a particular question filtering via the types of material flows or environmental impacts. Enabling navigation in time and displaying time series and anomaly conditions will also further enable the exploration of the model by users.

3.3 Pilot testing of the LCA Calculator

LCA tools are increasingly used to support decision makers with quantitative evaluations of the decisions they make throughout the lifecycle of their products or systems. However, the current generation of tools is mainly targeted at experts or users with a significant background in industrial and environmental processes. The Calculator developed in this project pushes the boundaries beyond expert users to develop a new generation of LCA tools for a wider range of decision makers, such as industry managers, developers, urban designers, infrastructure planners, estate managers, product users and local residents or community decision makers.

The Calculator was used with community participants in co-design workshop 2 as shown in Fig. 2. It was presented to the participants using a simple system of waste compaction, which had been previously determined as a system of interest to the community and which allowed for the exploration of broader environmental impacts through the discussion of the effect of waste compaction on GHG emissions and energy use. When presented to the workshop participants, the boundaries of the modelled system—the first scenario—were explained. These were then expanded in subsequent scenarios to introduce in a step-wise manner both systems thinking and the extension of impact beyond the immediate effect on the lives of residents in the estate. The Calculator was helpful in providing further information on the technology options and to anchor its use in practical, community-relevant questions. For example, the workshop participants based their design in each scenario on tangible questions such as how many households do I think will get involved in separating of their food waste? How much garden space do I want to see used for food growing? Do I want a compactor at every stairwell of the estate, or just one large one for the whole estate?

However, not all the indicators proved meaningful to the residents. The GHG emissions did not resonate as much with participants as more tangible outputs such as litres of water saved or volume of fertiliser produced. These categories sparked discussion and helped the residents use the Calculator to come up with systems the felt fitted into the estate. By contrast, GHG emission reduction was not seen as criteria to optimise system design for. This helps to show a tension between different users' perspectives. The management board was more used to thinking in terms of sustainability targets. It was our initial discussions with this body that had led us to include GHG emissions as one of the key impact categories. The residents had different expectations for how to understand the impact and potential for the system.

Broader aspects of implementing each technology, such as the impact of rainwater harvesting on the amount of chemicals and energy required to process wastewater, were presented to the participants verbally and in conjunction with "information sheet" handouts that acted as memory aides while working through scenarios using the Calculator. This proved helpful in advancing discussions around wastewater recycling. At the start of the process, some participants felt that the utility's water recycling process meant that there was no value to a small decentralised water recycling programme. The Calculator was able to demonstrate the energy and GHG emissions savings that could be realised by small-scale systems deployed in the estate in comparison to the utility recycled water coming from the tap.

The Calculator provided a solid base on which sustainable design discussions could happen. It provided to the participants valuable insights into the scale of material flow given different design choices—such as the amount of waste generated over a month or the irrigation requirements of a raised bed—and environmental impacts of these options. Participants used the sliders to adapt and scale the systems to their community and their area. For example, some participants used their experience of community engagement to restrict the amount of food waste flowing in to the system, judging that a maximum of 50% of residents would get involved with a local composting initiative. Other participants concentrated on the physical layout of the estate, adjusting the volume and number of wormeries or rainwater tanks to fit with what they felt would suit the topography. The outputs were also used to evaluate different options. Some participants were interested in the emissions figures and adjusted system sizes to maximise reductions; others focused on volume of useful resources (e.g. tomatoes) that their estate could produce. Overall, participants showed good engagement with the numbers provided by the Calculator, particularly when specific questions were raised about details of nexus design implementation. Consequently, the Calculator facilitated realistic decision-making in participants with little practical engineering experience.

4 Conclusions

This paper presents a novel process of developing LCA Calculator with the inputs from community members, embedded in a co-design process. It demonstrates how engineering tools can be developed to create a two-way exchange between community members and infrastructure designers that embed end-user perspectives in the design and implementation of the infrastructure they use, considering lifecycle impacts of technology and material options.

The LCA Calculator development to date has included a horizon scan of existing decentralised technologies and a synthesis of open LCA datasets for technologies and patterns of consumption and production. A prototype version of an LCA Calculator software tool has been developed to enable rapid assessment of conceptual design of engineering systems. The LCA Calculator was successfully tested at a community workshop, enabling clear engagement between engineering design choices and resource and environmental impacts. All participants responded well with the LCA Calculator and were able to use the Calculator by following the instructions. More specifically, participants found the quantitative information presented by the Calculator particularly useful and in technology options different from what they thought. The quantitative information shown in the Calculator enabled participants to understand the importance of evidence-based decision making in sustainability, and results from tools need to be interpreted in the specific context. The paper demonstrates how engineering tools can be developed and used in community engagement in designing more sustainable and resilient community infrastructure.

Future work will build on the prototype version improving user interaction patterns via information layers and time navigation. Scenario modelling and data integration features for LCA experts will also be added, allowing to broaden the impact categories considered by expanding the database of decentralised technology options in water, energy, food and waste systems and exploring integration opportunities of the Calculator with existing LCA tools such as SimaPro, OpenLCA and Eco Audit. The other areas of future work are to test the usability of the Calculator with a wider range of non-expert users, for example using expertise of human-computer interaction and applying the LCA Calculator in different communities/sectors.

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