PROJECT ACRONYM	ENOUGH
PROJECT TITLE	European Food Chain Supply to reduce GHG emission by 2050
PROJECT COORDINATOR	SINTEF OCEAN
PROJECT DURATION	2021-2025

D4.1

Food supply assessment tool including renewable energy sources

PROJECT NO: 101036588

TYPE OF ACTION: IA (INNOVATION ACTION)

CALL: H2020-LC-GD-2020-4

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

DOCUMENT INFORMATION

DELIVERABLE NO.	4.1 Food supply assessment tool including renewable energy sources
DISSEMINATION LEVEL [1]	PU
WORK PACKAGE	WP4
TASK	T4.1
LEAD BENEFICIARY	INRAE
CONTRIBUTING BENEFICIARY(IES)	INRAE, LSBU, KUL, SO, NTNU, UNIVPM, TUGRAZ, VDU, CNR, EPTA, ARCE
DUE DATE OF DELIVERABLE	31/03/2023
ACTUAL SUBMISSION DATE	31/03/2023

[1] PU = Public

PP = Restricted to other program participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

DOCUMENT HISTORY

Version	DATE	CHANGE HISTORY	AUTHOR	BENEFICIARY
1.0	09.03.2023		Denis Leducq	INRAE

QUALITY ASSURANCE, STATUS OF DELIVERABLE		
ACTION	PERFORMED BY	DATE
Reviewed	Graciela Alvarez (INRAE), Judith Evans (LSBU), Pieter Verboven (KUL)	23/03/2023
Approved (WP leader)	Graciela Alvarez (INRAE)	29/03/2023
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Table 1: LIST OF ACRONYMS

Acronym	Full name
COP	Coefficient of performance
FP7	Seventh European Framework Program
HFO	Hydrofluoroolefin
GHG	Greenhouse Gas
PM	Packaging Material
RES	Renewable Energy Sources
TEWI	Total Equivalent Warming Impact
UI	User Interface
URL	Uniform Resource Locator

EXECUTIVE SUMMARY

One of the main tasks within WP4 is to develop a software tool that can evaluate greenhouse gas (GHG) emissions from the food supply chain and help to identify the most critical points where improvements can be applied. Task 1 was dedicated to the development of the first version of the ENOUGH Tool. This version is an extension of the Frisbee tool that allows us to assess not only cold chains, but more extensively every food supply chain from farm to fork. Thermal and mechanical food processes, renewable energy sources, and transportation emissions have been added. An update of the calculation core for refrigerating systems has also been performed and several food products were added to the tool. More products and technologies will be added in the next WP4 task 2 .

Deliverable 4.1 - Food supply management tool including heating processes and renewable energy sources

1 INTRODUCTION

Simulation tools can be essential to aid reducions in GHG emissions from the food supply chain by at least 50% by 2050. In particular, such tools can help in identifying critical points where efforts should be concentrated to reduce energy consumption and GHG emissions.

The complexity of food supply chains and food processes management can be more easily addressed with decision support tools that can integrate quality preservation, energy consumption, and environmental impact .

Logistics management tools usually aim to reduce costs and improve responsiveness. But characteristics of food products such as perishability and quality, and growing sustainability concerns require the extension of tools to other criteria. Literature reviews show that there is a need for modelling tools that manage both quality and sustainability (Akkerman et al. 2010, Soysal et al. 2012).

Existing software solutions to evaluate food perishability aim to model the growth, inactivation, and survival of micro-organisms in food products such as the "Baseline Software Tool" (www.baselineapp.com), or "Combase" (http://www.combase.cc) or Sym'Previus (www.symprevius.net).

For energy calculations, software applications have been developed to calculate energy consumption and emissions of CO_2 for some refrigeration equipment. Examples include Pack Calculation Pro, an application for comparing the yearly energy consumption of refrigeration plants developed by the company IPU Innovative factory (http://en.ipu.dk/), "SuperSim" and "Cybermart" developed by Ge and Tassou (2011) and Arias et al. (2010) respectively, both for the simulating energy use of display cabinets in supermarkets. VCRS (Vapour Compression Refrigerator Simulator) was developed by Eames et al. (2012) to study the implications of design choices in terms of energy usage and carbon generation by refrigeration systems for chillers, freezers, and storage rooms.

The FRISBEE tool is a user-friendly software tool that was recently developed in the FRISBEE project (Food Refrigeration Innovations for Safety, consumers' Benefit, Environmental impact, and Energy optimization along the cold chain in Europe) It can be used to simultaneously evaluate the effect of temperature over a defined period of time on the final quality of refrigerated products, and to calculate the energy use and environmental impact of the refrigeration systems applied. This is particularly important because these three sustainability indicators (food quality, energy use, and CO_2 emissions) are coupled through temperature.

The use of Renewable Energy Sources (RES) or innovative low-carbon technologies in the FRISBEE tool was not the focus. The innovation potential of the tool presented in this deliverable rests in the development of a user–friendly web-based tool dedicated to increasing energy efficiency and reducing GHG emissions in food supply chains whilst at the same time simulating food quality in the cold chain. This new tool uses the FRISBEE calculation core and incorporates all the experience from the team who developed the first FRISBEE tool and the new expertise acquired from the ENOUGH group. The tool developed will be completely novel and will be applied to several representative food products in the food supply chain.

The new tool adds novel and innovative outputs to the FRISBEE tool:

- Simulation of whole food chains, from farm gate to fork. Post-harvest operation and transport from the farm are also included as well as food processes (including heating and mechanical operations)

- Simulation of renewable energy sources and innovative "green" technologies such as those demonstrated in the ENOUGH project
- Assessment of sectors where the largest levels of GHG emissions can be saved. The tool will allow the testing of different scenarios to reduce environmental impact on the overall food supply chain through a systems-based assessment. For each sector, we will be able to include suggestions for heat and cold integration, as well as to propose the most promising low-carbon technologies (RES, thermal stores, high-temperature heat pumps…).

We expect this new generation of tools will be instrumental in the choice and design of new food supply chains and new low-carbon technologies as well as integration within/between each sector of the food supply chain.

2 ENOUGH TOOL

2.1 Structure of the software and methodology

The Frisbee software tool was developed within the framework of the European Union FP7 Frisbee project. As mentioned in the previous part, the purpose of the Frisbee tool is to evaluate and compare various refrigeration and freezing technologies through indicators of food quality, energy consumption, and the environmental impact of food cold chains. It is based on kinetic models for quality evolution, heat load and refrigeration cycle models, and TEWI calculation for CO_2 emissions. The user starts by building a cold chain by selecting a product, then defines the technologies, properties of cold rooms, and refrigerating systems properties. The chain is then simulated, and results are presented graphically.

The Frisbee tool was initially developed in Matlab and available in a Windows version, downloadable through a website. To install the software, the user had to first download and install Matlab Run time. For legal reasons, the Matlab run time could not be distributed with the Frisbee software on the website. Installation of this run time also required admin rights on the computer.

A web app is a program configured and installed on a remote server and is available using a browser and network access. These applications are developed to run in browsers and do not require any installation on the physical machine. Consequently, they can be run regardless of system specifications (even with low RAM and low processing power) and operating systems. The application is updated directly in the server and so is automatically updated for any user.

For all these reasons, it was decided to develop a web version for the ENOUGH tool. The calculation core of the Frisbee tool was isolated from the rest of the code and is called by the web application when needed (Matlab Core in Figure 1). "ENOUGH Core" refers to python calculation libraries developed in the ENOUGH project. Part of the Web User Interface and the web services are handled by the Django framework (https://www.djangoproject.com/). Specific features of web apps such as URL mapping, user authentication, site maps, database management (through object-relational mapper), dynamic web pages (through templates), and administration interface are provided by the Django framework.

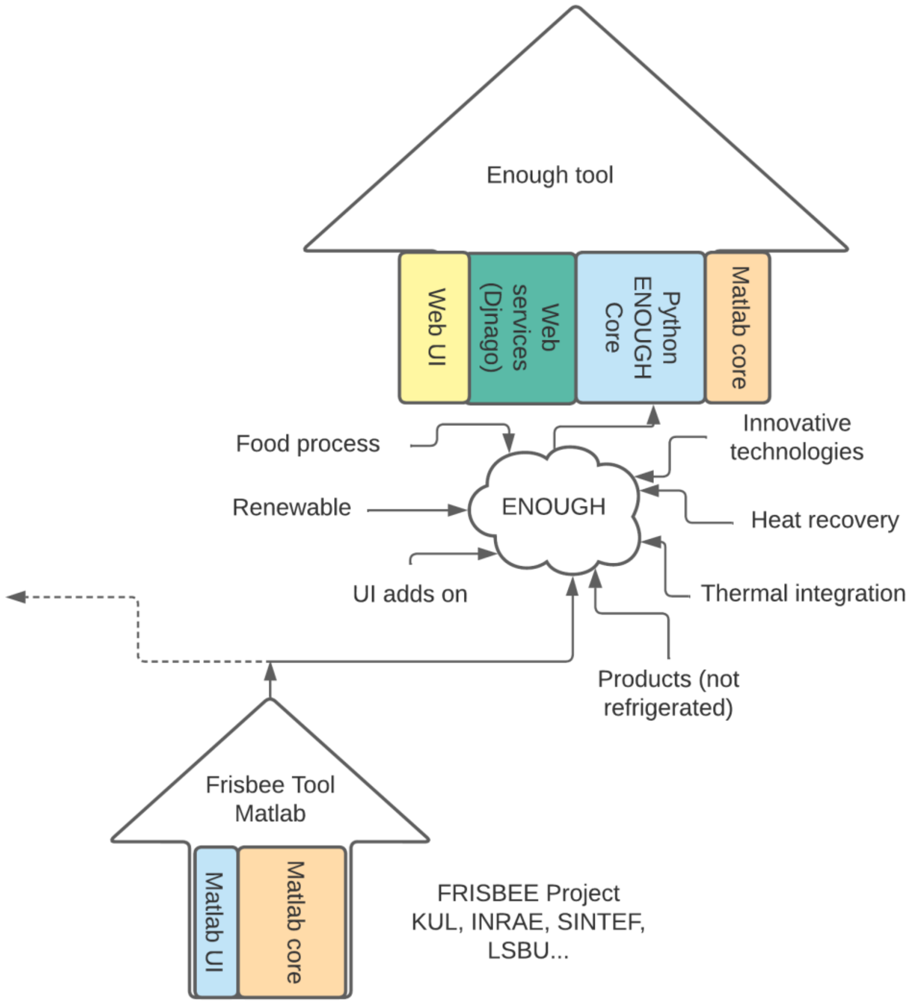


Figure 1 : Building Enough tool from Frisbee tool: modules management

The Web UI involves dynamic pages handled by the Django Framework in HTML. Some dynamic elements like graphs and graphic parts (blocks for example) are developed in JavaScript (see Annex 3 for more details on the structure and programming languages). Figure 2 presents the main page of the tool.

Gitlab platform (https://gitlab.com) is used as a Git repository manager to manage code repositories issue tracking, and team collaboration. Git is used as the version control system. This allows multiple developers to work on the project simultaneously and keeps track of the different versions of the code through what is called "commits". The Gitlab deposit is currently only available to developers and code reviewers.

2.2 Starting a simulation

The first page is presented in Figure 2. The purpose of this page is to present the software to new users in the simplest way possible. This page also provides registering or login access. The current URL is https://frisbee-etool.inrae.fr, but an URL dedicated to ENOUGH project will be available in the next few months.

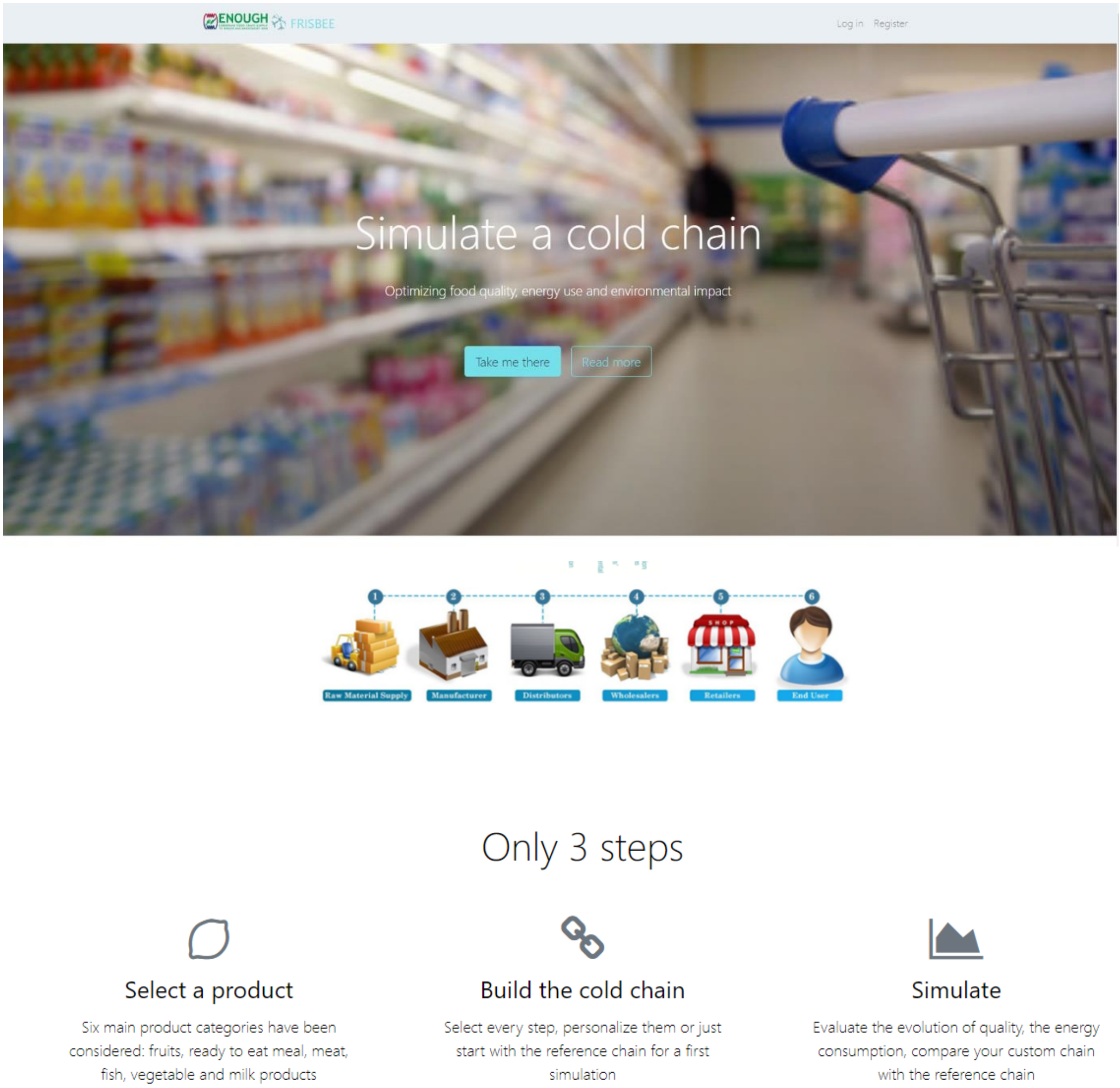


Figure 2: Main page of web ui

The user has first to register or login before starting a simulation. The purpose of this user identification is to offer the possibility to save a simulation for future use. To register, a user must choose a username, and indicate a name and an email address (necessary to recover lost passwords).

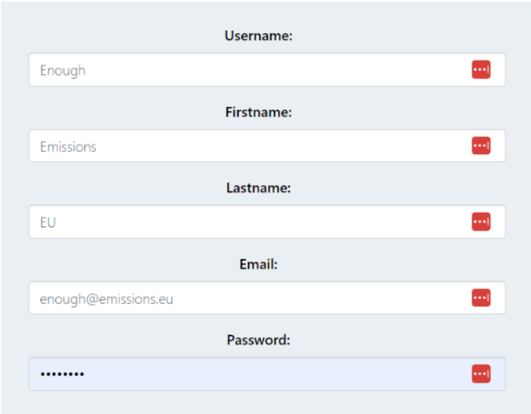
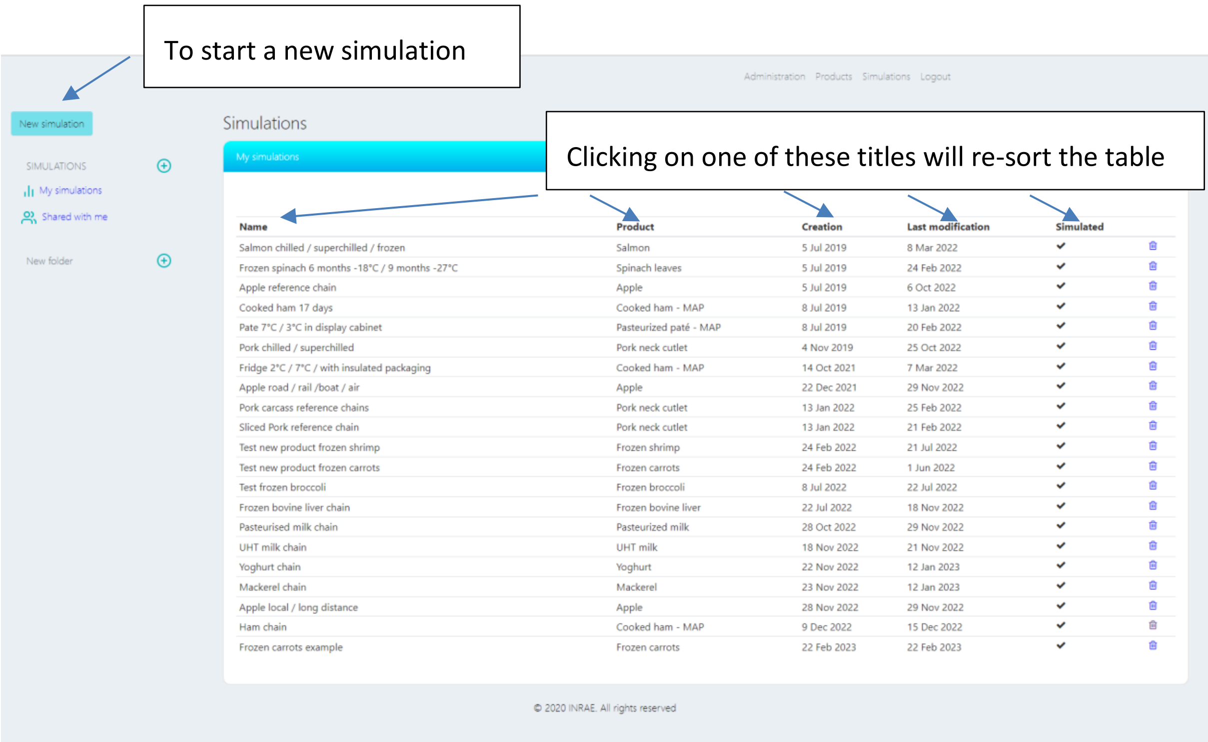


Figure 3: Registering page

After registering, the user is redirected to the simulations page (Figure 4). This page shows the previous simulations of the user. The table is empty for a new user.



Name	Product	Creation	Last modification	Simulated
Salmon chilled / superchilled / frozen	Salmon	5 Jul 2019	8 Mar 2022	✔
Frozen spinach 6 months -18°C / 9 months -27°C	Spinach leaves	5 Jul 2019	24 Feb 2022	✔
Apple reference chain	Apple	5 Jul 2019	6 Oct 2022	✔
Cooked ham 17 days	Cooked ham - MAP	8 Jul 2019	13 Jan 2022	✔
Pate 7°C / 3°C in display cabinet	Pasteurized paté - MAP	8 Jul 2019	20 Feb 2022	✔
Pork chilled / superchilled	Pork neck cutlet	4 Nov 2019	25 Oct 2022	✔
Fridge 2°C / 7°C / with insulated packaging	Cooked ham - MAP	14 Oct 2021	7 Mar 2022	✔
Apple road / rail /boat / air	Apple	22 Dec 2021	29 Nov 2022	✔
Pork carcass reference chains	Pork neck cutlet	13 Jan 2022	25 Feb 2022	✔
Sliced Pork reference chain	Pork neck cutlet	13 Jan 2022	21 Feb 2022	✔
Test new product frozen shrimp	Frozen shrimp	24 Feb 2022	21 Jul 2022	✔
Test new product frozen carrots	Frozen carrots	24 Feb 2022	1 Jun 2022	✔
Test frozen broccoli	Frozen broccoli	8 Jul 2022	22 Jul 2022	✔
Frozen bovine liver chain	Frozen bovine liver	22 Jul 2022	18 Nov 2022	✔
Pasteurised milk chain	Pasteurized milk	28 Oct 2022	29 Nov 2022	✔
UHT milk chain	UHT milk	18 Nov 2022	21 Nov 2022	✔
Yoghurt chain	Yoghurt	22 Nov 2022	12 Jan 2023	✔
Mackerel chain	Mackerel	23 Nov 2022	12 Jan 2023	✔
Apple local / long distance	Apple	28 Nov 2022	29 Nov 2022	✔
Ham chain	Cooked ham - MAP	9 Dec 2022	15 Dec 2022	✔
Frozen carrots example	Frozen carrots	22 Feb 2023	22 Feb 2023	✔

Figure 4: Simulations page

The user can then begin a new project by first selecting a product, and then giving a name to the simulation (Figure 5). The user can also open a saved simulation.

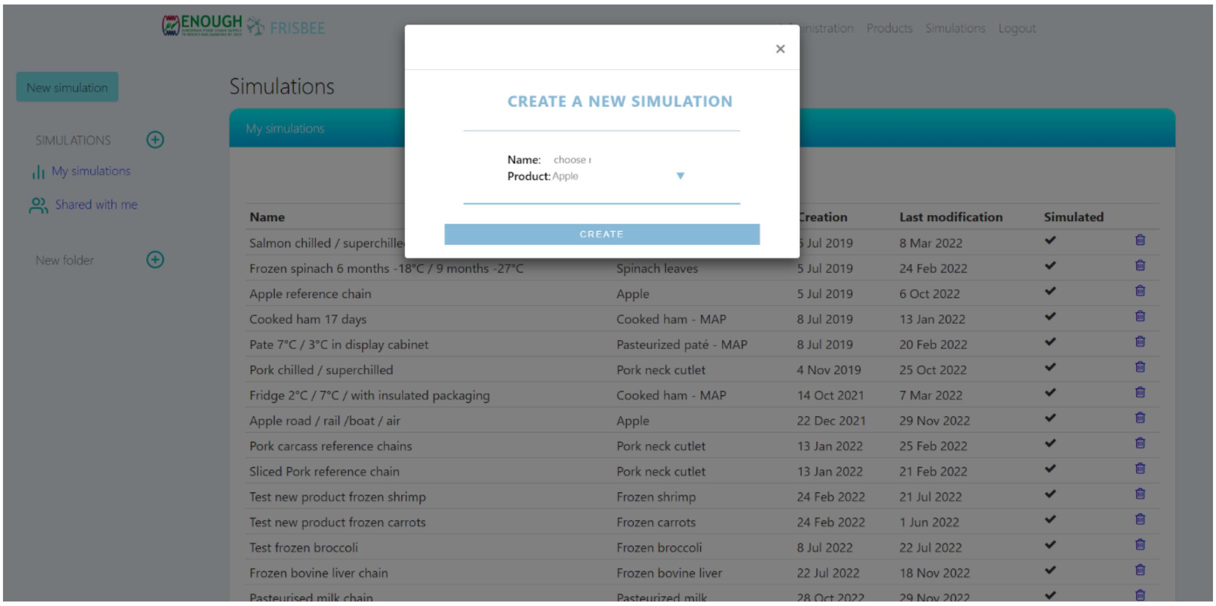


Figure 5: Starting a simulation

Originally, in the Frisbee tool, five **food categories** (fruit, meat, fish, milk products, and vegetables) were identified to be the main refrigerated and frozen food categories in the European cold chain.

Table 2 Products available in FRISBEE TOOL

Fruit	Apple
Meat	Cooked ham – MAP Pasteurized pate – MAP Pork neck cutlet
Fish	Salmon
Milk products	Regular vanilla ice cream Premium vanilla ice cream
Vegetables	Spinach chopped cubes Spinach leaves

For every product, a reference chain was defined and could be used as a start for the simulation. The kinetic models were developed and validated in the project using experimental results.

All the products available for simulation at this stage of development are presented in Annex 2: Products available in the tool.

The **main user interface** to build or modify a chain is presented in Figure 6. The user can begin to build a cold chain by adding cold chain blocks by selecting them in the left bar. Clicking one of these listed items adds the corresponding block at the end of the chain. The block can be drag and dropped to another position. Chains and blocks are automatically saved.

Clicking on a block shows two buttons to edit or delete. The user can modify the block properties by editing it. A property window then opens, and the user can modify properties like room temperature, product heat load (refrigeration load), refrigerant, refrigeration system, country, fans power, etc. The user can also delete the block if necessary.

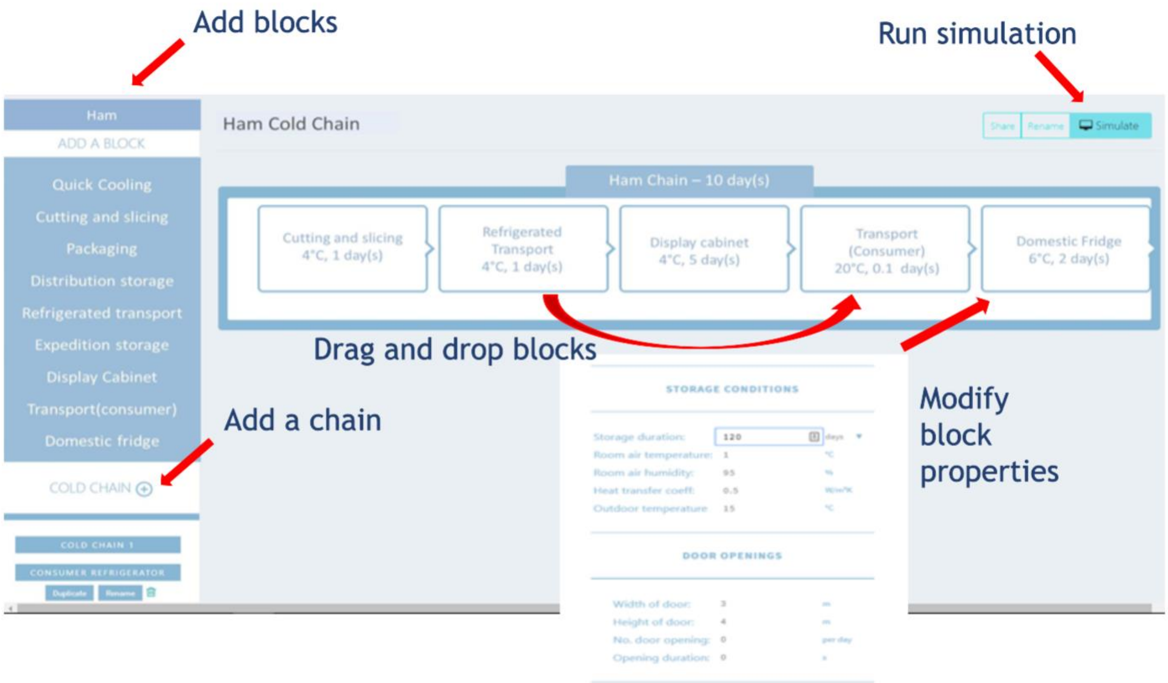


Figure 6: main user interface when a chain is built and modified

The blocks available to build a chain depend on the product and have been pre-set in an excel database (Figure 7).

	A	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	
1	cold chain blocks	other heat loads (kW)	product density (kg/m3)	chain icon	wall area (m2)	roof area (m2)	floor area (m2)	wall thick (mm)	roof thick (mm)	floor thick (mm)	wall insulation	roof insulation	floor insultion	Stacked	Length (m)	Height (m)	Bredth (m)	lower temp	upper	Distance (km)	Fuel	Heating loss ratio (%)	Mech ener (kWh
2	Freezing	0	300	cool room	200	100	100	100	150	500	Polystyrene foam	Polystyrene foam	Concrete	No	0,02	0,15	0,15	-29	-24	0	Diesel	10	
3	Packaging	0	300	cool room	200	100	100	100	150	500	Polystyrene foam	Polystyrene foam	Concrete	No	0,02	0,15	0,15	13	18	0	Diesel		
4	Frozen storage	0	300	cool room	1446	1008	1008	100	150	500	Polystyrene foam	Polystyrene foam	Concrete	yes	0,02	0,15	0,15	-20	-15	0	Diesel		
5	Distribution center	0	100	cool room	3220	4950	4950	100	150	500	Polystyrene foam	Polystyrene foam	Concrete	yes	0,02	0,15	0,15	-23	-18	0	Diesel		
6	Refrigerated transport	0	300	Refrigerated truck	63,6	33,5	33,5	100	150	100	Polystyrene foam	Polystyrene foam	Polystyren	yes	0,02	0,15	0,15	-20	-15	50	Diesel		
7	Display cabinet	0	100	display cabinet	24	5,4	5,4	100	150	100	Polystyrene foam	Polystyrene foam	Concrete	No	0,02	0,15	0,15	-19	-14	0	Diesel		
8	Transport (non-refrig.)	0	100	Car	63,6	33,5	33,5	100	150	100	Polystyrene foam	Polystyrene foam	Concrete	No	0,02	0,15	0,15	13	18	5	Gasoline		
9	Domestic fridge	0	100	house hold refrigerator	1	1	1	100	150	100	Polystyrene foam	Polystyrene foam	Concrete	No	0,02	0,15	0,15	-18	-13	0	Diesel		
10																							
11																							

Figure 7: Excel workbook containing the values used as default when a user selects a particular cold chain

The pop-up window for editing the properties depends on each block category. There are eight **categories for blocks** (refrigeration, display cabinet, household refrigerator, refrigerated transport, ambient storage, ambient transportation, heating/cooling, and mechanical process). The category will mainly determine the models used for energy consumption and GHG emissions calculations, but also the pop-up window when editing the block:

1. **Refrigeration** block: this category is used when the product is refrigerated (or frozen) in a room or tunnel. The energy consumption is deduced from the coefficient of performance of the system and the total heat load. The total heat load is the sum of the heat loads from the

process (energy needed to cool or freeze product to the desired conservation temperature), transmission through walls, heat input from door openings, fans, forklifts, personnel, lighting, fans, floor heating, defrosting and lighting. The corresponding pop-up is shown in Figure 8.

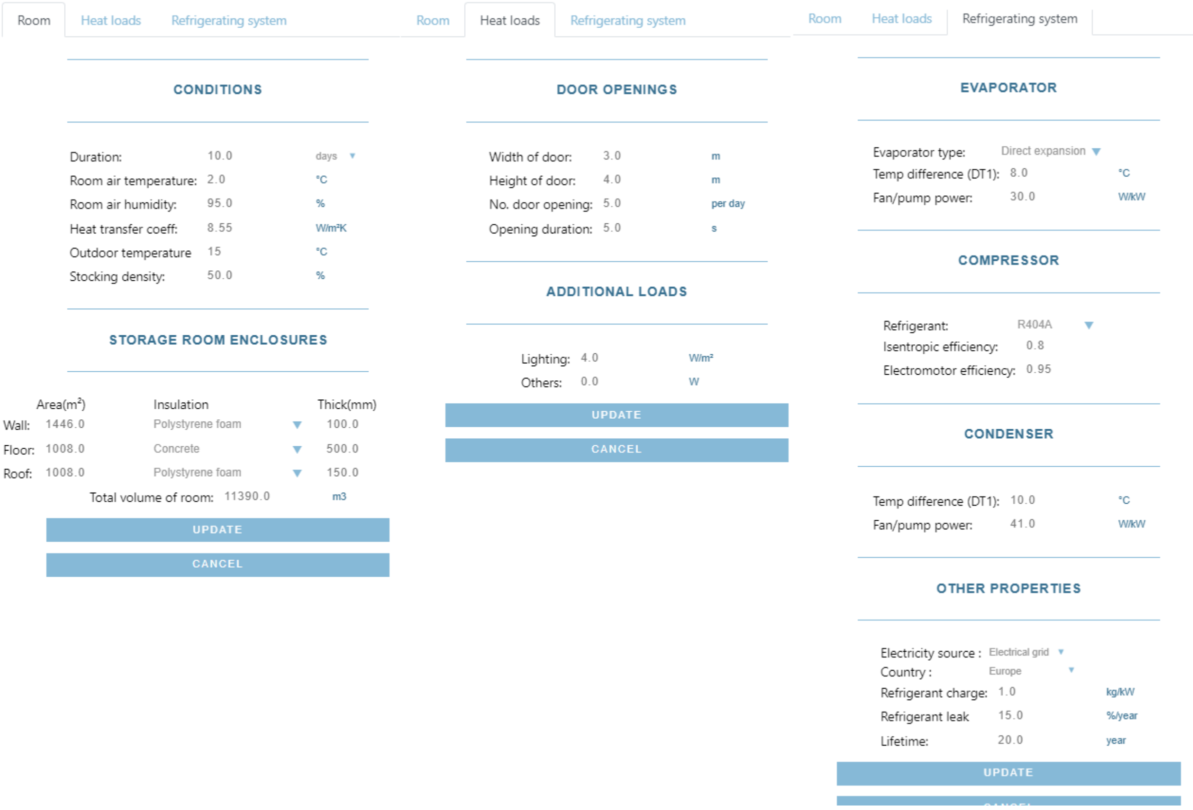


Figure 8: Refrigeration block pop up

Energy calculations are based on the evaluation of heat load and performance calculation from the characteristics of the system.

Scope 1 and scope 2 emissions of **refrigeration systems** are evaluated in the tool with the TEWI concept (Fisher et al., 1991) (Equation 1), the result depends on the country. The result also vary considerably on how the power is generated, especially the level of renewable energy or nuclear energy. The International Energy Agency (https://www.iea.org/data-and-statistics/data-product/emissions-factors-2022#overview) provides CO_2e emission factors in kg of CO_2 per kWh for all European countries and these values are used in the tool. Other GHG emissions will be also added, based on emission factors.

Equation 1: TEWI calculation

$$TEWI = GWP.L.n.m + GWP.m.(1-\alpha) + n.E_{annual}.\beta$$

where

GWP: Global Warming Potential of refrigerant [-]

L: Leakage rate [%/y]

n: operational life time [y]

β: CO2 emissions from energy usage [kg/kWh] m: refrigerant charge [kg]

α: recovery upon decommissioning [-]

E_{annual}: energy consumption per year [kWh/y]

When electricity from the grid is declared as energy source for refrigerating systems, emission *CO_2e* is calculated by:

$$CO_2e = W\,.\,CO_2i$$

where

W: energy consumption [kWh]

CO2i: carbon intensity of the grid for the country [kg CO_{2e}/kWh]

The user can select for heating, cooling or mechanical processes other energy sources than electricity grid such as r**enewable energy sources**:

- Diesel
- Natural gas
- Solar PV
- Wind
- Biogas
- Biomass
- Hydrogen

Emission factors used for each energy source have been obtained from the French Environment and Energy Agency

(https://bilans-ges.ademe.fr/documentation/UPLOAD_DOC_FR/index.htm?renouvelable.htm).

The Frisbee tool user could select the **refrigerant** from a list of the most common fluids: R717 (ammonia), R134a, R22, R404A, R407C, R600a (Butane), R744 (carbon dioxide).

A number of new refrigerants have been added to the Enough tool such as: R290 (propane), HFO-R1233zd(E), HFO-R1234yf, HFO-R1234ze(E), HFO-R1234ze(Z), HFO-R1243zf, R410A, R507a…

Fluid thermophysical properties such as saturated pressure and temperature, enthalpy, entropy, and density are obtained from the Coolprop library (http://coolprop.org/), an open-source database of fluid and humid air properties. GWP (Global Warming Potential) values for refrigerants are from IPCC AR6 report (chapter 7, supplementary material).

Coolprop library gives the possibility to select REFPROP, the NIST Reference Fluid Thermodynamic, and Transport Properties Database, as the source for calculation. Tests using REFPROP instead of Coolprop have been performed, but there were no significant differences in the results.

2. **Display cabinet**: energy consumption is calculated from the type of cabinet, energy label, dimensions and set temperature. An example of pop-up for a display cabinet is shown in Figure 9.

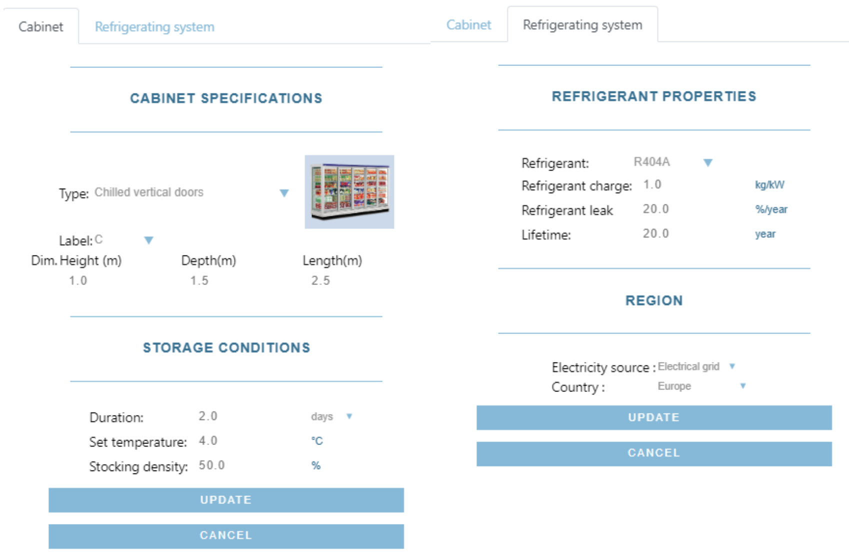


Figure 9: Display cabinet block pop up

The energy consumption and emissions calculation of **display cabinets** has been updated based on the recent eco-labelling standard for display cabinets (Europe regulation 2019/2018). Energy consumption can be evaluated from:

- The class of the display cabinet (from A to G)
- The dimensions
- The type of cabinet: horizontal, vertical, chilled, freezer
- The temperature classification (M1, M2, L1, L2, L3…)

The class of the display cabinet is determined by the ratio (EEI) between the real Annual Energy consumption (AE) and a "Standard Annual Energy consumption" (SAE):

$$EEI = \frac{AE}{SAE}$$

The reference SAE in kWh/year is calculated as:

$$SAE = 365\,.\,P.\sum_{c=1}^{n}(M + N.Y_c).C_c$$

Where c is the index number for a compartment type. M, N and C are constants and depend on the category of the cabinet and the temperature classification. P is a constant with values depending on the unit is an integral or remote device. Yc is an equivalent volume of the compartment.
Knowing the class of the display cabinet, the number and temperature of the compartments and the type of the display cabinet, the real energy consumption AE can then be computed from the SAE value.

3. **Household refrigerators**: Energy consumption depends on the energy label and the type of refrigerator. An example of pop-up is given in Figure 10.

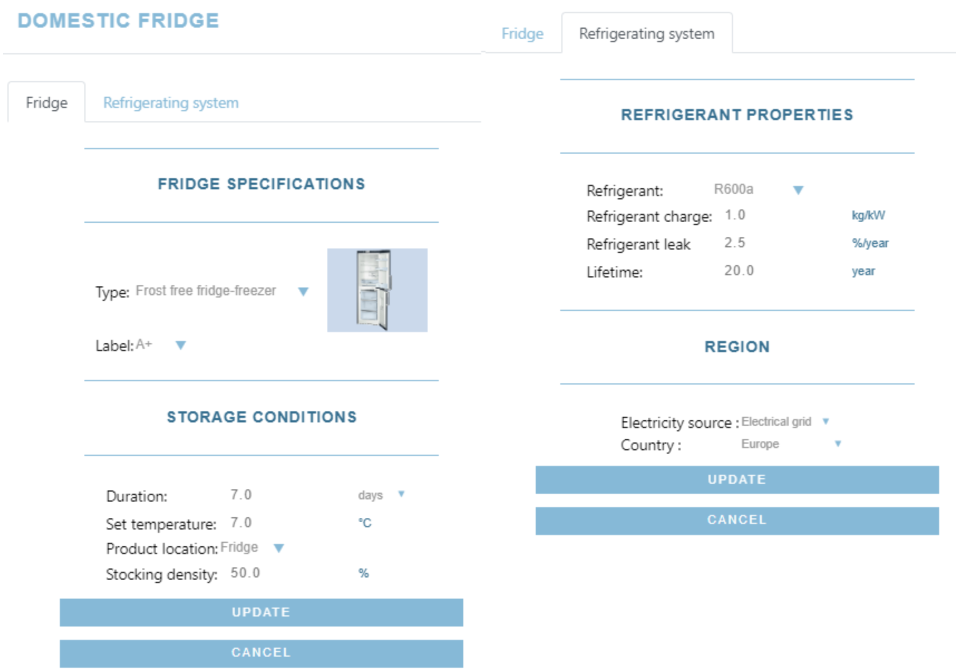


Figure 10:household refrigerator block pop up

4. **Refrigerated transport** block: the product is here transported by road, rail, sea, air in a refrigerated vehicle. The energy consumption is similarly computed from the total heat load of the vehicle room, plus the energy used by the engine (GLEC approach). An example of pop-up is shown in Figure 11.

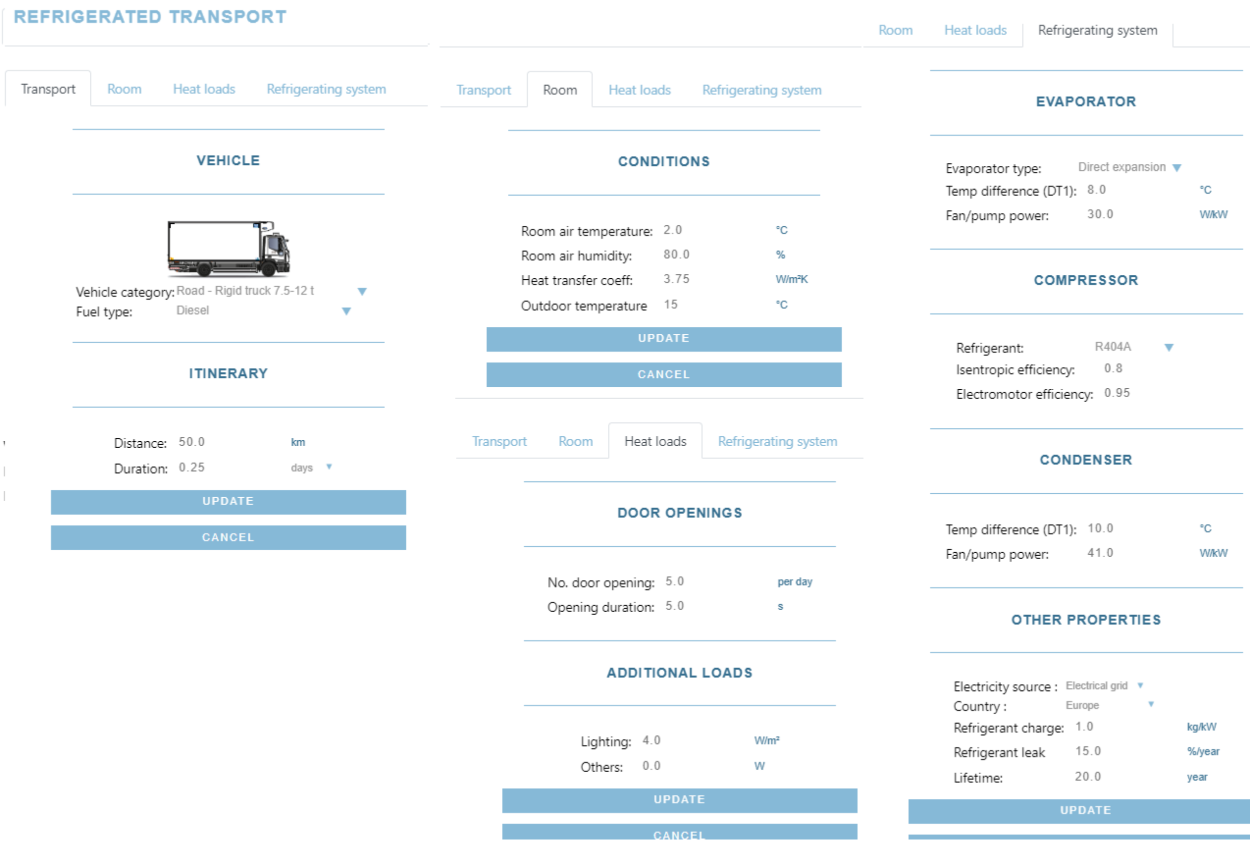


Figure 11: Refrigerated transport block pop up

Emission from transport in food supply chains comes mainly from freight transport, but also includes transport of domestic vehicles, food deliveries, and end-user shopping.

There are no ISO standards to measure GHG emissions in logistics. The Global Logistics Emissions Council (GLEC) has released the GLEC framework in alignment with Greenhouse Gas Protocol, the UN-led Global Green Freight Action Plan, and CDP reporting. It seems also in alignment with the European Standard EN 16258. This framework provides a lot of default data representative for Europe.

It is a guide on how to measure and report emissions from logistics operations and seems globally recognized as the methodology for harmonized calculation and reporting of the logistics GHG footprint across the supply chain. It is the methodology used for example by the French National Agency for ecological transition (Ademe).

This methodology has been implemented in the tool and is detailed in the following part.

The calculation for freight transport is based on the “tonne-kilometer” calculation:

$$tkm = tonnes\ x\ kilometers$$

Based on the category of vehicle and the average values for the load factor, the calculation of the tonne-kilometer can be done by:

$$tkm = vehicle\ capacity[tonnes]$$

$$. \, average\ load\ factor \left(\frac{average\ shipment\ weight\ (tonnes)}{vehicle\ capacity\ (tonnes)}\right)$$

$$. \, total\ distance\ (km)$$

$$. \, proportion\ of\ distance\ loaded\ \left(\frac{loaded\ distance\ (km)}{total\ distance\ (km)}\right)$$

Average load factor values can be found in the GLEC framework, depending on the vehicle used (see Annex 1). The calculation also considers a proportion of loaded distance /total distance to include the empty trips in the assessment.

Finally, the CO_2e emissions are evaluated by:

$$kg\ CO_2e\ emissions = \sum_1^n total\ tkm \times fuel\ efficiency\ factor \left(\frac{kg\ fuel}{tonne - km}\right) \times fuel\ emission\ factor \left(\frac{kg\ CO_2e}{kg\ fuel}\right)$$

Fuel efficiency factors and fuel emissions factors used are given in Annex 1: transport framework data

5. **Ambient storage**: the product is left at ambient temperature for some time. There is no energy consumption for this block. The product temperature rises nevertheless. The pop-up window is shown in Figure 12.

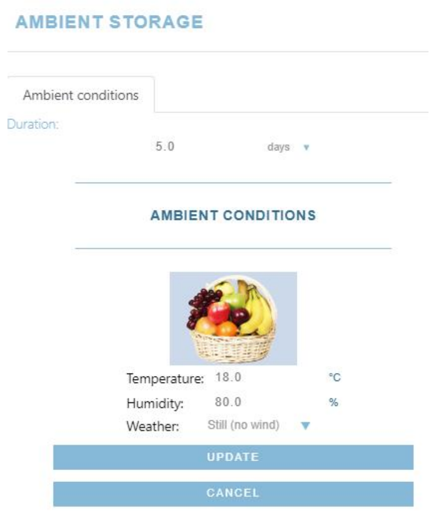


Figure 12: Ambient storage block pop up

6. **Ambient transportation**: an example of ambient transportation is the transportation of the food products by the consumer. Energy consumption here only includes the energy by the vehicle engine. An example of pop up is shown in Figure 13.

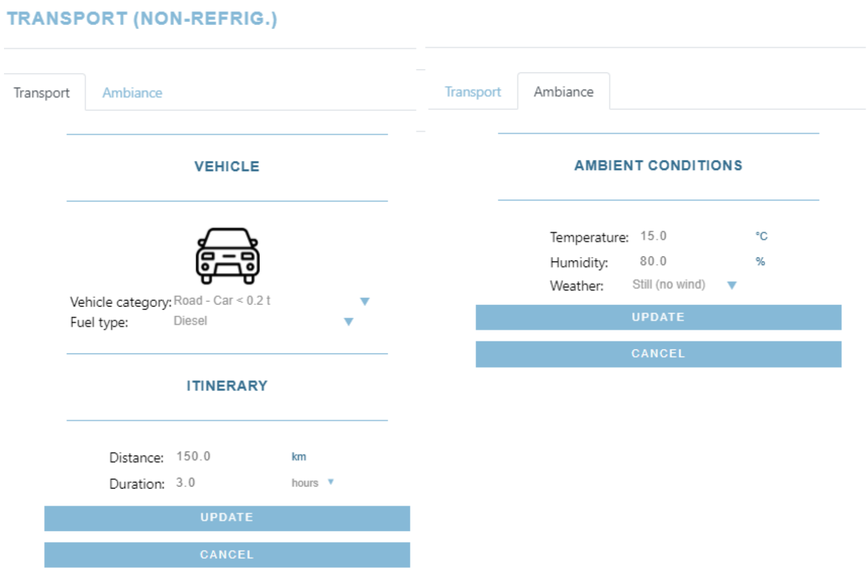


Figure 13: non refrigerated transport block pop up

7. **Heating /cooling** block: this block is used when the product is heated up or cooled down in a heat exchanger or in a process. Energy consumption is calculated from the heat load of the process (energy needed to heat up or cool down the product to the desired conservation temperature) and an efficiency factor depending on the process used. An example of the popup for this category of block is presented in Figure 14.

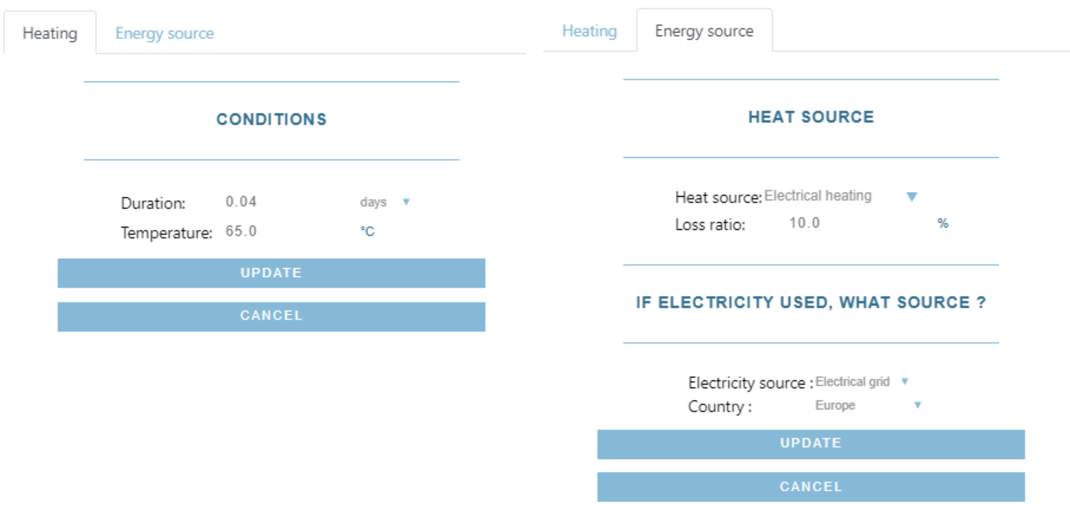


Figure 14: heating or cooling block pop up

Heating processes such as preheating, pasteurization, and sterilization are used in the manufacture of drinks, beverages, milk and in general for liquids. These processes are performed in heat exchangers. When heating solid food products in plants are often performed in ovens and stoves, such equipment and process are very high energy consuming and consequently GHG emissions are also high.

Energy consumption of these processes depends on many factors. Heat recovery is often used in heat exchangers where a large part of the energy is used to heat up the product and another part is due to heat losses. These losses depend on the technology used. Currently, energy consumption per kg of product is evaluated using a simple model:

$$W = Cp \, . \Delta T . (1 + \alpha)$$

where:

Cp [J/kg/°C]: heat capacity of the product ΔT: the difference between initial and final temperature

α (%): losses factor

The losses factor value is pre-set depending on the product and the process, based on literature data.

Nevertheless, this approach supposes there is no evaporation during the process, which is true for processes under pressure such as pasteurization, sterilization, but not for cooking processes. In the present version, we are ignoring evaporation and this will be improved in a next version when cooked products and ovens or cooking equipment will be added.

Some processes used for food do not involve heating or cooling, but only mechanical action such as mixing processes or homogenization for example. Modelling these processes would add much complexity to the tool and would require a lot of input from the user.

The approach in the tool consists of a pre-set mechanical work depending on the process and the product. The user can modify the value of energy per kg of product used and the source of energy if necessary.

8. **Mechanical process**: Mechanical processes can be homogenisers, pumps or mixing or another mechanical process. An example of pop-up is given in Figure 15.

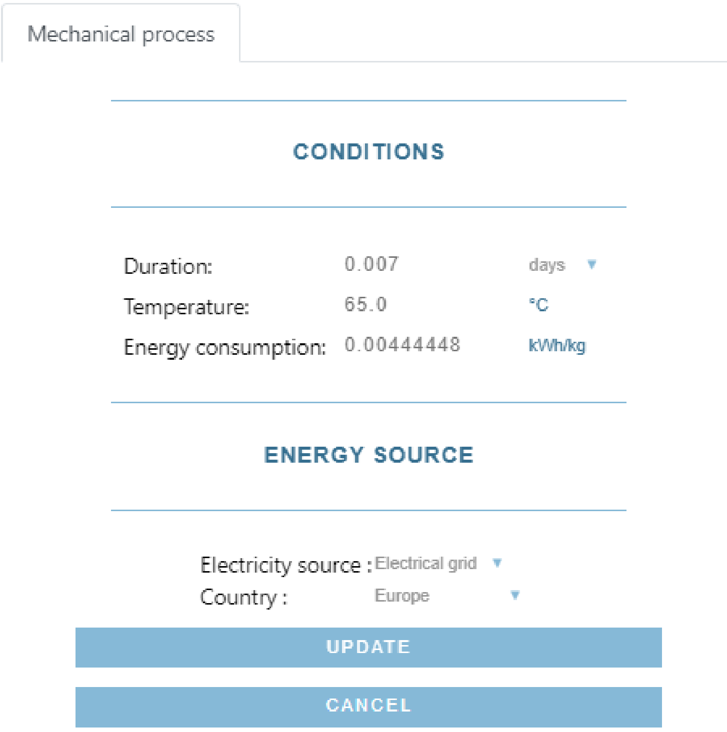


Figure 15: Mechanical process block pop up

Once a chain is built, the user can start the simulation by clicking on the "Simulate" button. A simulation can contain several chains. To add a new chain, the user can click on the "+" button as shown in Figure 6. The user can also duplicate the current chain by clicking the "Duplicate" button. This will create another chain with the same blocks. This is used mainly to compare chains with only a few changes without having to build again the chain.

2.3 Simulation

When the user presses the "Simulate" button, the Matlab engine is started in the background. Data for simulations are transmitted to Matlab through a file in ".mat" format (Matlab format). The calculation by the Matlab core starts with the time-temperature profiles solving the heat conduction equation for every block, then computes the quality indicators and finally the energy use and CO_2 emissions (Figure 16).

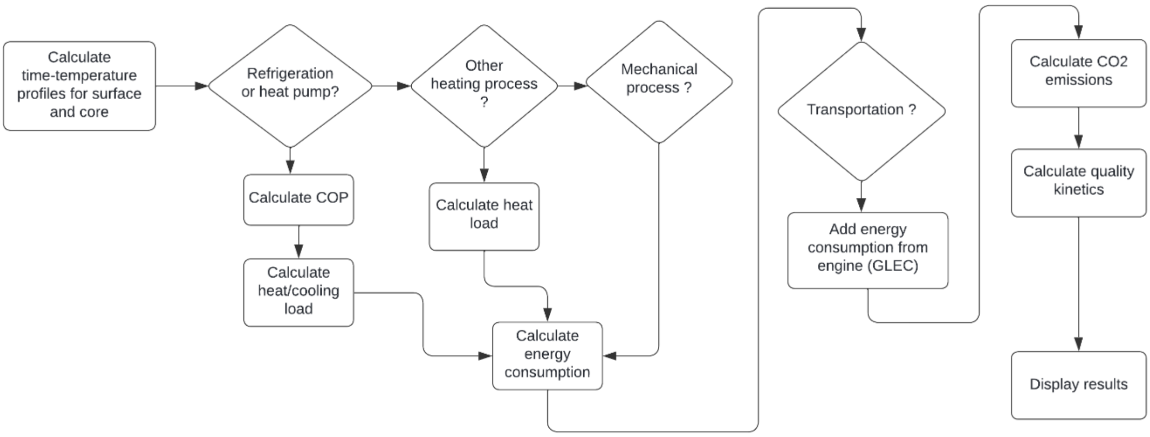


Figure 16: Calculation procedure to simulate food supply chains

During the calculation procedure, the progress is transmitted through a text file to the tool waiting for the calculation to be ended (Figure 17). The results are sent back to the tool through a ".mat" file and are read as soon as they are available. The results are then converted and saved to a "pickle" format file more easily handled by Python.

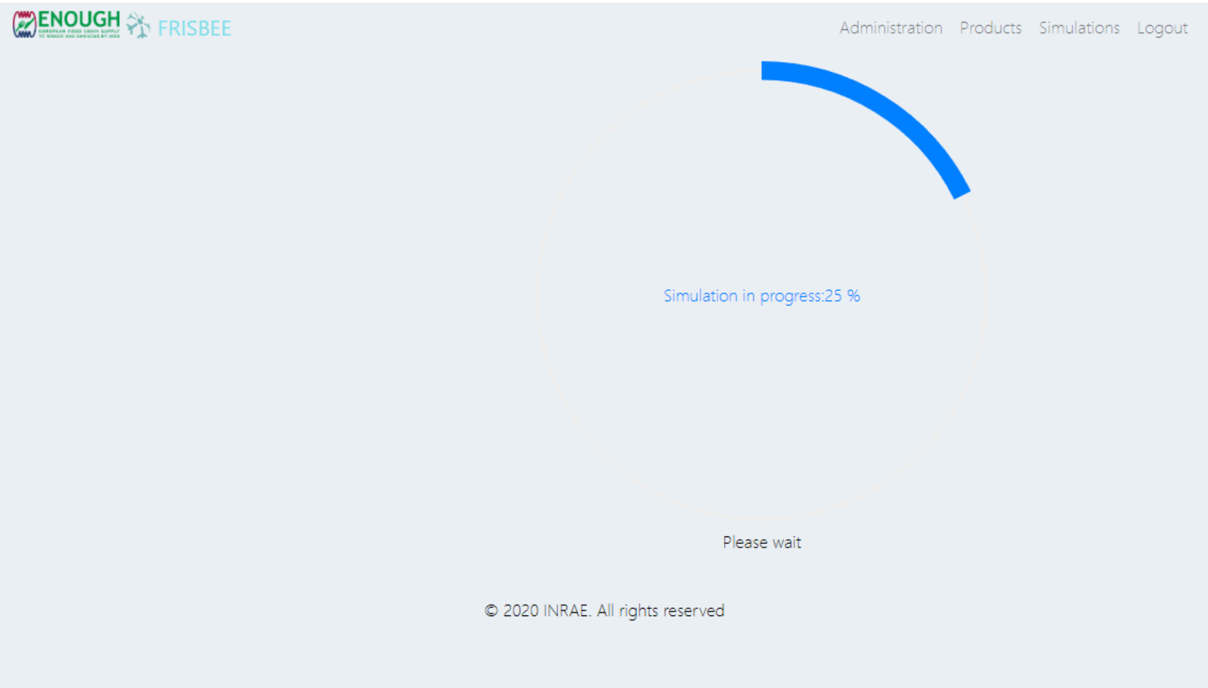


Figure 17: calculation in progress

In the current version of the Enough tool, the Matlab core is only used for time-temperature profiles and the quality indicators of Frisbee products. All other additional calculations are now computed in Python.

2.4 Post-processing

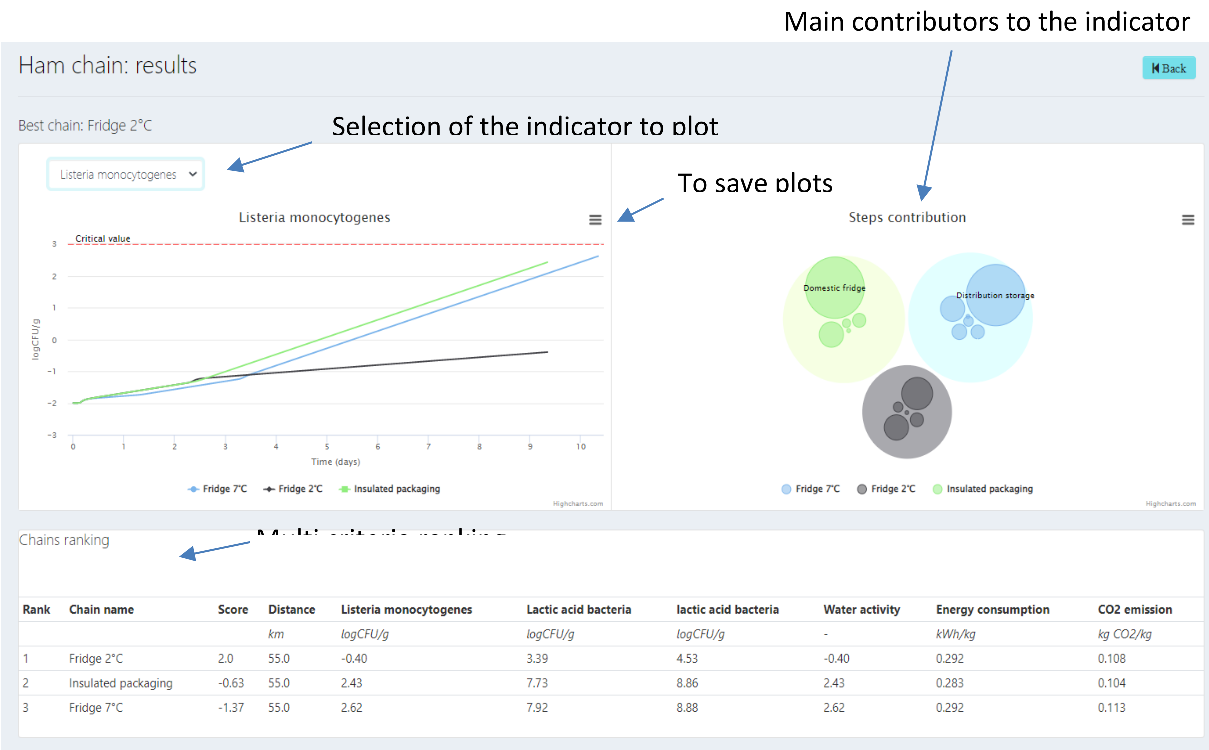
Once the calculations of the simulation are finished, results are presented in plots and tables as shown in Figure 18. The user can select the output (indicator) that needs to be plotted. All the chains are presented in the plot but a single click on an item of the legend can toggle a chain as not visible.

The left graph shows the time-product indicator profile. In this example the indicator is the log bacterial count for *Listeria Monocytogenes.* If there is a critical value for the indicator, it is shown in dash dots. *The critical value for this pathogen bacteria is log 2.* Moving the mouse cursor along the curve shows the corresponding food supply chain block at every time

The purpose of the right graph is to show at a first glance what are the main blocks contributing to the change of the selected indicator (for example the most energy consuming blocks).

The plots can be viewed in full screen, printed or saved as a picture (JPG, PNG, PDF, SVG). The data can be also displayed in a table and also exported to a CSV file or excel sheet.

The table at the bottom shows the value of indicators at the end



Rank	Chain name	Score	Distance	Listeria monocytogenes	Lactic acid bacteria	lactic acid bacteria	Water activity	Energy consumption	CO2 emission
			km	logCFU/g	logCFU/g	logCFU/g	-	kWh/kg	kg CO2/kg
1	Fridge 2°C	2.0	55.0	-0.40	3.39	4.53	-0.40	0.292	0.108
2	Insulated packaging	-0.63	55.0	2.43	7.73	8.86	2.43	0.283	0.104
3	Fridge 7°C	-1.37	55.0	2.62	7.92	8.88	2.62	0.292	0.113

Figure 18: Plot of simulation outputs

It must be noted that, even if the Matlab core has calculated a few indicators and energy use, only time-temperature profiles are read from the results file created during the calculation step. Every other indicator profile is recalculated on demand by the tool from the temperature profiles when the user selects this indicator to be plotted.

2.5 Adding products

New products have been added for simulation (Table 1). At this step of the development, only the administrator can add products to the database. Adding a product consists of:

- Defining a reference chain for the product and finding the thermal properties and quality indicators. The reference chain describes the current situation of the product supply chain

Table 1 : products added in Enough tool

Food product	Product category	T conservation	Quality criteria (number of)
Frozen shrimp	Fish	-18.0°C	5
Frozen carrots	Vegetables	-18°C	15
Frozen broccoli	Vegetables	-18°C	5
Frozen green beans	Vegetables	-18°C	12
Frozen green peas	Vegetables	-18°C	1
Frozen pumpkin	Vegetables	-18°C	5
Frozen ground beef	Meat	-18°C	2
Frozen bovine liver	Meat	-18°C	2
Pasteurized milk	Milk products	4.0°C	0
UHT milk	Milk products	20.0°C	0
Yoghurt	Milk products	4°C	1
Mackerel	Fish	1°C	0

- Adding to the products table specifying the base properties and quality indicators of the product (Figure 19): geometry, nutritional constituents including water content, basic thermal properties.

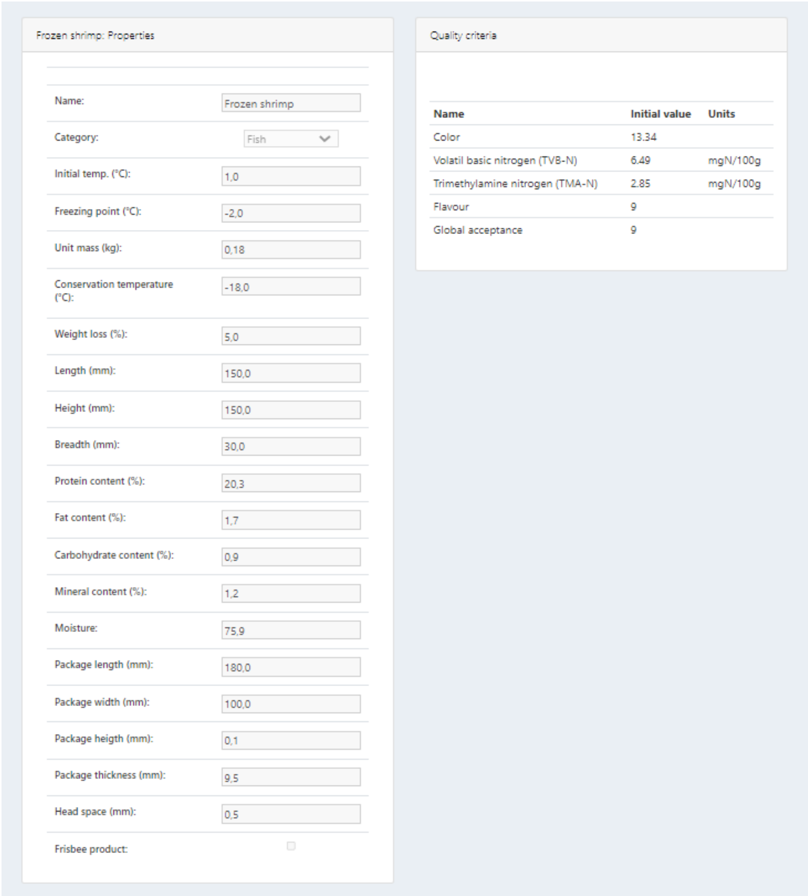
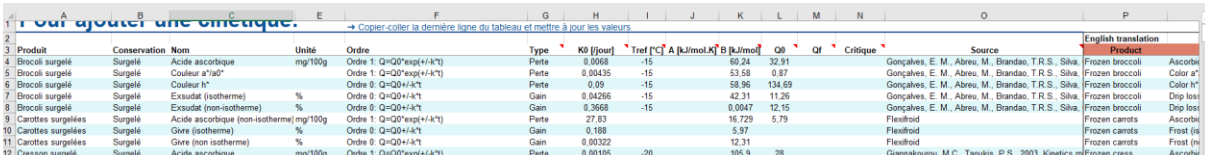


Figure 19: Product properties

- Find specific quality indicators for the product and adding the parameters of the kinetics in an excel file (Figure 20)



Pour ajouter une cinétique. → Copier-coller la dernière ligne du tableau et mettre à jour les valeurs

Produit	Conservation	Nom	Unité	Ordre	Type	K0 [/jour]	Tref [°C]	A [kJ/mol.K]	B [kJ/mol]	Q0	Qf	Critique	Source	English translation Product	
Brocoli surgelé	Surgelé	Acide ascorbique	mg/100g	Ordre 1: Q=Q0*exp(+/-k*t)	Perte	0,0068	-15		60,24	32,91			Gonçalves, E. M., Abreu, M., Brandao, T.R.S., Silva,	Frozen broccoli	Ascorbi
Brocoli surgelé	Surgelé	Couleur a*/a0*		Ordre 1: Q=Q0*exp(+/-k*t)	Perte	0,00435	-15		53,58	0,87			Gonçalves, E. M., Abreu, M., Brandao, T.R.S., Silva,	Frozen broccoli	Color a*
Brocoli surgelé	Surgelé	Couleur h*		Ordre 0: Q=Q0+/-k*t	Perte	0,09	-15		58,96	134,69			Gonçalves, E. M., Abreu, M., Brandao, T.R.S., Silva,	Frozen broccoli	Color h*
Brocoli surgelé	Surgelé	Exsudat (isotherme)	%	Ordre 0: Q=Q0+/-k*t	Gain	0,04266	-15		42,31	11,26			Gonçalves, E. M., Abreu, M., Brandao, T.R.S., Silva,	Frozen broccoli	Drip loss
Brocoli surgelé	Surgelé	Exsudat (non-isotherme)	%	Ordre 0: Q=Q0+/-k*t	Gain	0,3668	-15		0,0047	12,15			Gonçalves, E. M., Abreu, M., Brandao, T.R.S., Silva,	Frozen broccoli	Drip loss
Carottes surgelées	Surgelé	Acide ascorbique (non-isotherme)	mg/100g	Ordre 1: Q=Q0*exp(+/-k*t)	Perte	27,83			16,729	5,79			Flexifroid	Frozen carrots	Ascorbi
Carottes surgelées	Surgelé	Givre (isotherme)	%	Ordre 0: Q=Q0+/-k*t	Gain	0,188			5,97				Flexifroid	Frozen carrots	Frost (is
Carottes surgelées	Surgelé	Givre (non isotherme)	%	Ordre 0: Q=Q0+/-k*t	Gain	0,00322			12,31				Flexifroid	Frozen carrots	Frost (n
Cresson surgelé	Surgelé	Acide ascorbique	mg/100g	Ordre 1: Q=Q0*exp(+/-k*t)	Perte	0,00105	-20		105,9	28			Giannakourou, M.C., Taoukis, P.S., 2003. Kinetics m	Frozen cress	Ascorbi

Figure 20: excel file used to define kinetic parameters of quality indicators

- Add a table for interpolation of thermal conductivity, heat capacity and density as a function of temperature (Figure 21). These data are preferably from experimental measurements if existing or calculated with ASHRAE formulas if not. (ASHRAE Handbook Refrigeration Chapter 9 - Thermal properties of food)

	A	B	C	D
1	Temp	k(W/mK)	heat capacity (J/kgK)	density (kg/m3)
2	-40	1,910523	2164,87	701,64
3	-39	1,899333	2181,01	701,642
4	-38	1,888231	2198,44	701,646
5	-37	1,877215	2217,3	701,653
6	-36	1,866278	2237,75	701,663
7	-35	1,855414	2259,98	701,676
8	-34	1,844619	2284,21	701,693
9	-33	1,833883	2310,66	701,715
10	-32	1,8232	2339,64	701,74
11	-31	1,81256	2371,47	701,771
12	-30	1,801954	2406,53	701,807
13	-29	1,791369	2445,28	701,849
14	-28	1,780793	2488,26	701,897
15	-27	1,770209	2536,1	701,952
16	-26	1,759602	2589,56	702,015
17	-25	1,748951	2649,57	702,088
18	-24	1,738232	2717,23	702,17
19	-23	1,727418	2793,91	702,264
20	-22	1,716476	2881,29	702,37
21	-21	1,705369	2981,44	702,492
22	-20	1,694049	3096,98	702,63
23	-19	1,682461	3231,25	702,788
24	-18	1,670537	3388,51	702,968
25	-17	1,658192	3574,33	703,175
26	-16	1,645322	3796,07	703,414
27	-15	1,631793	4063,62	703,691
28	-14	1,617434	4390,53	704,015
29	-13	1,60202	4795,75	704,395

Spinach leaves | Frozen carrots | Frozen broccoli | Frozen shrimp

Figure 21: excel workbook with table used for interpolation of thermal properties for frozen food

- Adding the list of blocks and the properties for each block in an excel file based on the reference chain (Figure 7)

The list of the products currently available for simulation with the tool is presented in Annex 2.

3 CONCLUSION

A web application to simulate food supply chains and evaluate GHG emissions has been built. It should be noted that the current version of the tool presented in this report is not the final version.

Further development in the user interface will be for example to add the possibility for a user to add a product with a user interface to add quality indicators. Technologies demonstrated in the ENOUGH project will be also added.

Suggestions for better integration between cold, heat and mechanical energy used throughout the chain and for technologies reducing emissions will be added in task 3 of WP4.

This first version of the ENOUGH tool will be publicly presented at the 26th IIR International Congress of Refrigeration in 2023 and made available on the website in April 2023.

4 REFERENCE

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Eames, I.W., Brown, T., Evans , J.A., Maidment, G.G. 2012. Description and validation of a computer-based refrigeration system simulator. Computers and Electronics in Agriculture, 85, 53 – 63. ENOUGH sec. 1-3 19 H2020-LC-GD-2020 2.

Fischer, S., P.; Fairchild; Kusick, C.; Dieckmann, J.; McMahon, E.; Hobday, N. 1991 Energy and Global Warming Impacts of CFC Alternative Technologies. AFEAS and DOE

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Soysal M., Bloemhof J.M., Meuwissen M.P.,Van der Vorst. J.G.A.J. 2012. A review on quantitative models for sustainable food logistics management.Int. J. Food Syst. Dyn., 3, pp. 136-155

Appendices

5 ANNEX 1: TRANSPORT FRAMEWORK DATA

Table 2: Fuel emission intensity (NF EN 16258)

Tableau A.1 — Carburants destinés au transport : densité, facteur d'énergie et facteur d'émission de GES

	Densité (d)	Facteur d'énergie				Facteur d'émission de GES					
		Du réservoir à la roue (e_r)		Du puits à la roue (e_p)		Du réservoir à la roue (g_r)			Du puits à la roue (g_p)		
Description du type de carburant	kg/l	MJ/kg	MJ/l	MJ/kg	MJ/l	gCO_2e/MJ	$kgCO_2e/kg$	$kgCO_2e/l$	gCO_2e/MJ	$kgCO_2e/kg$	$kgCO_2e/l$
Essence	0,745	43,2	32,2	50,5	37,7	75,2	3,25	2,42	89,4	3,86	2,88
Éthanol	0,794	26,8	21,3	65,7	52,1	0	0	0	58,1	1,56	1,24
Mélange essence/éthanol 95/5	0,747	42,4	31,7	51,4	38,4	72,6	3,08	2,30	88,4	3,74	2,80
Diesel	0,832	43,1	35,9	51,3	42,7	74,5	3,21	2,67	90,4	3,90	3,24
Biodiesel	0,890	36,8	32,8	76,9	68,5	0	0	0	58,8	2,16	1,92
Mélange diesel/biodiesel 95/5	0,835	42,8	35,7	52,7	44,0	71,0	3,04	2,54	88,8	3,80	3,17
Gaz de pétrole liquéfiés (GPL)	0,550	46,0	25,3	51,5	28,3	67,3	3,10	1,70	75,3	3,46	1,90
Gaz naturel comprimé (GNC)		45,1		50,5		59,4	2,68		68,1	3,07	
Essence aviation (AvGas)	0,800	44,3	35,4	51,8	41,5	70,6	3,13	2,50	84,8	3,76	3,01
Carburéacteur large coupe (Jet B)	0,800	44,3	35,4	51,8	41,5	70,6	3,13	2,50	84,8	3,76	3,01
Kérosène (Jet A1 et Jet A)	0,800	44,1	35,3	52,5	42,0	72,1	3,18	2,54	88,0	3,88	3,10
Fioul lourd (HFO)	0,970	40,5	39,3	44,1	42,7	77,7	3,15	3,05	84,3	3,41	3,31
Diesel marin (MDO)	0,900	43,0	38,7	51,2	46,1	75,3	3,24	2,92	91,2	3,92	3,53
Gasoil marin (MGO)	0,890	43,0	38,3	51,2	45,5	75,3	3,24	2,88	91,2	3,92	3,49

Table 3 Emission factors: european values (GLEC framework)

Table 32. European Values

Global	WTT	TTW	WTW	WTT	TTW	WTW
	kg CO_2e/kg fuel			kg CO_2e/l fuel		
Marine diesel oil	0.68	3.24	3.92	0.61	2.92	3.53
Marine gas oil	0.68	3.24	3.92	0.61	2.88	3.49
Gasoline	0.61	3.25	3.86	0.45	2.42	2.88
Bioethanol	1.56	0.00	1.56	1.24	0.00	1.24
Gasoline, 5% bioethanol blend	0.66	3.08	3.74	0.50	2.30	2.80
Diesel	0.69	3.21	3.90	0.57	2.67	3.24
100% biodiesel (B100)	2.16	0.00	2.16	1.92	0.00	1.92
Diesel, 5% bio-diesel blend (B5)	0.76	3.04	3.80	0.63	2.54	3.17
Liquefied petroleum gas	0.36	3.10	3.46	0.20	1.70	1.90
Compressed natural gas	0.39	2.68	3.07	N/A	N/A	N/A
Liquefied natural gas	0.94	2.68	3.62	N/A	N/A	N/A
Biomethane	0.49	0.00	0.49	N/A	N/A	N/A
Bio-liquefied natural gas	1.04	0.00	1.04	N/A	N/A	N/A

Tableau 4: road transport emission intensity factors

Table 41. Europe and South America road emission intensity factors

Mode	Vehicle characteristics and size	Combined Load Factor & Empty Running	Fuel	Consumption factor (kg/t-km)	Consumption factor (l/t-km)	Emission intensity (g CO_2e/t-km)		
						WTT	TTW	WTW
Road	Van ≤ 3.5 t	36%	Diesel, 5% biodiesel blend	0.180	0.215	140	550	680
		24%	Petrol	0.263	0.353	160	850	1000
		36%	CNG	0.200	-	80	540	620
		36%	LPG	0.189	0.345	70	590	660

Table 42. Europe and South America road emission intensity factors

Vehicle characteristics and size	Load characteristics	Basis		Fuel	Consumption factor (kg/t-km)	Consumption factor (l/t-km)	Emission intensity (g CO_2e/t-km)		
		Load Factor	Empty Running				WTT	TTW	WTW
Rigid truck 3.5–7.5 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.098	0.118	74	300	370
				CNG	0.117	-	45	310	360
Rigid truck 7.5–12 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.062	0.074	47	190	240
				CNG	0.073	-	28	190	220
Rigid truck 12–20 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.040	0.048	30	120	150
				CNG	0.050	-	15	130	150
				LNG	0.050	-	46	130	180
Rigid truck 20–26 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.033	0.039	26	99	130
				CNG	0.038	-	15	100	120
				LNG	0.038	-	36	100	140
Rigid truck 26–32 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.026	0.031	20	78	98
	Container	72%	30%		0.023	0.027	18	69	87
Artic truck up to 34 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.024	0.029	18	74	92
	Container	72%	30%		0.027	0.033	21	83	100
Artic truck up to 40 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.021	0.025	16	64	80
	Container	72%	30%		0.020	0.024	15	60	75
Artic truck up to 40 t GVW	Average/ mixed	60%	17%	CNG	0.024	-	10	66	75
	Container	72%	30%		0.024	-	10	65	75
	Average/ mixed	60%	17%	LNG	0.024	-	23	65	88
	Container	72%	30%		0.024	-	23	64	87
	Average/ mixed	60%	17%	LNG with 20% bio content	0.024	-	23	52	75
	Container	72%	30%		0.024	-	23	51	75
Artic truck 40 t GVW, inc light-weight trailer	Heavy	100%	38%	Diesel, 5% biodiesel	0.016	0.019	12	48	60
Artic truck up to 44 t GVW	Light	30%	9%	Diesel, 5% biodiesel blend	0.029	0.034	23	87	110
	Average/ mixed	60%	17%		0.018	0.021	14	54	68
	Heavy	100%	38%		0.015	0.018	12	46	58
	Container	72%	30%		0.018	0.021	14	54	67
Artic truck up to 60 t GVW	Average/ mixed	60%	17%	Diesel, 5% biodiesel blend	0.017	0.020	12	51	63
	Heavy	100%	38%		0.014	0.017	11	44	55
	Container	72%	30%		0.017	0.020	13	50	63
Artic truck up to 72 t GVW	Heavy	100%	38%	Diesel, 5% biodiesel blend	0.013	0.015	10	38	48
	Container	72%	30%		0.014	0.017	11	43	54

Rail transportation
Region: Europe
EU average (where traction energy type unknown*): 17 g CO_{2e}/t-km (WTW)
EU average (diesel traction): 28 g CO_{2e}/t-km (WTW)
EU average (electric traction): 10 g CO_{2e}/t-km (at the average 2016 EU electricity generating mix**)

Air transport
Average value for airfreight GHG emission: 1060 g $C0_{2e}$/t-km
Depending on the distance and the category of transport:

Table 5: air transport emission intensity factors

Table 35. Air transport emission intensity factors

	ICAO/IATA RP1678			EN16258		
	WTW g CO_2e/t-km			WTW g CO_2e/t-km		
	unknown	belly freight	freighter	unknown	belly freight	freighter
Short haul (← 1000 km)	1130	920	1390	1430	1490	1340
Medium haul (1000–3700 km)	700	690	710	920	1110	700
Long haul (→ 3700 km)	630	680	560	800	990	560

Table 6: inland waterways emissions intensity factors

Table 36. Inland waterways transport emissions intensity factors

Vehicle characteristics and size	Loading Basis: Combined Load Factor & Empty Running	Fuel	Consumption factor (kg/t-km)	Consumption factor (l/t-km)	Emission intensity (g CO_2e/t-km)		
					WTT	TTW	WTW
Motor vessels <– 80 m (<– 1000 t)	55%	Diesel	0.0076	0.0091	5.2	24	30
Motor vessels 85–110 m (1000–2000 t)	52%	Diesel	0.0048	0.0058	3.3	15	19
Motor vessels 135 m (2000–3000 t)	50%	Diesel	0.0049	0.0059	3.4	16	19
Coupled convoys (163–185 m)	61%	Diesel	0.0044	0.0052	3.0	14	17
Pushed convoy – push boat + 2 barges	70%	Diesel	0.0044	0.0053	3.1	14	17
Pushed convoy – push boat + 4/5 barges	70%	Diesel	0.0025	0.0030	1.7	8.0	10
Pushed convoy – push boat + 6 barges	70%	Diesel	0.0019	0.0023	1.3	6.1	7.4
Tanker vessels	65%	Diesel	0.0055	0.0066	3.8	18	21
Container vessels 110 m	75%	Diesel	0.0065	0.0079	4.5	21	26
Container vessels 135 m	75%	Diesel	0.0051	0.0061	3.5	16	20
Container vessels – Coupled convoys	68%	Diesel	0.0051	0.0061	3.5	16	20

Table 7: sea transport emission factors

Table 45. Sea transport emission intensity factors

Vehicle characteristics and size	Load char-acteristics	Basis		Fuel	Consumption factor (kg/t-km)	Consumption factor (l/t-km)	Emission intensity (g CO_2e/t-km)		
		Load Factor	Empty Running				WTT	TTW	WTW
Oil tanker ←5 dwkt*	Heavy	89%	25%	HFO	0.0178	0.0183	4.6	56	61
	Heavy	89%	25%	MGO	0.0168	0.0186	11	54	66
Oil tanker 5–60 dwkt	Heavy	82%	25%	HFO	0.0062	0.0063	1.6	19	21
	Heavy	82%	25%	MGO	0.0058	0.0064	3.9	19	23
Oil tanker 60–200 dwkt	Heavy	79%	56%	HFO	0.0026	0.0027	0.70	8.1	8.8
	Heavy	79%	56%	MGO	0.0024	0.0027	1.6	7.9	9.5
Oil tanker →200 dwkt	Heavy	89%	52%	HFO	0.0008	0.0008	0.20	2.4	2.6
	Heavy	89%	52%	MGO	0.0007	0.0008	0.50	2.3	2.8
	Heavy	89%	52%	LNG	0.0007	-	0.7	1.9	2.6
General Cargo ←10 dwkt	Average/ mixed	85%	31%	HFO	0.0056	0.0057	1.4	17.5	19
	Average/ mixed	85%	31%	MGO	0.0052	0.0058	3.6	16.9	21
General Cargo 10–20 dwkt	Average/ mixed	83%	37%	HFO	0.0039	0.0041	1.0	12	13
	Average/ mixed	83%	37%	MGO	0.0037	0.0041	2.6	12	15
Bulk carrier ←10 dwkt	Average	86%	25%	HFO	0.0096	0.0099	2.5	30	33
	Average	86%	25%	MGO	0.0091	0.0101	6.2	29	36
Bulk carrier 10–100 dwkt	Average	85%	43%	HFO	0.0022	0.0022	0.5	6.9	7.4
	Heavy	88%	43%		0.0022	0.0021	0.5	6.7	7.2
	Average	85%	43%	MGO	0.0021	0.0023	1.3	6.7	8.0
	Heavy	88%	43%		0.0020	0.0022	1.4	6.4	7.8
Bulk carrier →100 dwkt	Average	86%	43%	HFO	0.0009	0.0008	0.2	2.7	2.9
	Heavy	90%	43%		0.0008	0.0008	0.2	2.6	2.8
	Average	86%	43%	MGO	0.0008	0.0009	0.5	2.6	3.1
	Heavy	90%	43%		0.0008	0.0009	0.5	2.5	3.0
	Average	86%	43%	LNG	0.0008	-	0.7	2.0	2.7
	Heavy	90%	43%		0.0007	-	0.6	2.0	2.6
Ro-Ro fleet average	Average, freight only	40%	0%	HFO	0.0132	0.0136	3.4	42	45
		40%	0%	MGO	0.0124	0.0140	8.4	40	49
	Truck + Trailer, ave load factor	40%	0%	HFO	0.0295	0.0304	7.6	93	100
		40%	0%	MGO	0.0280	0.0316	19	90	110
	Trailer only, ave load factor	40%	0%	HFO	0.0198	0.0204	5.2	63	68
		40%	0%	MGO	0.0192	0.0217	13	61	74
Ro-Pax	Average	40%	0%	HFO	0.0613	0.0632	16	190	210
		40%	0%	MGO	0.0578	0.0649	39	190	230

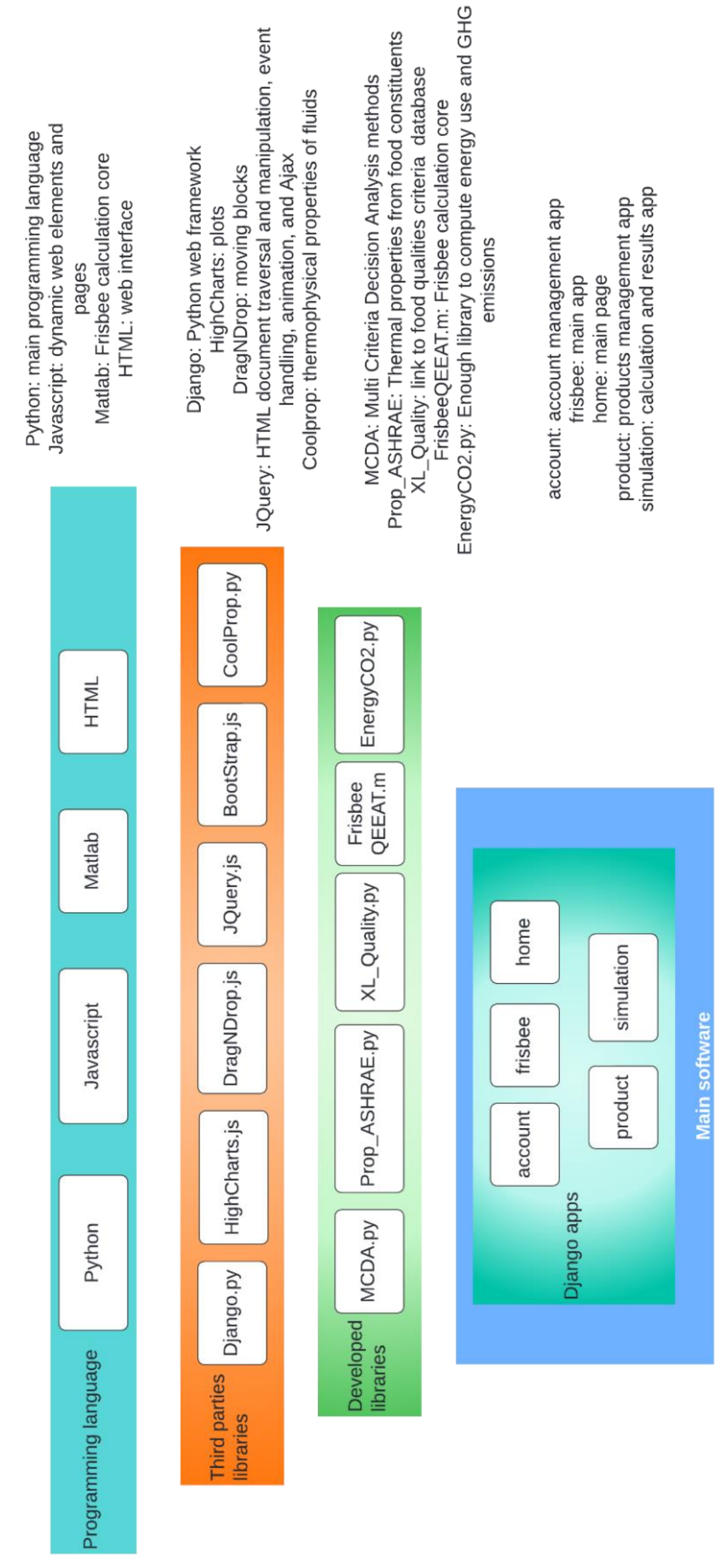
* dwkt = 1000 deadweight tonnage (DWT)

6 ANNEX 2: PRODUCTS AVAILABLE IN THE TOOL (MARCH 2023)

Food product	Product category	T conservation	Quality criteria
Apple	Fruit	1°C	Firmness, colour, relative volatile, weight loss
Cooked ham – MAP	Meat	4°C	Listeria moncytogenes, lactic acid bacteria, water activity
Pasteurized paté – MAP	Meat	4°C	Listeria monocytogenes, Leuconostoc mesenteroides, Lactobacillus sakeii, Water activity
Pork neck cutlet	Meat	-1.5°C	Lactic acid bacteria, pressure drip loss, spoilage limitation, colour
Salmon	Fish	4°C	Lactic acid bacteria, water holding capacity, colour Hue, colour saturation
Regular vanilla ice cream	Milk products	-18°C	Sensory perception, damping factor, firmness, thermal conductivity
Premium vanilla ice cream	Milk products	-18°C	Sensory perception, damping factor, firmness, thermal conductivity
Spinach chopped cubes	Vegetables	-18°C	Vitamin C, chlorophyll
Frozen shrimp	Fish	-18.0°C	Color, volatile basic nitrogen, trhimethylamuine nitrogen, flavor, global acceptance
Frozen carrots	Vegetables	-18°C	Ascorbic acid, frost, color, drip loss, firmness, vitamin C, salmonella, virus, listeria monocytogenes
Frozen broccoli	Vegetables	-18°C	Ascorbic acid, color, drip loss
Frozen green beans	Vegetables	-18°C	Ascorbic acid, chlorophyll, stress, color, firmness, break point, frost
Frozen green peas	Vegetables	-18°C	Ascorbic acid
Frozen pumpkin	Vegetables	-18°C	Ascorbic acid, color, firmness, break point
Frozen ground beef	Meat	-18°C	Rancidity, flavour
Frozen bovine liver	Meat	-18°C	Lactic acid bacteria, pressure drip loss, spoilage limitation, colour, carbonyl, thiobarbituric acid, peroxide value
Pasteurized milk	Milk products	4.0°C	-
UHT milk	Milk products	20.0°C	-

Yoghurt	Milk products	4°C	Evident spoilage
Mackerel	Fish	1°C	-

7 ANNEX 3: SOFTWARE STRUCTURE



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Disclaimer: This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588.