Improving environmental performances in wine production by a Life Cycle Assessment analysis

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In the last years, the wine production industry had gradually focused its attention in the improvement of the product quality rather than quantity. This tendency generated an increase in the wine's price/litre, and, as a consequence, the entrance in the market of various small wine producers that developed new product trademarks of good qualities. The product quality obtained through better raw materials and more careful processes (with a semi-handcrafted quality) cannot be separated from an accurate evaluation of the environmental sustainability. Unfortunately, a higher number of small producers may generate greater emissions with respect to a small number of big industrial producers and, therefore, these small emerging productions have to be, even more so, studied.

The aim of this paper is to deepen the environmental impacts and the energy efficiency of four kinds of wines made by a small producer in the southern part of Italy using a Life Cycle Assessment (LCA) analysis. Vinification, bottling, packaging, distribution and waste disposal treatments were taken into account in the performed analysis. Wines were produced using different processes and different raw materials, depending on the specific characteristics (high or medium quality) and kind (red or white). The materials and energy consumption and the emissions to air, soil and water were reported to the chosen functional unit (a bottle of Italian wine). The data were analysed using SimaPro 8.0.2 software and the Ecoinvent database, in accordance with the reference standard for LCA (i.e., ISO 14040-14044) to identify the environmental performance indicators of the IMPACT 2002+ methodology. Once evaluated the global environmental impact on all the categories, we focused our attention and we proposed an improved solution in terms of global warming potential (GWP). In particular, for the red high quality wine (that was the most environment affecting wine), carbon dioxide emissions lowered from 0.99 to 0.05 kg_{CO2}/bottle.

1. Introduction

Carbon dioxide emissions reduction achieved a leading position in the last two decades research. Nevertheless considered "not dirty" if compared to chemicals and mining industries, the food industry is a large user of energy and, therefore, largely contributes to total carbon dioxide emissions (Roy et al., 2009). Environmentally friendly-products are approved with favour by the consumers (Barber et al., 2009) and local communities and governments encouraged the diffusion of environmentally relevant results. Some industries, like the one of wine, which environmental issues were for years unexplored, with the aim of improve market quota or consumer satisfaction, became among the most studied ones (Christ and Burritt; 2013; Rugani et al., 2013). Indeed, the cultivation of wine grapes and the production of wine are far from being environmentally clean processes (Gabzdylova et al., 2009).

Historically, the production of wine concentrated in Europe, in particular in France, Italy and Spain. According to the International Organisation of Vine and Wine (OIV), Italy is the second in a list of ten major wine producing countries, with more than 41 Mhl produced in 2011 (OIV, 2012), as shown in Figure 1.

This work concerns the environmental impact and the energy efficiency of different wines produced in the southern part of Italy and exported in the whole country. A recent trend in the wine production industry led to the production of products of higher qualities rather than quantities; this tendency opened the market doors to small wine producers, which have developed good qualities wines on a small scale. Four main stages have to be considered in the production of wine: viticulture (related to vineyard planting and grapes cultivation), wine production and bottling (from vinification to storage), wine transportation, distribution and sales, and disposal of empty bottles. To assess the environmental impacts due to the production of a bottle of wine, a Life cycle assessment (LCA) analysis can be used.

LCA is an internationally recognized and ISO standardized accounting tool to quantify the environmental impacts of a product, a process or a service throughout its life cycle, by identifying, quantifying and evaluating all the resources consumed and all the emissions and wastes released in an analysis known as a "from cradle to grave". In the last years, various LCA analyses have been performed in the case of agricultural productions, that are more complex because, for the agricultural phase, the LCA methodology is not well established, since the process cannot be easily standardised (Haas et al., 2000). Among the agri-food products, wine has been one of the most studied and several papers on LCA using a *cradle to grave* analysis have been published. In particular, Gazulla et al. (2010) identified the most critical, from the point of view of the environmental impacts, life cycle stages of a Spanish red wine production (starting from viticulture & grape growing phase) and compared its environmental performance with other wines and beers. Bosco et al. (2011) made a carbon footprint (life cycle of greenhouse gases emitted in the atmosphere evaluated in terms of global warming potential) analysis of four high quality wines produced in the Maremma Italian district, including all the products' life cycle stages, with a special interest on the agricultural phase (including also the vineyard planting phase). Point et al. (2012) used an LCA analysis to quantify environmental impacts for a bottle of wine produced in Nova Scotia, Canada, providing different scenarios in which lighter bottles or different transport modes and distances were considered. Fusi et al. (2014) performed an attributional LCA to deepen the assessment of the environmental impacts of a *Vermentino* white wine produced in Sardinia, Italy and exported all over the world. Amienyo et al. (2014) estimated the environmental impacts in the life cycle of a red wine produced in Australia and consumed in the United Kingdom. Other studies, like the one made by Ardente et al. (2006) or by Neto et al. (2013), used a *cradle to gate* approach, considering the distribution but not the waste disposal stage. Other studies considered the waste disposal but not the distribution (Pizzigallo et al., 2008; Iannone et al., 2014); other did not consider neither the distribution nor the waste disposal step (Benedetto, 2013). When in the aims of the work there is a decisional support, a *gate to gate* approach with the comparison of different scenarios was performed; in these cases, a single step of the process, that can be, for example, the viticulture (Vázquez-Rowe et al., 2012) or the end-of-life (Ruggieri et al., 2009) was studied.

The analysis of the state of the art underlines that a limited attention has been paid to the industrial wine vinification stages. Indeed, in most cases, the analyses made in the literature considered the industrial stages as a unique phase without details and deepening. Therefore, the step forward of this paper with respect to the existing literature is the in-depth analysis of the industrial vinification stages; i.e., preliminary phases, wine clarification, fermentation, cleaning, refining, bottling, distribution and end-of-life to verify the relevance of each phase on the total environmental impact in order to prioritize the powering up actions to improve the environmental performances. The results of the LCA analysis are related to the industrial stages of four different wines made by a small Italian producer.

2. LCA methodology

LCA is a multi-stage analysis in which a broad set of data, regarding the life-cycle of a product or a process, if properly collected and organized, are used to compare different products, different life-cycle of the same product or to individuate the most critical phase of a life-cycle from the environmental perspective. In the following sub-sections and paragraphs, the main steps that constitute the LCA methodology are presented: 1) goal definition, functional unit and system boundaries; 2) life cycle inventory; 3) Impact assessment; 4) Most affecting parameters evaluation.

2.1 Goal definition, functional unit and system boundaries

Goal definition is one of the most important phases of the LCA methodology, because the choices made at this stage influence the entire study. The purpose of this study is to estimate the environmental impacts and identify improvement opportunities in the life cycle of four different wines produced in Southern Italy: one Red of High Quality (RHQ), one Red of Medium Quality (RMQ), one White of High Quality (WHQ) and one White of Medium Quality (WMQ). The characteristics of the different wines are represented in Table 1. The analysis is focused on the wine production stages to highlight the different four wines environmental performances.

The definition of the functional unit (FU) is based on the quantity or mass of the product under analysis, and it is a reference unit to which all the inputs and outputs have to be related. The chosen FU was one 0.75 L bottle of wine produced by a small company in Italy instead of a 1 L bottle of packaged wine, since all four wines are sold in the same format of 0.75 L.

The system boundaries of the analysis, generally illustrated by a general input and output flow diagram, were set from grapes transportation to waste disposal. All the activities, the processes and the materials (included water and energy) used in the industrial wine production stages were taken into account. The proposal study does not refer to a “from cradle to grave” analysis, but to a “from gate to gate” and “from gate to grave” one regarding, in particular, the vinification, wine bottling and packaging, distribution and waste disposal. The viticulture was not included in the system boundaries because several papers have been already published on the LCA of these stages (Villanueva-Rey et al., 2014), whereas industrial phases in details received a limited attention. The transportation of the grapes to the winery was included into the boundaries, because the four kind of grapes came from different farms. Activities as the potential impacts regarding the consumption of refrigerated wine were not taken into account. Another activity that was not included is the transportation of wastes as it was considered to be negligible. Other activities concerning the cork stoppers and the caps production as well as the labelling materials used in the bottles were also not considered in the study. The scheme of the industrial wine production chain is reported in Figure 2.

2.2 Life cycle inventory (LCI)

The life cycle inventory (LCI) is one of the most effort-time consuming step compared to other phases in an LCA and consists on the activities related to the search, the collection, and interpretation of the data necessary for the environmental assessment of the observed system. The Ecoinvent database was employed as the principal source of background data. However, the majority of the processes and materials information required for the analysis are specific of the observed system and the collection of these primary data was obtained from a wine producer using questionnaires, phone and personal interviews. Data from previous literature, when specific data were not available, were used to complete inventory data. For each type of wine, the procedure for the determination of energy consumption, emissions, and yields follows the stages represented in Figure 2 and takes into account mass and energy balances typical of each transformation and of the equipment owned by the producer. For each unit process within the system boundaries, input data; i.e., energy, water, natural sources, temperatures and pressures, and output data in terms of emission to air, water and soil were collected.

The energy usage impact was evaluated considering the Italian energetic mix available in the Ecoinvent. The white and red wines vinifications are different, as underlined also in Figure 2. Table 2 lists the main energy and direct material input to the product systems under the study of a 0.75 L bottle of wine.

2.2.1. Preliminary phases

After the agricultural stages (vineyard planting and grape production), the grapes are harvested and **transported** to the winery. As indicated in Table 1, the sources of the grapes are different for the four wines under study. The wine production process, both for white and red wines, starts with **crushing and destemming** of the grapes, with the aim of totally remove rasps.

2.2.2. White wine vinification

White wine vinification starts with the **pressing** of the destemmed grapes. In the case of the WHQ wine, the chosen pressure is 1.3 bar, whereas, in the case of the WMQ wine, the pressure is equal to 1.7 bar. Then, prior to fermentation, must is **clarified** for 24 h at 10 °C to avoid the presence of visible particles suspended in it; for this aim, pectin-splitting enzymes are added to the must to promote the agglomeration. The **fermentation** is initially activated by yeast inoculation; during fermentation, yeasts transform sugars present in the juice into ethanol and carbon dioxide. For the white wines, this stage lasts for about 20 days and is carried out under a controlled temperature of about 16 °C. The production of carbon dioxide during fermentation was included into the analysis, because the viticulture stages are out of the system boundaries and, therefore, the carbon sequestration by grape vines cannot compensate for the biogenic carbon dioxide production. Ethanol emissions in air were included as they contribute to photochemical oxidation (Notarnicola et al., 2003; Neto et al., 2013); they were estimated considering the emission factors determined by the United States Environmental Protection Agency (USEPA) (1995). After the fermentation, the wine is **cleaned**; i.e., it is separated from lees; then, the wine is **stabilized** using potassium metabilsulfite (MBK) that, being an antioxidant, will stop further fermentation by removing oxygen, therefore preserving the flavor and color of the wine. The WMQ wine is, then, ready for the bottling, whereas the WHQ wine is subjected to a **refining** in steel tanks, at a controlled temperature of 16 °C for four months. Data on yeast, enzymes and potassium metabisulfite were included in the inventory, but not in the impact assessment, considering the lack of information (Bosco et al., 2011) and their negligible contribution to the overall impacts (Notarnicola et al., 2003).

2.2.3. Red wine vinification

After crushing and destemming (chapter 2.2.1), the must is **fermented** at a temperature of about 24 °C, during which yeast is fed into the fermentators to convert the sugars into ethanol and carbon dioxide; the fermentation lasts for about 12 days. After the fermentation, the must is **pressed** (for the RHQ wine, the chosen pressure is 1.2 bar, whereas for the RMQ wine is 1.5 bar). In this kind of vinification, the pressing is performed after the fermentation, because the red color derives from grape skins and, therefore, the prolonged contact between the juice and skins is essential for color extraction. After the pressing, the wines are headed for a first **cleaning** to obtain the separation of lees. The first **refining** stage is conducted at 18 °C; for the RHQ wine, it takes place in barriques for twelve months, whereas, for the RMQ wine, it takes place in steel tanks for six months. Red wines are, then, undergoing to a second **cleaning** to complete the separation of lees. Finally, the RHQ wine is again **refined** in barriques, at a controlled temperature of 18 °C for twelve months.

2.2.4. Bottling, packaging and distribution

The four wines are bottled in green 0.75 L glass bottles with a weight of 0.4 kg, using cork stoppers and paper labels. Then, the secondary package consists of a six-bottle cardboard box. The distribution phase has been included only in some studies made on wine life cycle assessment, because sufficient information may not always be accessible to model this stage. In our study, this phase was included, because transport can be relevant in the overall environmental impact of wine, especially in the case of WHQ and RHQ wines, that are exported within national borders and in China (as reported in Figure 3). The distribution in the Italian peninsula was performed only by road transportation, whereas the distribution in Sardinia and in China was performed by road and by sea transportation. Due to the lack of information, the China distribution was only considered until the port of Shangai, excluding the road distribution from that port to the possible destinations.

2.2.5. Waste disposal

The organic wastes (stalks, lees and dewatered sludge) traditionally are incinerated or disposed in landfill. A more recent trend to reduce the environmental impact concerns their total composting. Therefore, according to the study performed by Ruggieri et al. (2009), we assumed that all the organic wastes were composted. For the waste management of the labels and cork stoppers, we assumed to deposit them in landfill, whereas for the disposal of glass bottles, we considered two different waste scenarios, referring to the Italian and Chinese realities. Indeed, for the Italian scenario, we considered that the 34 % of the glass is landfilled and 66 % is recycled, while for the Chinese scenario, we considered that the 90 % of the glass is landfilled and 10 % recycled.

2.3 Impact assessment

The LCA study is conducted using the LCA software SimaPro 8.0.2 in accordance with the reference standard for LCA (i.e., ISO 14040-14044). The interpretation of the data collected in the LCI phase and the evaluation of the wine productions' environmental impact were made considering four damage categories: human health, ecosystem quality, climate change and resources. The inventory results can be classified by different impact categories in accordance with impact assessment step. According to the life cycle impact assessment methodology IMPACT 2002+, several midpoint categories are used to link all types of LCI results to those damage categories. In particular, the human health is affected by carcinogens (C), non-carcinogens (NC), respiratory inorganics (RI), respiratory organics (RO), ionizing radiations (IR) and ozone layer depletion (OLD); the ecosystem quality is affected by aquatic ecotoxicity (AET), terrestrial ecotoxicity (TET), aquatic acidification (AA), aquatic eutrophication (AE), terrestrial acidification/nitrification (TAN) and land occupation (LO); the climate change is quantified using the global warming potential (GWP); the resources are affected by non-renewable energy consumption (NRE) and mineral extraction (ME).

2.4 Most affecting parameters evaluation

For each industrial stage, the variables that most affect electricity consumption, transportation and wastes were evaluated. To correlate the sets of data, the Pearson coefficients were used, and the strong, moderate and weak relationships were calculated.

3. Results and discussion

3.1 Environmental IMPACT 2002+ analysis

Impact 2002+ that considers 15 midpoint categories was used for the LCA analysis. In Table 3, the total emissions for the production of one bottle of Italian wine are reported.

In Figure 4, a radar chart is proposed with the relative contributions of the four wine's productions on each impact category.

From Figure 4, it is possible to observe that the WMQ wine generates lower emissions for all the impact categories, except for OLD; this result can be explained considering that, for WHQ wine, the higher emissions are related to different reasons: the vineyards from which the grapes are transported to the factory are farer, the grapes' quantity is greater and, therefore, it was necessary to choose a wider truck producing higher emissions/tkm. The two medium quality wines with respect to the corresponding high quality wines showed lower emissions for almost all the impact categories, because some phases for them are absent (the refining for the WMQ and the final refining for the RMQ) and other phases have shorter processing times. Among the two high quality wines, the one with the higher impacts is the RHQ, due to the higher fermentation temperature and the long period of refining at controlled temperature (12 months for each refining stage).

3.2 Global warming potential analysis

To evaluate stage by stage the emissions for the four wines, we focused on global warming potential (GWP), considering that a high attention is paid on the earth global heating, which strongly depends on this parameter. The GWP of the main stages of the wines' production is reported in Figure 5; in particular, in Figure 5a, the emissions were evaluated considering also the contribution of the raw materials, whereas the graph in Figure 5b is related to the emissions without considering the raw materials. In the choice of the mean room temperature the historical climate data for the years 2010-2013 were considered and, for each vinification stage, the period of time in which it occurs was taken into account. In particular, for white wines clarification (24 h) and fermentation (20 days for white and 12 days for red wines) stages, the mean room temperature was 18.8 °C, whereas, for the refining stage (4 months for the WHQ, 6 months for the RMQ and 24 months for the RHQ wines), it was taken into account the variability of the room temperature during the months.

The GWP of the industrial vinification phases of the four investigated wines was found to lie between 0.068 and 0.99 $kgCO_2eq/FU$. The RHQ wine showed the higher GWP/FU, followed by the other red wine and the WHQ wine. The contribution of the industrial stages, excluding the raw materials, is equal to 89.4 % for RHQ, 76.4 % for RMQ, 64.9 % for WHQ and 66.9 % for WMQ. Therefore, in order to optimize the process, once quantified the weights of the different stages, we studied in details the emissions related to the stages from the arrival of the grapes to the factory to the bottling, without considering the distribution and the waste disposal. The results in terms of GWP are reported in Figure 6.

The preliminary phases (transportation, crushing and destemming, and pressing) were put together, but their contribution to GWP was very low (it goes from 0.0015 $kgCO_2/FU$ for the RMQ wine to 0.016 $kgCO_2/FU$ for the WMQ wine). The clarification is performed only in the case of the white wines, and it represents the 20.9 % for the WHQ wine and the 47.7 % for the WMQ wine. The higher contribution to GWP is due to the refining stages, especially in the case of the red wines; in that stage, the wines are taken in barriques (RHQ) or in steel containers (WHQ, RMQ): for the RHQ wine, the two refining phases represent the 95.6 % of the total GWP, for the RMQ wine, the refining represents the 85.3 %, whereas for the WHQ wine, it represents the 62.8 %. These high percentages are related to the fact that the refining stages are taken for several months at controlled temperature, which is equal to 18 °C for the red wines and 16 °C for the white wine. The high GWP is, therefore, related to the high electricity consumption of the conditioning systems.

3.2.1. Most affecting parameters evaluation

Some of the parameters influencing the vinification processes are variable and not easily controllable (i.e., temperatures, efficiencies, yields, pressures) and they can condition the results in terms of emissions. Therefore, a sensitivity analysis was performed, in order to individuate which are the parameters mainly affecting the emissions through electricity, transportation and wastes. In Table 4, the Pearson correlation coefficients for each input and each parameter are reported. The parameters with moderate or strong correlation are shown in “italic type”, whereas the ones with weak correlation are shown in “regular type”. The results take into account the total emissions for the productions of the four wines (they are not referred to the FU).

Table 4 shows that the electricity consumption depends on the room temperature of fermentation (for white wines) and refining (for red wines). On the other hand, the effect on transportation and wastes is mainly related to the yields and pressure values. From the last row of Table 4, it is possible to notice that the 90.17 % of the total CO_2 emissions is due to electricity consumption, therefore, in order to optimize the process, the further part of this study will regard the temperatures optimization.

3.2.2. Process optimization

A study on the possibility of producing the wines in a place with a storage in a cellar with a naturally stable temperature (constant during the different stages) was made to minimize the GWP. First of all, we evaluated the carbon dioxide emissions, considering that the industrial stages are conducted at constant temperature, without taking into account the emissions related to the transfer in a different location.

Figure 7 shows the GWP of the industrial phases in the production of each wine at constant cellar temperature; the actual situation (with variable room temperature) is represented with the black line. The minimum value of the GWP is reached at 16 °C for the white wines that is the temperature at which fermentation and refining have to take place, whereas, for the red wines, it is reached at 18 °C, which is the refining temperature. Therefore, if there are not cellars (at constant temperature) in the proximity of the wine firm, it is necessary to transfer the must in a place where that cellars are available. The hypothesis of transferring the must induces the need of looking for a tradeoff between the higher emissions related to the transfer and the lowering of the carbon dioxide emissions due to the reduced conditioning ΔT. It is important to notice that this one is just an environmental analysis and didn't take into account any economical evaluation related to the must transferring. For each cellar temperature, the maximum distance that can be travelled (using Lorries Euro 5 with a capacity of 32 tons), in order to have GWP equivalent to the actual solutions, were evaluated and reported in Table 5.

The reported analysis was performed hypothesizing a distinct cellar for each wine. Considering the possibility of transferring all wines to a unique cellar, the emissions due to the overall wines' production were evaluated and reported in Figure 8, where for each couple distance/cellar temperature, the total emissions are represented.

The temperature corresponding to the lower total emissions is equal to 18 °C, because the process times, in the case of red wines, are considerably longer with respect to the ones of white wines. The quota of the emissions due to the transfer to the cellar obviously linearly increases with the distance, and, therefore, it is necessary to choose the best available couple cellar temperature/distance.

4. Conclusions

The purpose of this study was to present a quantitative and detailed analysis of the environmental performances for different Italian wines production and to find solutions to minimize the GWP. For the first time, the LCA analysis was made considering the emissions related to the stage by stage industrial phases. The performed LCA analysis showed that the RHQ wine has the higher impact on the environment, due to its refining stages, that go on 24 months at controlled temperature. An analysis to individuate the parameters that mostly influence the GWP of the wines' productions was performed. The most relevant parameter is the room temperature, therefore, a solution considering the placement of the wines in cellars at constant room temperature was proposed. Two different scenarios were developed: a first one that considers for each wine a cellar at optimized temperature (that takes into account the different red and white vinification temperatures); a second one with a unique cellar at constant temperature for all the wines.

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FIGURE CAPTIONS

Figure 1. Top 10 wine producer countries (data from OIV, 2012).

Figure 2: System boundaries.

Figure 3: Distribution for the four wines in Italy (by road) and from Naples to Shangai (by sea).

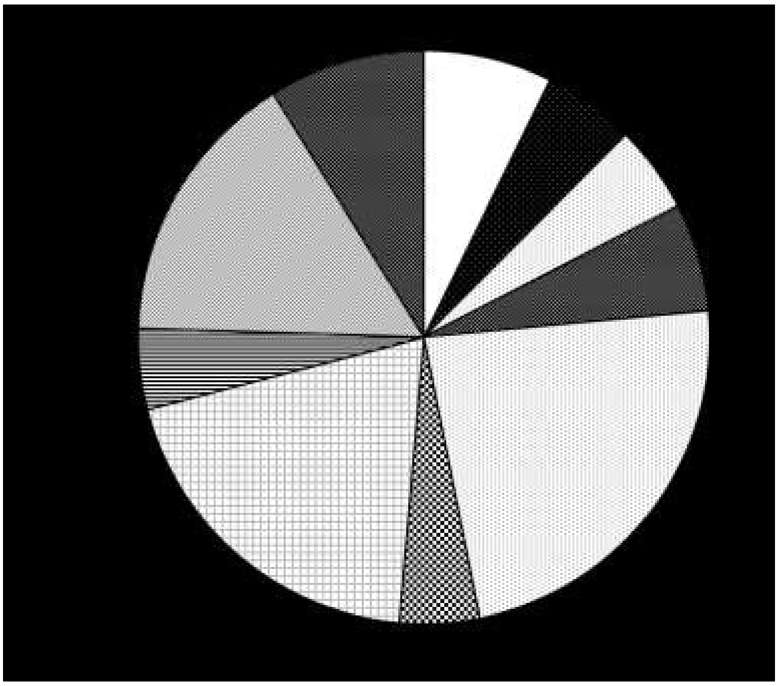
Figure 4: Life cycle environmental impacts of the different wines. [C carcinogens, NC non-carcinogens, RI respiratory inorganics, IR ionizing radiation, OLD ozone layer depletion, RO respiratory organics, AET aquatic ecotoxicity, TET terrestrial ecotoxicity, TAN terrestrial acidification & nutrification, LO land occupation, AA aquatic acidification, AE aquatic eutrophication, GWP global warming potential, NRE non-renewable energy, ME mineral extraction].

Figure 5: Contribution to GWP for the main phases of the four analysed wines; (a) with raw materials; (b) without raw materials.

Figure 6: Global warming potential of the industrial stages during the wine production (kgCO_2eq/FU) for the four wines.

Figure 7: Global warming potential emissions (kgCO_2 eq/FU) at constant cellar temperatures; (a) RHQ; (b) RMQ; (c) WHQ; (d) WMQ. The horizontal line indicates the emissions of the actual situation.

Figure 8: Global warming potential emissions (kgCO_2 eq) using a unique cellar with constant temperature.



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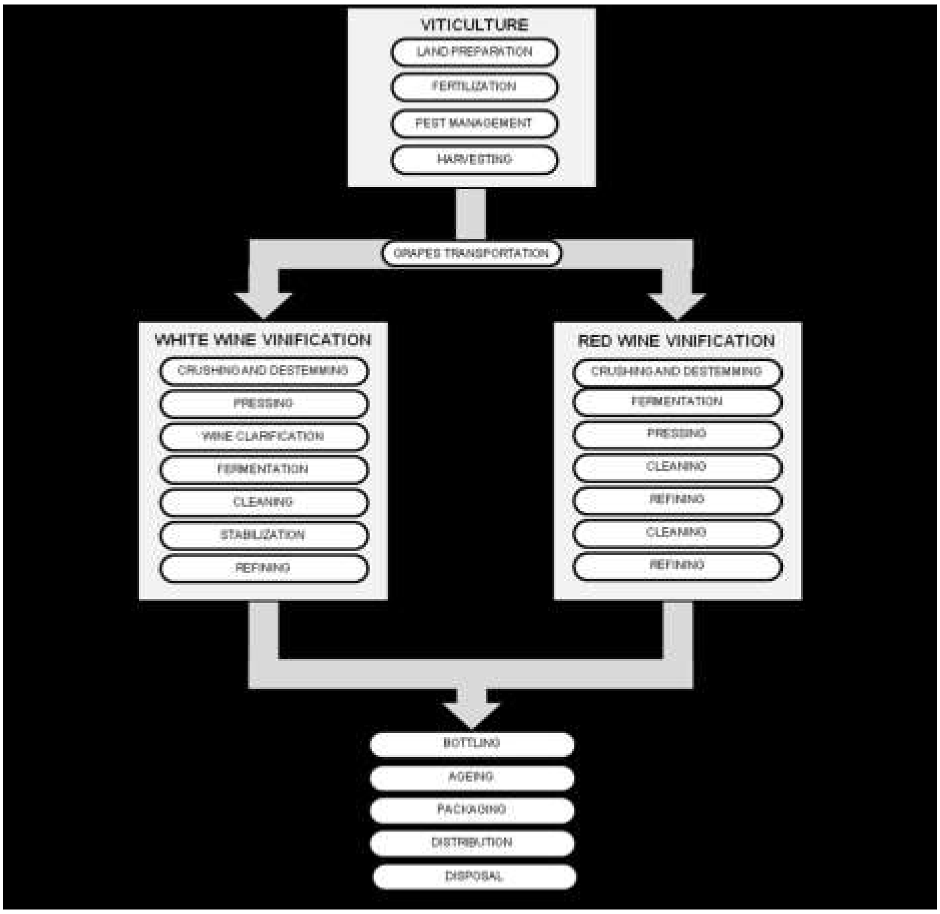

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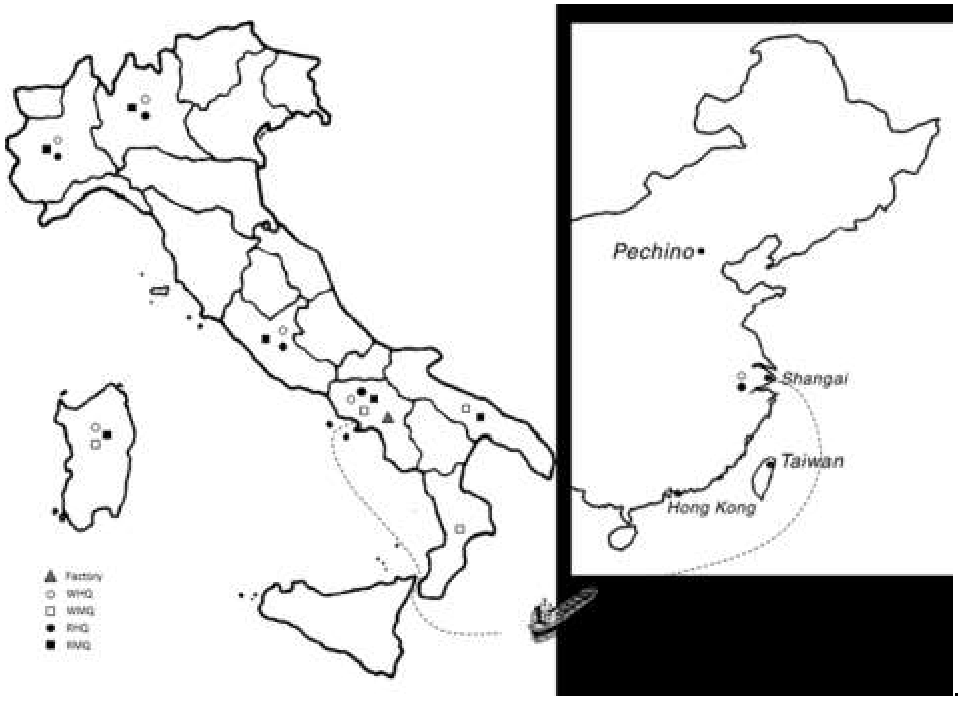

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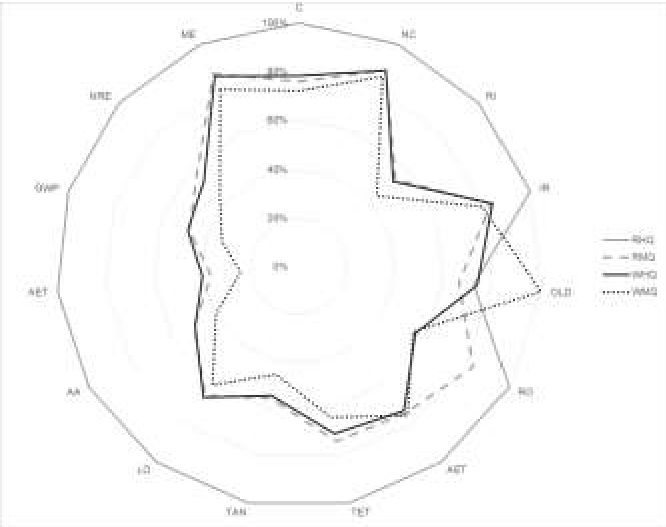

Figure 4: Life cycle environmental impacts of the different wines. [C carcinogens, NC non-carcinogens, RI respiratory inorganics, IR ionizing radiation, OLD ozone layer depletion, RO respiratory organics, AET aquatic ecotoxicity, TET terrestrial ecotoxicity, TAN terrestrial acidification & nutrification, LO land occupation, AA aquatic acidification, AE aquatic eutrophication, GWP global warming potential, NRE non-renewable energy, ME mineral extraction].

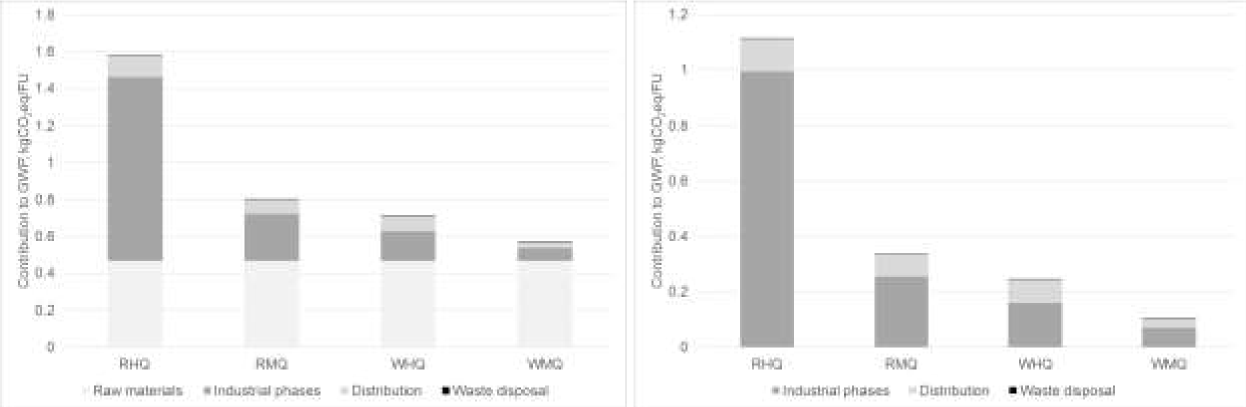

Figure 5: Contribution to GWP for the main phases of the four analysed wines; (a) with raw materials; (b) without raw materials.

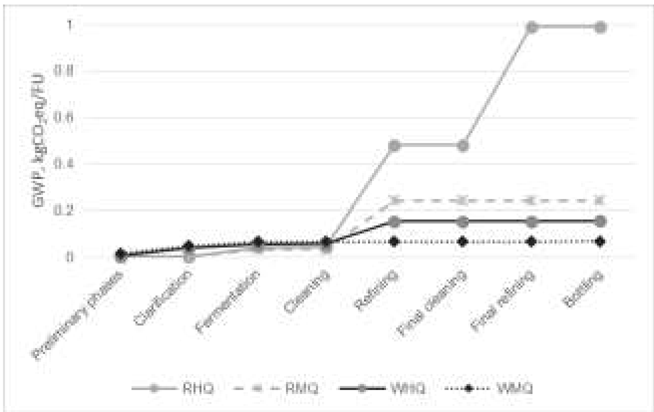

Figure 6: Global warming potential of the industrial stages during the wine production (kgCO_2eq/FU) for the four wines.

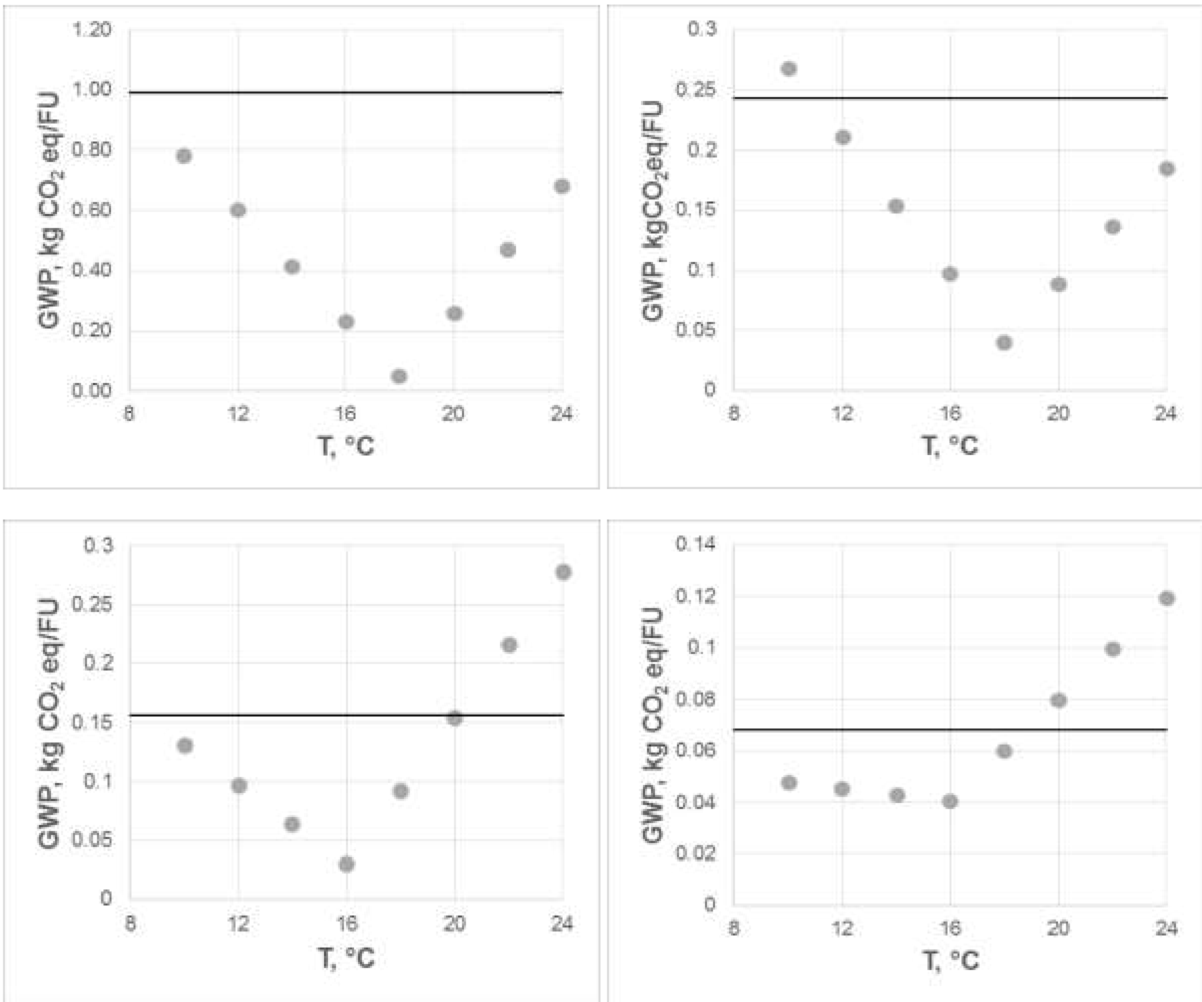

Figure 7: Global warming potential emissions (kgCO_2 eq/FU) at constant cellar temperatures; (a) RHQ; (b) RMQ; (c) WHQ; (d) WMQ. The horizontal line indicates the emissions of the actual situation.

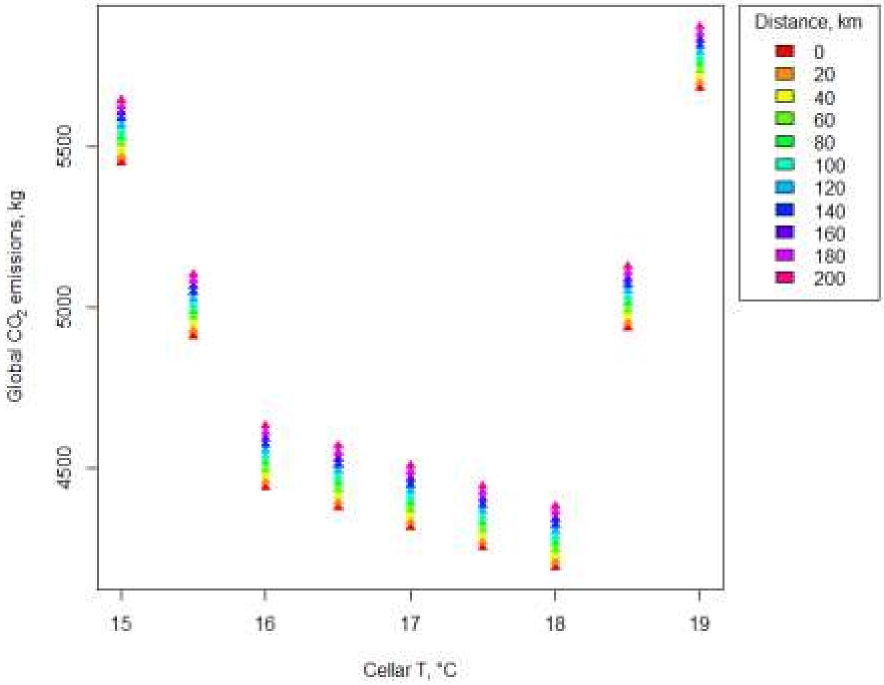

Figure 8: Global warming potential emissions (kgCO_2 eq) using a unique cellar with constant temperature.

TABLE CAPTIONS

Table 1: Characteristics of the four produced wines used to perform the LCA analysis.

Table 2: Life cycle inventory of the main inputs for the four wines investigated.

Table 3: Emissions for each midpoint category.

Table 4: Correlation coefficients between process parameters and main categories affecting CO_2 emissions.

Table 5: Maximum distances for the placement of the cellar at constant temperature.

Table 1: Characteristics of the four produced wines used to perform the LCA analysis.

	WHQ	**WMQ**	**RHQ**	**RMQ**
Municipality	Giffoni Valle Piana, Battipaglia, Giovi	Benevento	Giffoni Valle Piana	Giffoni Valle Piana
Grapes pressing	1.3 bar	1.7 bar	1.2 bar	1.5 bar
Wine clarification	10 °C, 24 h	10 °C, 24 h		
Fermentation	16 °C, 20 d	16 °C, 20 d	24 °C, 12 d	24 °C, 12 d
Refining			Barrique, 18 °C, 12 m	Steel, 18 °C, 6 m
Stabilization	MBK	MBK		
Refining	Steel, 16 °C, 4m	/	Barrique, 18 °C, 12 m	/
Bottling	0.75 L green glass	0.75 L green glass	0.75 L green glass	0.75 L green glass
Number of bottles	15000 b/y	30000 b/y	2500 b/y	20000 b/y
Ageing	6m	/	12m	6m
Packaging	6 bottles	6 bottles	6 bottles	6 bottles

Table 2: Life cycle inventory of the main inputs for the four wines investigated.

Industrial Phase	Input	Unit	WHQ	WMQ	RHQ	RMQ
Transportation	Transport by truck	tkm	1.61E-02	9.92E-02	2.93E-03	2.42E-03
Crushing and destemming	Electricity	MJ	3.58E-03	2.84E-03	3.86E-03	3.18E-03
	Grapes	kg	1.362E+00	1.078E+00	1.465E+00	1.208E+00
	Output					
	Stalks	kg	4.77E-02	4.64E-02	6.59E-02	5.56E-02
Pressing	Destemmed grapes	kg	1.31E+00	1.03E+00		
	Electricity	MJ	5.04E-03	3.96E-03		
	Output					
	Pips and skins	kg	5.26E-01	2.48E-01		
Wine clarification	Must	kg	7.88E-01	7.84E-01		
	Enzymes	kg	1.81E-05	2.74E-05		
	Electricity	MJ	3.53E-04	3.51E-04		
	Electricity for cooling	MJ	1.12E-01	1.11E-01		
	Output					
	Lees	kg	3.94E-02	3.14E-02		
Fermentation	Must	kg	7.49E-01	7.53E-01	1.40E+00	1.153E+00
	Yeast	kg	2.70E-04	3.01E-04	1.89E-04	1.73E-04
	Electricity for cooling	MJ	1.41E-02	1.42E-02	3.98E-02	3.28E-02
	Output					
	Carbon dioxide	kg	1.22E-02	1.23E-02	2.58E-02	2.13E-02
	Heat	MJ	6.01E-05	6.03E-05	1.29E-04	1.02E-04
Pressing	Wine	kg			1.40E+00	1.15E+00
	Electricity	MJ			5.37E-03	4.42E-03
	Output					
	Peels	Kg			6.16E-01	3.69E-01
Cleaning	Wine	kg	7.49E-01	7.53E-01	7.84E-01	7.84E-01
	Electricity	MJ	2.04E-03	2.05E-03	2.14E-03	2.14E-03

	Output					
	Lees	kg	7.49E-03	1.13E-02	3.92E-02	3.92E-02
Stabilization	Wine	kg	7.41E-01	7.41E-01		
	MBK	kg	1.61E-02	9.92E-02		
Refining	Wine	kg	7.41E-01		7.44E-01	7.45E-01
	Electricity	MJ	1.04E-01		4.08E-01	2.20E-01
	Electricity for cooling	MJ	3.38E-01		1.51E+00	7.13E-01
Final cleaning	Wine	kg			7.58E-01	7.41E-01
	Electricity	MJ			1.02E-03	1.02E-03
	Output					
	Lees	kg			3.72E-03	3.72E-03
Final refining	Wine	kg			7.41E-01	
	Electricity	MJ			4.06E-01	
	Electricity for cooling	MJ			1.75E+00	
Bottling	Electricity	MJ	9.00E-03	9.00E-03	9.00E-03	9.00E-03
	Wine	kg	7.41E-01	7.41E-01	7.41E-01	7.41E-01
	Glass bottle	kg	4.00E-01	4.00E-01	4.00E-01	4.00E-01
	Cork	kg	1.30E-02	1.30E-02	1.30E-02	1.30E-02
	Capsule	kg	2.00E-03	2.00E-03	2.00E-03	2.00E-03
	Label	kg	3.00E-03	3.00E-03	3.00E-03	3.00E-03
	Output					
	Bottle of 0.75 L	m^3	7.50E-04	7.50E-04	7.50E-04	7.50E-04
	Wine loss	kg	3.71E-03	3.71E-03	3.71E-03	3.71E-03
Packaging	Number of bottles	p	6	6	6	6
	Cardboard package	m^2	1.39E-02	1.39E-02	1.39E-02	1.39E-02
Waste management	Glass bottle	kg	4.00E-01	4.00E-01	4.00E-01	4.00E-01
	Capsule	kg	2.00E-03	2.00E-03	2.00E-03	2.00E-03
	Label	kg	3.00E-03	3.00E-03	3.00E-03	3.00E-03
	Cork	kg	1.30E-02	1.30E-02	1.30E-02	1.30E-02

Table 3: Emissions for each midpoint category.

Impact category	Unit	WHQ	WMQ	RHQ	RMQ
Carcinogens	kg C_2H_3Cl eq	1.62E-02	1.49E-02	2.07E-02	1.57E-02
Non-carcinogens	kg C_2H_3Cl eq	1.85E-02	1.79E-02	2.10E-02	1.85E-02
Respiratory inorganics	kg PM2.5 eq	8.89E-04	7.36E-04	1.70E-03	9.13E-04
Ionizing radiation	Bq C-14 eq	5.54E+00	5.25E+00	6.59E+00	5.48E+00
Ozone layer depletion	kg CFC-11 eq	3.99E-08	5.39E-08	3.91E-08	3.58E-08
Respiratory organics	kg C_2H_4 eq	3.19E-04	3.13E-04	5.76E-04	4.79E-04
Aquatic ecotoxicity	kg TEG water	5.96E+01	6.15E+01	8.07E+01	6.05E+01
Terrestrial ecotoxicity	kg TEG soil	1.62E+01	1.46E+01	2.29E+01	1.69E+01
Terrestrial acid/nutri	kg SO_2 eq	1.78E-02	1.49E-02	3.26E-02	1.82E-02
Land occupation	m2org.arable	3.07E-02	2.78E-02	4.58E-02	3.02E-02
Aquatic acidification	kg SO_2 eq	5.33E-03	4.26E-03	1.08E-02	5.41E-03
Aquatic eutrophication	kg PO_4 P-lim	1.05E-04	6.41E-05	2.63E-04	9.61E-05
Global warming	kg CO_2 eq	6.76E-01	5.30E-01	1.58E+00	7.49E-01
Non-renewable energy	MJ primary	9.96E+00	8.32E+00	1.89E+01	1.07E+01
Mineral extraction	MJ surplus	1.92E-02	1.79E-02	2.25E-02	1.95E-02

Table 4: Correlation coefficients between process parameters and main categories affecting CO_2 emissions.

Process Stage	**Parameter**	**Wine**	**Electricity, kWh**	**Transportation, tkm**	**Waste, kg**
Crushing & destemming	stalks (%)	WHQ	0.016	0.001	- 0.000
		WMQ	- 0.025	- 0.014	0.036
		RHQ	0.003	- 0.004	- 0.005
		RMQ	0.018	- 0.027	0.034
Pressing	pressure (bar)	WHQ	0.137	0.189	- 0.171
		WMQ	0.123	0.228	- *0.360*
		RHQ	0.002	0.030	- 0.038
		RMQ	0.066	*0.362*	- *0.240*
Clarification	efficiency (%)	WHQ	0.078	0.198	- 0.169
		WMQ	0.057	0.270	- *0.406*
	room T (°C)	W	0.262	0.014	0.015
Fermentation	room T (°C)	W	*0.475*	0.015	0.004
		R	- 0.220	- 0.007	0.016
Cleaning	efficiency (%)	WHQ	0.060	0.191	- 0.182
		WMQ	0.014	0.235	- *0.373*
		RHQ	- 0.004	0.044	- 0.025
		RMQ	0.046	*0.393*	- 0.272
Refining	room T (°C)	RHQ	0.222	- 0.014	0.012
		RMQ	*0.567*	0.017	0.005
Final cleaning	efficiency (%)	RHQ	0.016	0.049	- 0.034
		RMQ	- 0.001	*0.384*	- 0.252
Final refining2	room T (°C)	WHQ	- 0.259	0.009	- 0.032
		RHQ	- 0.084	0.025	0.005
Bottling	efficiency (%)	WHQ	- 0.001	0.191	- 0.154
		WMQ	0.009	0.263	- *0.398*
		RHQ	- 0.013	0.030	- 0.020
		RMQ	0.014	*0.376*	- 0.282
	CO_2 emission percentage		**90.17%**	**9.00%**	**0.83%**

Table 5: Maximum distances for the placement of the cellar at constant temperature.

T, °C	T=24	T=22	T=20	T=18	T=16	T=14	T=12	T=10
WHQ, km	/	/	6	197	388	285	182	78
WMQ, km	/	/	/	24	86	78	70	62
RHQ, km	588	987	1388	1787	1439	1092	744	397
RMQ, km	183	335	488	640	460	281	100	/