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The energy and carbon intensity of wine distribution: A study of logistical options for delivering wine to consumers

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ABSTRACT

Logistics within the food and beverage sector are often energy-intensive, especially for the wine industry. We consider how California wines may be routed to U.S. consumers near and far, basing scenarios and supporting data on interviews and literature review. We use a web-based tool, CargoScope, to calculate the energy and carbon emissions associated with each transportation link and storage echelon. We find that supply chain configurations can result in vastly different energy and emissions' profiles, varying by up to a factor of 80, and discuss how these results could be incorporated into a winery's overall sustainability strategy.

1. Introduction

In the past few years mainstream corporate interest in environmental sustainability has blossomed, especially with regards to reducing energy usage and carbon emissions. A key component of such understanding is the ability to create a model to analyze the problem, quantify metrics for success and evaluate alternatives based on their effectiveness. We present an analysis of the carbon and energy profiles of wine distribution, using a U.S. case study of logistical options for delivering wine to consumers, supported by a model developed in CargoScope. We show that different supply chain configurations vary dramatically in overall energy and emissions impact, and provide recommendations that wineries can consider for improvement.

Despite recent media awareness to what is popularly known as "carbon foot printing," measuring the carbon intensity of the supply chain has received comparatively scant research attention. Kleindorfer et al.'s comprehensive review [13] of the extant literature on sustainability in a respected operations management journal focuses on three topics: production and process development, waste minimization through lean operations, and remanufacturing through closed loop supply chains. While reverse logistics has generated much recent excitement, fewer articles have been published on the carbon intensity of basic outbound logistics. Seuring and Müller's recent extensive survey [22] of peer-reviewed articles shows few directly consider energy and emissions impact of supply chains. The lack of guidance from the research community creates a relative vacuum that may inadvertently aid the promulgation of potentially simplistic and misleading metrics. For instance, some retailers are considering labeling products with "food-miles," defined as the distance that a product has traveled from manufacture to point of sale. Even Tsoulfas and Pappis [23] in their well-delineated decision model, frame their first principle for transportation as "minimizing distance covered."

Yet different transport modes vary greatly in energy and emissions' profiles, and higher transportation emissions may offset emissions produced elsewhere in the supply chain. For instance, Saunders and Barber [21] show that lamb raised in New Zealand and shipped to the UK on ocean-going vessels is more carbon efficient than lamb from British feed lots. Lebel and Lorek [14] point to examples where localization may reduce emissions but result in greater negative ecological or social effects. Even just considering energy and emissions, other factors within a supply chain may dominate pure distances. Delivery lot sizes have a profound effect on carbon emissions in the food and beverage sector; Venkat and Wakeland [27] show that the extra energy needed for transporting more partial loads may be less than that associated with stockpiling products in cold storage for greater durations, making lean operations less attractive. Van Hauwermeiren et al. [25] demonstrate that the organically grown food is not necessarily more carbon efficient

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than its conventional counterpart, as economies of scale may make the latter less intensive to transport and dominate the net carbon impact.

With supply chains that span long distances, the transportation and storage of food products can be very energy-intensive. Transportation, namely diesel fuels from trucking, is estimated by Heller and Keoleian [10] to account for 25% of the total energy consumed within the U.S. food system. We consider the wine industry, one of the pioneering consumer goods sectors in respect to addressing environmental issues. Much of this sector's efforts concern sustainable growing practices or improving the process of winemaking. Typical research can be seen in Marchettini et al.'s [15] quantification of energy inputs, erosion factors, pesticides and fertilizers and Ruggieri et al.'s LCA study [20] investigates reducing and reusing winemaking wastes.

We target another area, namely the logistical processes that occur after wine has been packaged for consumer sale. While it is often myopic to consider just a single area (logistics) and just a single impact (CO_2 emissions), we feel this is justified for the following reasons. Most wineries have a fractional share of the overall consumer market, so a unilateral attempt by a winery to redefine package formats or make other significant changes requiring acceptance by supply chain partners and, ultimately, the end consumer, would be difficult. Decisions made for supporting this part of the product cycle are separable from the sourcing and winemaking processes and also any post-consumer recycling/recovery efforts. Energy usage associated with post-production logistics is high for wine as the standard consumer packaging is fragile, heavy and bulky. Wine itself comprises just half the weight and under 40% of the volume of a case of twelve 750 ml glass bottles. Wine is also sensitive to temperature and must be stored in a controlled climate for all but the shortest periods. In short, changes to a winery's outbound supply chain can have a high impact and be implemented quickly without requiring major retooling of producers or extensive re-education of consumers. Over the longer term a winery may be able to reconsider all aspects of production, marketing and logistics.

Of the research reviewed, only 2 works consider the outbound supply chain for wineries. Colman and Päster's lifecycle study of wine [6] shows that outbound logistics may contribute to over half of the total carbon emissions for many regions' wines. Point [19] performs a life cycle assessment for Nova Scotia wines and assumes localized consumption, as Nova Scotia wines are not widely distributed in other provinces or export markets. Point [19] shows that post-production logistics, even given the short distances of her study, are the second highest contributor to CO_2 emissions, after the emissions associated with producing and transporting bottles. Both of these works assign a single outbound logistics routing to a winery. Our research attempts to help fill this gap by examining the carbon intensity of several different options that a winery may have for delivering products to consumers.

The remainder of this paper is organized as follows. We provide an overview of the U.S. wine distribution system, discussing the available options to reach U.S. consumers. We construct a representative network to model delivery of specialty wines to end consumers both nearby and cross-country. We introduce the software used to estimate the energy usage and carbon emissions associated with these delivery scenarios. We compare scenario results and show how different supply chain configurations can impact emissions. We suggest how these findings could be of use within a winery's emissions reduction program, as a component of an overall corporate social responsibility (CSR) strategy. Lastly, we suggest directions for future research.

2. Distributing wine in the United States

2.1. An overview of the U.S. wine market

The logistics network for the U.S. wine market is complex, with many echelons and options, as seen in Fig. 1. This complexity exists for historical and regulatory reasons. At the repeal of prohibition, the 3-tier system was designed to prevent over-consumption by requiring alcohol producers to sell to retailers via distributors, all of which must be separately owned entities. Cholette [4] emphasizes that although distributors in other industries can coordinate funds and information while the actual products may be shipped directly from the manufacturer to the retailer, alcohol distributors are legally bound to take physical possession of the stock. Additionally, supermarkets and other chain stores with several outlets in a geographical area may consolidate merchandise at regional distribution centers before delivery to the store. Cholette [5] reports that nearly half of wine in the U.S. is sold through such retailers, effectively adding an additional echelon to the supply chain.

Although most U.S. produced wine is shipped to domestic consumers via the 3-tier system, Fig. 1 shows alternative routings exist. Wineries can self-distribute in California, although this option is typically not practical for smaller wineries. Wineries can apply to sell wine directly to consumers in many states. The traditional direct sales channel is for consumers to visit a tasting room at a winery. Purchases can either be carted away by the consumer or shipped to the consumer's home, via a small package carrier. Wineries may also support direct sales through a mailing list or a website, where customers select from the wines advertised and place orders from their home. Additionally, many wineries offer wine clubs, where members periodically receive deliveries of small allotments of pre-selected wines. Smaller wineries often utilize 3PL (third party logistics) providers to support these direct-to-consumer sales' programs.

In many states wine sold directly to consumers can either be picked up by the consumer or shipped to the consumer's home. However, direct-to-consumer delivery is illegal in some states. In such locales, wineries may be able to route customer orders through a certified wholesaler who in turn sends the wine to a retailer close to the consumer. Although this is not an issue for direct shipping within California, we consider this logistical option

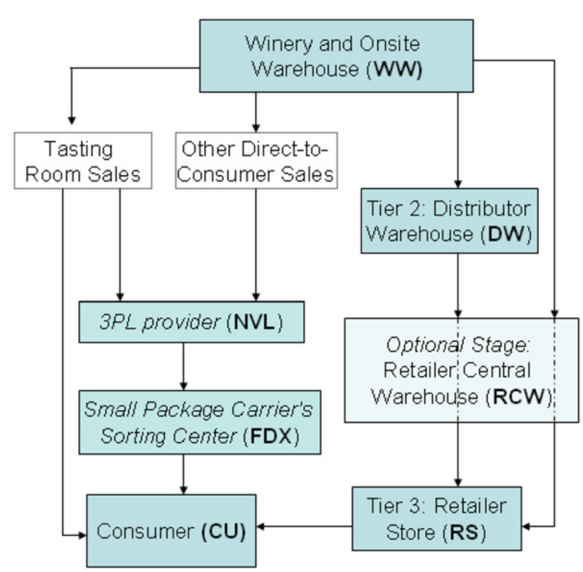

Fig. 1. The supply chain for U.S. wineries.

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for the following reason. Many wine retailers support customer ordering of limited availability wines not normally stocked in store. Wine ordered this way follows a similar path as direct-to-consumer sales that must be routed through a distributor and retailer.

2.2. Mapping the logistical network for domestic distribution

In order to analyze the energy usage of the various supply chain options, we consider the case of a Sonoma winery that is attempting to deliver specialty wine to consumers located in San Francisco and in Manhattan. We pick these two regions as they are centers for wine consumption, especially of specialty wines, and allow for consideration of local and long distance supply chains. In addition to the literature sources provided throughout the paper, the structure and data of our model are based on input from professionals representing every echelon, save for the distributor/wholesaler tier, as summarized in Table 1, as well as from a carrier and a 3PL provider.

As Table 1 shows, we engaged in discussions with several wineries. Our representative Sonoma winery, is based most closely upon Cline Cellars, a medium-sized winery with a line of moderately priced wines (approximately $10/bottle) in retail stores nationwide as well as several higher-end wines ($25/bottle+), many of which are primarily available thorough direct-to-consumer channels. Although large firms with low-margin products like the Wine Group can use alternate packaging formats such as bag-in-a-box and TetraPak™ or even ship product in bulk for bottling closer to the retail market, these options are not currently feasible for most smaller wineries or for those with more upscale wines. Wine is predominantly sold in 750 ml glass bottles, and Twede et al. [24] emphasize that packaging beverage products is a high-speed automated process involving expensive equipment, favoring centralization. We can reasonably assume that most California wineries bottle and warehouse products onsite, as Cline Cellars indeed does. Dividing the standard 12-bottle case of wine into 2 separate customer orders of six bottles each represents a typical order size.

We select representative locations for the logistical echelons for each of the two regional markets and code them with acronyms. For instance, Southern/Glazer's, which distributes over 80% of the wine and spirits sold in the U.S. [29], has a large regional facility in Union City. Union City is thus chosen as the location for our representative distributor's warehouse (DW). We also consider the optional layer of the regional customer warehouse (RCW) and select Richmond as a representational site since Cost Plus World Market™, a retail chain noted for its wine sales, has a large facility here.

For direct shipping to this local market, we consider one of the major third party logistics (3PL) providers for California wine shipments, which is New Vine Logistics (NVL). New Vine's fulfillment center is located in American Canyon. While New Vine partners with several small package carriers, we select Federal Express, which has a sorting center and warehouse (FDX) in South San Francisco. Distances between points are calculated via Google™ maps to determine appropriate routes. We locate both the retail store (RS) and the consumer (CU) in San Francisco and assume that the consumer is located 3.6 km from the store. This distance is below the national average of 10 km, as BAEF research [1] shows that consumers in the Bay Area typically have to travel much shorter distances. While many researchers, such as Hutchins and Sutherland [11], terminate the supply chain at the retail outlet, we include transport to the end consumer for reasons that shall shortly become apparent.

Servicing the metropolitan New York market requires considering a much larger geographical area and additional transport modes. We add the following nodes: OAK, as Oakland houses the Bay Area's pre-eminent cargo rail terminal, and SFO, as this airport services much of the region's outbound air cargo. We include two hubs: rail companies often route East-bound trains through Chicago (CHI), and Memphis (MEM) is the super hub through which much of FedEx's air cargo travels. Newark has both an airport and rail terminal (EWR). New Jersey has the sorting/distribution centers for FedEx in Edison (SSE) and for Southern/Glazer's in Monroe Township (DC–NJ). The retail store in Manhattan is designated as RS–NY. The location of all Northern California and Metropolitan New York nodes are shown side by side to the same scale in Fig. 2.

Table 1
Interviews by echelon and transportation partner.

Echelon	Information provided
Wineries: Cline Cellars, Hess Collection, LionHeart Wines, Nicholson Ranch	Direct shipment frequency and volumes, rough percentages of sales supported each by delivery options
Retailer: Cost Plus World Market	Location of stores and RDC, dwell times, storage and replenishment policies. Inbound and outbound transportation modes.
Distributor: None interviewed, SWS/Glazer's selected as representative	Location of warehouses available online at www.southernwine.com. Parameters and policies are assumed to be comparable to that of the retailer's RDC
Carrier: FedEx	Locations of nodes and routes, inbound and outbound transport modes utilized, rough estimates of utilization and backhaul rates, dwell times at sorting center
3PL provider: New Vine Logistics	Inbound and outbound transportation modes, dwell times, estimates of backhaul and utilization rates for inbound shipments. Corroboration of winery-related data (shipping frequency and volumes).

Individuals' names have been withheld upon request.

3. Solution methodology and model scenarios

We first introduce the software utilized, presenting both the mechanics and the interface. We then describe the options available to our representative Sonoma winery in fulfilling delivery of a half cases (6 bottles) of wine to a consumer located in San Francisco. This construct mimics the business model of a wine club. We next consider the order fulfillment options available for delivering that half case wine to a Manhattan consumer. Each of the scenarios depicts a different configuration for transporting wine from the winery's onsite warehouse to an end consumer.

3.1. CargoScope: introducing the software

In order to be understood and usable by non-specialists, models must balance simplicity and usability with analytic power. Developed and maintained by CleanMetrics, CargoScope is a web-based tool that allows users to build a supply chain network and define the storage, transit and processing parameters for every echelon. While many websites support calculators for determining personal "carbon footprints" there are fewer, if any, tools online that allow the user to configure a general supply chain. CargoScope was also selected for this study because it was free, and trial subscriptions are available on request. CargoScope's built-in parameters are based on data from U.S. governmental [7–9] and international [30] agencies, as well as academic studies [18]. Users can create, share and revise their models and CargoScope will calculate and display the energy needs and equivalent amount of carbon emitted. While more detailed documentation on underlying software mechanics is available from CleanMetric's website [3] and Venkat [26], this section briefly presents the functionality relevant for our analysis.

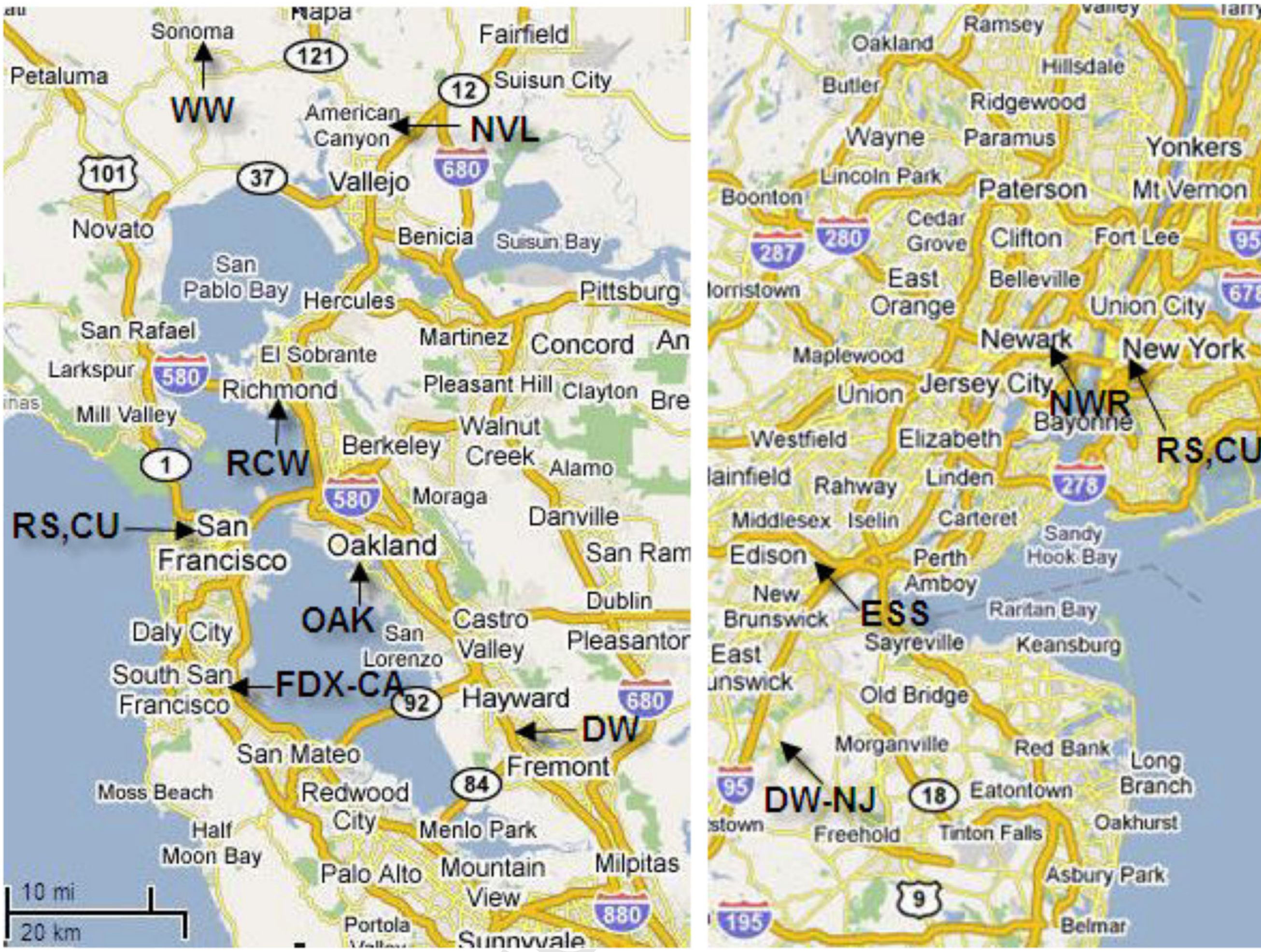

Fig. 2. The location of supply chain nodes.

The user-defined inputs, fixed parameters and output relevant to our model are summarized in Table 2.

CargoScope can be used to model the production, storage and distribution of any discrete packaged good. Venkat [26] documents that SEAT, a prior version of CargoScope that was not web-enabled, has been used to model the supply chains of diverse goods such as automotive supplies, printers, dairy products, biscuits, and frozen foods. CleanMetrics, the company which created and maintains CargoScope, has worked with clients to develop detailed models for supply chains supporting the distribution of cleaning products, soy milk, produce, and textiles. While many food products have been analyzed, this is the first time that CargoScope has been used to model the distribution of wine.

A model is constructed in CargoScope by starting with the end consumer as the first node and then adding nodes for each echelon in the supply chain. Fig. 3 illustrates a high level view of one the scenarios studied, that of 3PL local fulfillment through New Vine Logistics (NVL) via FedEx (FDX). Each node represents either a storage or processing echelon, and the inter-echelon connections represent transportation links, where the user specifies the distance, selects from a predefined list of transport modes, and sets three key parameters: temperature control, utilization rate and backhaul rate. Fig. 3 shows that the user has opted for a closer view of storage properties for NVL, one of the echelons. The user would then be presented with Fig. 4, which shows that products reside 14 days in a temperature-controlled (cooler) storage with very high (100%) utilization, powered by electricity from the Pacific region. Selecting "transport properties" in Fig. 3 instead would display Fig. 5. Notice the user-specified parameters that define the link to the downstream echelon; non-temperature controlled midsized trucks travel from NVL to FDX with high (100%) utilization but no (0%) backhaul. It should be noted that carrying limits are calculated both for weight and volume. As bottled wine is heavy, carrying capacity will be maxed out by weight instead of volume for all commercial vehicles utilized in these scenarios.

Using characteristics of road transport modes, distances, regional energy estimates for power generation, and other industry data, CargoScope calculates the energy usage and carbon emissions associated with transport and storage for each echelon. While CargoScope is a more general tool that allows energy and emissions from processing to be calculated, present scenarios consider no other energy usage beyond that associated with transportation or temperature-controlled storage.

While it is possible to perform similar analyses with custom spreadsheet models, we feel CargoScope is more intuitive for non-specialists, with its visual, interactive interface. Users can quickly configure a model with predefined menus listing types of transit options or regional power sources. The user can redefine key parameters, such as dwell times or distances traveled and select from different menu options for quick comparative analyses. This makes CargoScope a useful tool for demonstration purposes and initial evaluations of supply chain processes.

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Table 2
Inputs, parameters and outputs for CargoScope.

User-supplied inputs		Parameters provided by CargoScope	
Universal Inputs	Product weight	*Transport Mode Parameters*	Energy usage, per km
	Product volume		CO_2 emissions profile, per km
	Overall supply chain configuration		Carrying capacity, by volume
			Carrying capacity, by weight
Transportation Inputs	Distances between nodes		
	Transport mode	*Storage Parameters*	Energy usage, per day
	Level of temperature control		Emissions profile, per day
	Utilization rate		
	Backhaul rate		
		Outputs calculated by CargoScope	
Storage Inputs	Dwell times	Energy usage for each node and link	
	Location and type of power used	CO_2 emissions by node and link	
	Level of temperature control		
	Utilization rate		

3.2. *Scenarios supporting local deliveries*

We first consider how our representative Sonoma winery could fulfill the orders of San Francisco consumers. Table 3 provides a summary breakdown of these methods. We describe a base case scenario in detail and then indicate how alternative scenarios differ. Scenario configurations and data were drawn from discussions with operations' managers at various echelons, as seen in Table 1. We provide justification for assumptions when data are unavailable.

3.2.1. *Standard scenario L1: 3-tier distribution*

The base scenario for local distribution (L1) is represented by the 3-tier system, as it is the predominant outbound logistical method; Cholette [4] shows that it supports 90% of all U.S. wine purchases. Midsized trucks are used to transport wine from the winery's warehouse (WW) to the distributor's warehouse (DW). We assume that the rest of the truck's capacity is utilized efficiently to transport other products from nearby wineries to the same destination. Indeed, for the delivery portion of a trip we assume that capacity is utilized with 100% efficiency in all commercial vehicles for every scenario. Although our interviewees and other data sources could not provide us with definitive backhauling and utilization rates, we can partially justify assuming high utilization rates by use of significant dwell times at all intermediate warehousing echelons. Unless stated otherwise, no backhauling is assumed to occur. For instance, the model considers that the truck is empty when it drives to the winery's warehouse from the distributor, but that the trip back to the distributor's warehouse utilizes the full capacity of the truck. As the distances are relatively short, the vehicles used in all local scenarios are assumed not need any temperature control to prevent wine spoilage.

As the wine has been ordered by end consumers, we utilize a pull model. We assume wine spends a week at the distributor's warehouse until another midsized truck is used to transfer wine from the distributor's warehouse to the retailer store (RS), making such deliveries every week. We assume that the wine remains in temperature-controlled storage at the retailer for a week before the customer (CU) drives to the store and back in a gasoline powered Honda Accord, at a fuel efficiency of 9.8 l per 100 km, for the sole purpose of picking up the wine, thus utilizing only 24% of the car's stated hauling capacity by weight. We also consider two scenario variants. In L1a the consumer reaches the retail store without a car and in L1b the consumer more effectively utilizes the car by fully loading it with other purchases.

Wine storage facilities should be cooled but not refrigerated, with 13 °C the ideal temperature. The energy cost associated with warehousing wine is calculated by determining the area necessary to store the wine and the duration of the stay. We assume that the warehouse is highly utilized and record energy use only for when wine remains in storage and not after the wine has been moved to another echelon. We also cease considering energy usage associated with storage after final delivery to the consumer has occurred. While some consumers may possess wine refrigerators, most store wine at ambient house temperature.

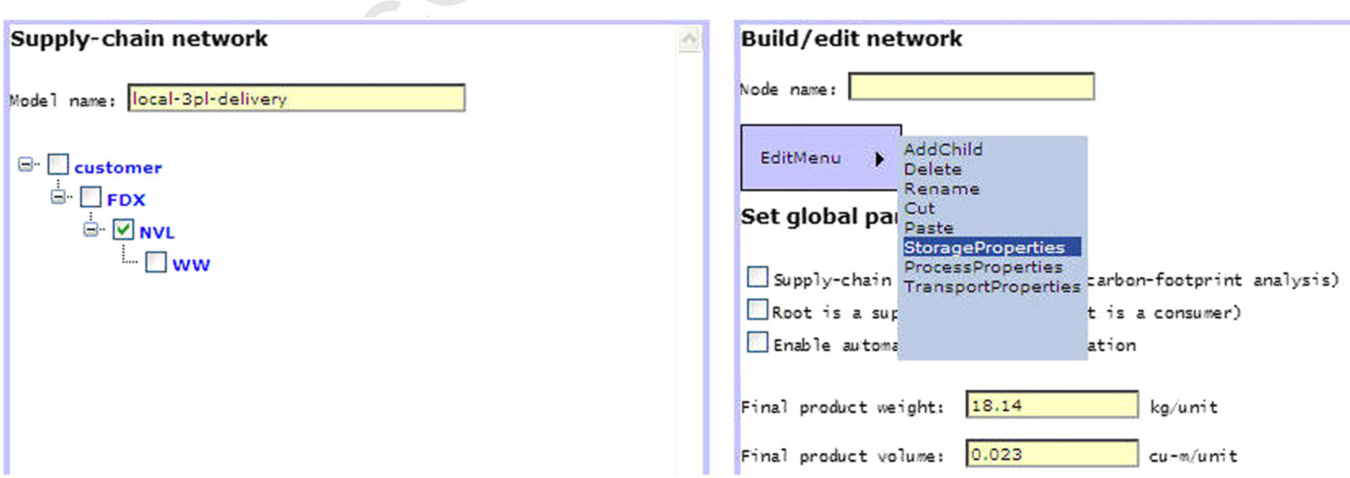

Fig. 3. Graphical view of example supply chain in CargoScope.

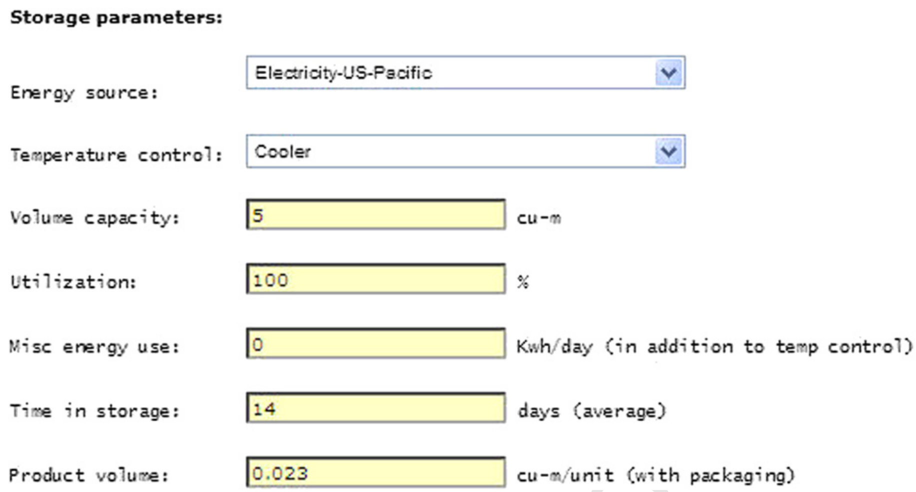

Fig. 4. Configuring a storage echelon in CargoScope.

3.2.2. L2: 3-tier distribution via retailer warehouse

Given that many chain retailers make use of regional distribution centers, we modify the network to route the distributor's midsized truck to the additional echelon of a regional centralized warehouse (RCW) instead of the retail store (RS). We assume that the wine will stay in temperature-controlled storage at the RCW for an additional week. This assumption also allows us to justify high (100%) utilization rates for transit to the retail store. Otherwise this scenario (L2) is similar to the base scenario (L1).

3.2.3. L3: winery self-distribution

The difference from the base scenario (L1) is that the winery is now permitted to engage in self-distribution. Although 3-tier distribution is the most common channel, some California wineries have filed the paperwork to obtain the legal right to bypass distribution for direct sale to an instate retailer. The winery provides or contracts for a truck to deliver wine directly to the retail store (RS) from the winery's warehouse (WW). As always, we assume 100% utilization. As some wineries may not generate sufficient order volumes to fill a midsized truck, with a 6250 kg of carrying capacity equivalent to 344 cases of wine, we additionally consider utilizing a light truck with a vastly reduced capacity of a mere 600 kg, the equivalent of 33 cases of wine. Removing the distributor echelon results in one less week of storage costs and slightly decreases the total distance traveled in this scenario (L3).

3.2.4. L4: fulfillment via 3PL

This scenario (L4) considers wine that is shipped to customers through direct sales channels, via New Vine Logistics, a leading 3PL provider focused on wine industry clients. Midsized trucks from New Vine Logistics (NVL) pickup wine from the winery's warehouse (WW) for transport back to NVL's temperature-controlled warehouse. The small package carrier sends a midsized truck to pickup wine from New Vine and bring it to the sorting center (FDX) in South San Francisco every 2 weeks. The sorting center is not climate controlled, but as packages reside only briefly, spoilage is unlikely to occur. The wine is then sent by a light parcel truck to the end consumer in San Francisco. Carriers such as Federal Express have domain expertise in being efficient, and parcel trucks returning from customer drop offs will pickup outbound parcels from urban drop points in the return trip to the sorting center. Therefore, both high utilization (100%) and that significant (50%) backhauling are assumed to occur. This is the only transport link in any of the local scenarios to have a non-zero backhauling rate.

3.2.5. L5abc: consumer drives to winery

The final local scenarios also result from the direct sales channel, but consider consumers who make dedicated trips to the winery to take possession of wine orders. This supply chain option is the simplest and considers only the fuel used in the round trip. We continue to employ the same car that consumes 8.9 l of gasoline per

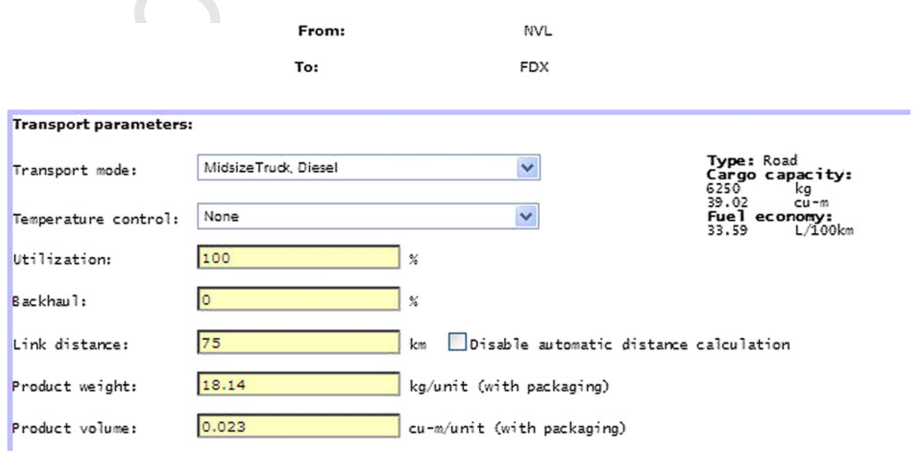

Fig. 5. Configuring an inter-echelon link in CargoScope.

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Table 3
Summary of local scenarios' inter-echelon links.

	L1: 3-tier distribution		L2: 3-tier distribution with RDC		L3ab: self-distribution		L4: delivery via 3PL		L5abc: consumer drives	
Echelon 1–2	WW > DW	112 km, midsized truck	WW > DW	112 km, midsized truck	WW > RS	72 km, light (a) or midsized (b) truck	WW > NVL	29 km, midsized truck	WW > CU	72 km, car (a), hybrid (b) or mid-pickup (c)
Echelon 2–3	DW > RS	60 km, midsized truck	DW > RCW	48 km, midsized truck	RS > CU	112 km, midsized truck	NVL > FDX 75 km, midsized truck			
Echelon 3–4	RS > CU	3.6 km, car	RCW > RS	32 km, midsized truck			FDX > CU	10 km, light truck		
Echelon 4–5			RS > CU	3.6 km, car						

100 km, for scenario L5a. We also consider a scenario variant L5b, a variant where the car in question is a hybrid, averaging 4.3 l per 100 km. Additionally, we consider a further extension to this scenario to model the consumer who may take the trip and consolidate several purchases, such as picking up wine club purchases on behalf of neighbors and nearby friends, none of whom need to drive any distance to receive their orders from this generous driver. We thus assume the consumer in Scenario L5c fully utilizes a midsized pickup truck, which has half the cargo space of a light commercial truck and holds 33 half cases of wine. It should be noted that individuals or companies offering such a service for a fee would need special permits to avoid legal issues associated with transporting and distributing alcohol.

3.3. Scenarios supporting long distance delivery

For the Manhattan consumer, the sheer distances change the scenarios under consideration. No rational consumer would make a dedicated cross-country drive for a wine purchase. Nor is winery self-distribution an option with interstate sales. However, a variety of other network configurations exist. In addition to traditional 3-tier distribution, 3PLs such as New Vine Logistics, supported by carriers such as FedEx, offer a choice between air shipping and ground based delivery via truck. We also consider an intermodal transport option, utilizing rail for the cross-country link. The scenarios are summarized in Table 4.

3.3.1. D1: standard long distance scenario: 3-tier distribution

The 3-tier distribution system is the prevalent method for supporting longer distance wine supply chains within the U.S. We continue to make use of the same distributor's warehouse, as Southern/Glazer's is also the dominant player in the New York market. The initial part of the supply change is identical to that of scenario L1, described in Section 3.2.1; the midsized truck from the winery warehouse (WW) to the distributor warehouse (DW) is filled with wine destined for both local and far markets. A heavy-duty diesel truck with cooling is used to make the cross-country journey to the company's distribution center in Monroe Township, New Jersey (DW-NJ). Because this is a long, expensive link, we assume that the distributor sets capacity and backhauling rates at 100%. Such efficiencies are possible as Southern/Glazer's also distributes European imported wine and Eastern produced spirits to California retailers. The example retailer we consider, Whole Foods™, does not have any distribution warehouses in New Jersey so we bypass the optional retailer warehouse echelon, with the distributor sending wine to the Manhattan retailer via midsized truck. With the density of retail outlets and residential housing in Manhattan, we assume that consumers need to travel at most 0.8 km (0.5 mile) to reach the store and that they take public transit or walk to the store. As a half case of wine is fragile, heavy and awkward to carry by hand, our hypothetical consumer hails a cab for their return trip, effectively resulting in a 100% backhaul rate.

3.3.2. D2: long distance fulfillment via 3PL ground delivery

New York state has allowed direct-to-consumer sales from California since 2005. Wineries often offer remote consumers a choice between ground and air delivery. This scenario (D2) considers ground delivery, supported by a service such as FedEx Ground, with New Vine Logistics as the 3PL provider. The supply chain is identical to that of scenario L4 in Section 3.2.4, up to the point at which the wine is ready to leave the NVL facility. As wine transported long distance by truck may be subject to spoilage, we assume that New Vine Logistics packs shipments in a proprietary multi-day temperature-regulating packaging, as documented by their partner's website [28]. We account for the energy associated with this additional packaging by modeling all subsequent links as being cooled. After the wine is transported to the FedEx center in South San Francisco (FDX-CA), a heavy-duty diesel truck carries the wine cross-

Table 4
Summary of long distance scenarios' inter-echelon links.

	D1: 3-tier distribution		D2 3PL fulfillment via truck		D3 3PL via air		D4 3PL via rail	
Echelon 1–2	WW > DW-CA	112 km, midsized truck	WW > NVL	29 km, midsized truck	WW > NVL	29 km, midsized truck	WW > NVL	29 km, midsized truck
Echelon 2–3	DW-CA > DW-NJ	4700 km, heavy-duty truck, cooler	NVL > FDX-CA	75 km, midsized truck, cooler	NVL > FDX-CA	75 km, midsized truck	NVL > FDX-CA	75 km, midsized truck, cooler
Echelon 3–4	DW-NJ > RS-NY	74 km, midsized truck	FDX-CA > ESS	4675 km, heavy-duty truck, cooler	FDX-CA > NWR, via MEM	4960 km, Airfreight	FDX-CA > OAK	50 km, midsized truck, cooler
Echelon 4–5	RS-NY > CU	0.8 km, car	ESS > CU	53 km, light truck, cooler	EWR > CU	21 km, light truck	OAK > EWR, via CHI	5500 km, rail, cooler
Echelon 5–6							EWR > CU	21 km, light truck, cooler

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country to the FedEx sorting center in Edison (ESS). We justify a 100% backhaul rate on this link, as the same truck is used to ship packages west to California clients. Once the package reaches Edison, it is sent by parcel truck to home of the Manhattan consumer.

3.3.3. D3: long distance fulfillment via 3PL airfreight

Most 3PL providers offer air shipment as well as delivery service by truck. Many clients are willing to pay the higher price for airfreight not only for faster delivery, but also because transporting wine cross-country on trucks without temperature controls can spoil wines. This scenario (D3) replaces the long distance diesel truck link with a FedEx air cargo route, routing the plane from San Francisco Airport, adjacent to FDX-CA, to Newark International Airport (NWR) via Memphis. CargoScope assigns both a 100% utilization and backhaul rate to airfreight. As this link is of comparatively short duration, temperature-controlled packaging is not necessary. The New Jersey FedEx facility, also very near the airport, is assumed to dispatch a Manhattan-bound parcel truck to the consumer, assuming the same utilization rate (100%) and backhaul (50%) as its Bay Area counterpart.

3.3.4. D4: long distance fulfillment via 3PL utilizing rail

Although carriers like FedEx have both extensive ground and air networks, they do not have the same presence in rail in part because of a lack of an open, national rail network. However, public pressure and rising fuel costs may convince companies to increase rail usage. We consider a scenario (D4) where the long distance link is via rail, through a company such as CSX, one of the dominant rail carriers in the U.S. This scenario has the same configuration as that of scenario D2, until it is time for the package to leave the FedEx facility in South San Francisco. At that point, a midsized truck is sent to the Oakland rail terminal (OAK), with 100% loading and 0% backhaul. The rail company would then route the shipment to the rail terminal (NWR) adjacent to Newark International Airport. CargoScope assigns both 100% utilization and backhaul rate to all rail cargo. As with the air shipping scenario (D3) we assume that the package does not dwell for any measurable time at FedEx's EWR facilities, but instead is sent on a Manhattan-bound parcel truck to the consumer's home. Given this journey takes several days on vehicles lacking temperature control, NVL would package the wine in the same temperature-regulating packaging as featured in scenario D2.

4. Model results

We present and interpret the results for each scenario and then perform a summary comparison across all scenarios, local and long distance. Although we include figures for both energy usage and emissions, we focus on the latter. Transportation energy usage dominates that associated with storage, and the emissions' profiles of the various fuels consumed by different transport modes are similar. Thus, total energy expended correlates closely with emissions. Results are presented in terms of per-order emissions associated with each echelon and link in the supply chain, where each order is 6 bottles of wine.

Table 5
Energy and emissions by link and echelon, scenario L1.

Scenario L1: local 3-tier, standard scenario		Distance/ time	Energy – MJ	Carbon – kg CO_2
Transport	Midsize truck, diesel	112 km	4.05	0.3
Transport	Midsize truck, diesel	60 km	2.17	0.16
Transport	HondaAccord, gasoline	3.6 km	24.22	1.68
Storage	None, electricity-US-Pacific	0 days	0	0
Storage	Cooler, electricity-US-Pacific	7 days	0.37	0.02
Storage	Cooler, electricity-US-Pacific	8 days	0.37	0.02
Storage	None, electricity-US-Pacific	0 days	0	0
		Total	31.19	2.18

4.1. L1: local 3-tier distribution results

Table 5 lists the energy and emissions associated with each link and node that can be assigned to the half case of wine being routed through the supply chain in our base case scenario for local distribution (L1). In total, 31 MJ of energy are utilized in getting this order from the winery to the end consumer's home, resulting in 2.18 kg of CO_2 being emitted. Transportation link emissions are presented in top-down order, followed by storage echelons emissions, ordered top-down. Emissions associated with transportation from the winery to the retail store (0.46 kg of CO_2 per half case) dominate those from storage (0.04 kg of CO_2 per half case) by a factor of ten. While dwell times at the different echelons may vary from our assumptions, these results suggest that dwell times have minimal impact on emissions and are of less concern for this analysis.

The eye-catching result from Table 5 is that the most energy-intensive transit link is the last one. Given our assumptions, driving to the retail store on dedicated trips accounts for over three fourths of the total supply chain emissions. This result may seem surprising with the short distance involved. However, per-case energy usage is much lower for freight vehicles, which tend to be more highly utilized than individual personal vehicles. Our assumed low utilization rate for consumer vehicles is echoed by a government study [16] showing average Americans do not tend to engage in energy-saving behaviors, such as carpooling to work. Other studies in apparel [2] and food [25] also find that the retailer-to-consumer link can be the most carbon intensive, even in European countries where consumers are traditionally more energy conscious than their U.S. counterparts. If San Francisco consumers walk or take well-utilized public transit, only 0.50 kg of CO_2 per half case in total would be emitted. More realistically, if these consumers drive but make additional purchases to fully utilize the car's cargo space up to the specified weight limit, emissions drop to 0.90 kg of CO_2 per half case. We discuss implications of these findings in Section 5.

4.2. L2: 3-tier distribution via retailer warehouse results

Comparing Table 6 with Table 5 reveals that inclusion of a regional centralized warehouse (RCW) increases overall energy usage and emissions by 3%. However, it should be noted that our standard assumption is that outbound transit from the distributor results in 100% utilization. Use of this consolidation echelon would result an overall efficiency gains if our distributor instead typically provides relatively small volumes to the client store or set of stores and routinely fills a midsized truck to 50% or less of capacity.

4.3. L3ab: winery self-distribution results

We now consider what happens when we bypass the distribution tier. As a winery may not send large orders to the retailer, we compare results from use of a light truck (L3a) to that of a midsized truck (L3b), assuming 100% utilization of each vehicle. As can be seen in Table 7, the choice of which truck to use has great impact. If a winery generates sufficient volume of sales, self-distribution with highly utilized midsize trucks is more efficient (at 1.89 kg of CO_2 per half case) than the previously presented standard scenario (2.18 kg of CO_2 per half case). However, for smaller wineries that have insufficient volume to fill a midsized truck, the use of a distributor would result in lower emissions than would self-distribution via a light truck or a highly underutilized midsized truck. As consumer's driving still dominates all of these local scenarios, the efficiency differences are even greater than the emissions' totals would suggest. Fully

Table 6
Energy and emissions by link and echelon, scenario L2.

Scenario L2: local 3-tier, with retailer warehouse			Distance/ time	Energy – MJ	Carbon – kg CO_2
WW > DW	Transport	Midsize truck, diesel	112 km	4.05	0.3
DW > RCW	Transport	Midsize truck, diesel	60 km	1.74	0.13
RCW > RS	Transport	Midsize truck, diesel	32 km	1.16	0.09
RS > CU	Transport	HondaAccord, gasoline	3.6 km	24.22	1.68
WW	Storage	Cooler, electricity-US-Pacific	0 days	0	0
DW	Storage	Cooler, electricity-US-Pacific	7 days	0.37	0.02
RCW	Storage	Cooler, electricity-US-Pacific	7 days	0.37	0.02
RS	Storage	Cooler, electricity-US-Pacific	7 days	0.37	0.02
Customer	Storage	None, electricity	0 days	0	0
			Total	32.28	2.25

utilized light truck usage results in nearly 5 times the emissions (0.94 kg of CO_2 per half case) of those from a fully loaded midsized truck (0.19 kg of CO_2 per half case). These results are similar to findings by Van Hauwermeiren et al. [25] economies of scale from consolidating transit dramatically impact emissions efficiency of the overall supply chain.

4.4. L4: results for local fulfillment via 3PL

Table 8 shows that the direct shipping option (L4) produces the lowest emissions of all: 0.42 kg of CO_2 per half case, or 19% of the emissions associated with the standard 3-tier scenario (L1). Much of this improvement can be traced to eliminating driving to the store. End-customer delivery is comparatively fuel efficient as parcel trucks are assumed to have 100% utilization in delivery and employ some (50%) backhauling. If we consider removing consumer driving from the standard scenario, the direct shipping scenario would result in only slightly lower (88%) emissions. The minor savings can be attributed to the more efficient routing and the services of the 3PL provider. For instance, if the winery had to drive orders to a consolidation point or if FedEx had to directly send parcel trucks to the winery, emissions would likely increase.

4.5. L5abc: results for the consumer driving to winery

If a casual observer might be tempted to expect that eliminating layers in a supply chain automatically increases energy efficiency, the following results would put this misconception to rest. Driving a conventional car to the winery (L5a) results in the most emissions being produced, 33.75 kg of CO_2 per half case, over 15 times the amount produced from distribution through the 3-tier system. Even if the consumers were to utilize a hybrid car such as a Toyota Prius (L5b), emissions would still total 14.5 kg of CO_2 per half case, over six times of those associated with the 3-tier scenario (L1). Of course, many consumers may not undertake a round trip to the wine country just to pick up a single wine shipment. Drivers may justify such trips by picking up additional wine orders from nearby wineries. An analogous situation would be that of a consumer collecting additional orders for neighbors and nearby friends. Scenario L5c thus represents an extreme version of the latter possibility. It assumes the consumer fills a midsized pickup truck, representing a total of 33 half case orders. Emissions would drop to 1.43 kg of CO_2 per half case, but this efficiency holds only if none of the other consumers require a special car trip to the pickup truck owner's home to get their orders. Note that even with this unrealistic expectation, per-order emissions are still higher than those from the 3PL scenario, in part because large personal vehicles, even when fully loaded, are less efficient than well utilized commercial ones.

Table 7
Energy and emissions by link and echelon, scenarios L3a and L3b.

L3a: Winery self-distribution, via light truck			Distance/ time	Energy – MJ	Carbon – kg CO_2
WW > RS	Transport	Light truck, diesel	72 km	12.68	0.94
RS > CU	Transport	HondaAccord, gasoline	3.6 km	24.22	1.68
WW	Storage	None, electricity-US-Pacific	0 days	0	0
RS	Storage	Cooler, electricity-US-Pacific	7days	0.37	0.02
CU	Storage	None, electricity	0 days	0	0
			Total	37.27	2.64
L3b: Winery Self-Distribution, via midsized truck					
WW > RS	Transport	Midsize truck, Diesel	72 km	2.6	0.19
RS > CU	Transport	HondaAccord, gasoline	3.6 km	24.22	1.68
WW	Storage	None, electricity-US-Pacific	0 days	0	0
RS	Storage	Cooler, electricity-US-Pacific	7days	0.37	0.02
CU	Storage	None, electricity	0 days	0	0
			Total	27.2	1.89

Table 8
Energy and emissions by link and echelon, scenario L4.

Scenario L4: local 3PL delivery			Distance/ time	Energy – MJ	Carbon – kg CO_2
WW > NVL	Transport	Midsize truck, diesel	29 km	1.05	0.08
NVL > FDX	Transport	Midsize truck, diesel	75 km	2.71	0.20
FDX > CU	Transport	Light truck, diesel	10 km	1.32	0.10
WW	Storage	Cooler, electricity-US-Pacific	0 days	0	0
NVL	Storage	Cooler, electricity-US-Pacific	14 days	0.75	0.04
FDX	Storage	None, electricity-US-Pacific	0 days	0	0
Customer	Storage	None, electricity-US-Pacific	0 days	0	0
			Total	5.83	0.42

4.6. D1: results for the standard long distance scenario of 3-tier distribution

We now consider the results for cross-country orders. The base long distance scenario of shipping a half case of wine via the 3-tier distribution system results in 48.61 MJ of energy usage and 3.62 kg of CO_2 emitted. These emissions are only 66% more than those from local 3-tier shipping. This result can be explained by examining Table 9. While the trip between the California and New Jersey distribution centers contributes the most to emissions, this link is relatively efficient, accounting for 78% of the emissions, but 96% of the distance covered. Additionally, the Manhattan consumer travels a shorter distance by car, resulting in the least amount of emissions produced of all the scenario's transit links. It can also be seen that Mid-Atlantic electricity results in more carbon emissions than Pacific electricity, although emissions from cold storage have minimal impact in our results.

Table 9
Energy and emissions by link and echelon, scenario D1.

D1: Long distance: 3-tier distribution		Distance/time	Energy – MJ	Carbon – kg CO_2
Transport	Midsize truck, diesel	112 km	4.05	0.3
Transport	Heavy-duty truck, diesel, Cooler	4700 km	38.07	2.82
Transport	Midsize truck, diesel	74 km	2.68	0.20
Transport	HondaAccord, gasoline	0.8 km	2.69	0.19
Storage	None, electricity-US-Pacific	0 days	0	0
Storage	Cooler, electricity-US-Pacific	7 days	0.37	0.02
Storage	Cooler, electricity-US-MidAtlantic	7 days	0.37	0.05
Storage	Cooler, electricity-US-MidAtlantic	7 days	0.37 0.05	
Storage	None, electricity-US-MidAtlantic	0 days	0	0
		Total	48.61	3.62

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Table 10
Energy and emissions by link and echelon, scenario D2.

D2: Long distance 3PL fulfillment via truck			Distance/time	Energy – MJ	Carbon-kg CO_2
WW > NVL	Transport	Midsize truck, diesel	29 km	1.05	0.08
NVL > FDX-CA	Transport	Midsize truck, diesel, cooler	75 km	2.72	0.20
FDX-CA > ESS	Transport	Heavy-duty truck, diesel, cooler	4675 km	37.87	2.80
ESS > CU	Transport	Light truck, diesel, cooler	53 km	7	0.52
WW	Storage	None, electricity-US-Pacific	0 days	0	0
NVL	Storage	Cooler, electricity-US-Pacific	14 days	0.75	0.04
FDX-CA	Storage	Cooler, electricity-US-Pacific	0 days	0	0
ESS	Storage	Cooler, electricity-US-MidAtlantic	0 days	0	0
CU	Storage	None, electricity-US-MidAtlantic	0 days	0	0
			Total	49.39	3.64

4.7. D2: results for long distance 3PL fulfillment via ground delivery

As can be seen from comparing Tables 9 and 10, negligible difference in overall emissions exists between this scenario and that of 3-tier distribution. Most emissions occur on the cross-country routing of the truck. Slight savings from this scenario's decreased electricity usage are offset by the fact that highly utilized light parcel trucks, even with some backhauling, are still less efficient than midsized trucks. Thus, the inbound Manhattan transit link results in more emissions even though FedEx's staging center for receiving cross-country shipments is slightly closer to the city than is Southern/Glazer's distribution center. Likewise, parcel delivery's elimination of having the consumer drive to the retail store has less impact when that trip to the retail store is much shorter and has effective backhauling.

4.8. D3: results for long distance 3PL fulfillment via airfreight

Opting for 3PL delivery via airfreight (D3) instead of trucking (D2) increases total emissions by over a factor of seven. Although carriers can be presumed to maximize their air fleet's utilization and backhauling rates, flying the half case from San Francisco to Newark (via Memphis) results in over 25 kg of CO_2 emitted. Table 11 shows that air transit is responsible for 98% of the scenario's total emissions.

4.9. D4: results for long distance 3PL fulfillment utilizing rail

Were rail to become a viable option for 3PL providers, significant emissions savings could be realized for long-haul land shipments. Table 12 shows that total emissions for this scenario (D4) are 60% of those associated with 3PL trucking (D2). Although routing through Chicago increases total distance traveled by over 800 km, the lower energy usage of rail results in about half as much emissions as the cross-country trucking link. The outbound logistics for a South San Francisco based carrier such as FedEx are more complicated, since Oakland has the closest commercial rail terminal. These savings would be even greater for shipments routed between points with better established rail infrastructure, such as sending cargo from Los Angeles to Chicago. It should also be expected that a 3-tier distribution plan utilizing rail would result in emissions efficiencies similar to those realized in this scenario.

4.10. Comparison across all scenarios

Our study considers many scenarios with a variety of transport modes, echelons and distances. One informative way to present results is to consider the emissions and energy totals from all the scenarios and list them in increasing order of emissions generated. Table 13 illustrates that significant emissions difference exist. The least efficient scenario, driving to the winery in a typical gas powered car (L5a), results in 80 times the emissions that would occur if that local delivery were handled via our 3PL scenario (L4). While most local supply chain configurations produce lower emissions than their long distance counterparts, there are some notable exceptions. In particular, long distance 3PL delivery via rail (D4) makes the top half of the list and is effectively equivalent to the standard, local 3-tier distribution scenario (L1). Total emissions for 3PL rail are 60% of those associated with trucking (D2), and only 8% of those associated with airfreight (D3). Interestingly, the most emissions-intensive scenario of our study involves one with the least amount distance traveled, that of the consumer driving to the winery (L5a). In determining efficiency, the utilization of vehicles repeatedly dominates pure distance traveled.

Our results suggest that wineries should focus more on minimizing the emissions from transportation instead of those from storage, which contribute very little, no doubt because cool, rather than cold storage is required. Thus stockpiling larger inventory buffers at echelons may be useful if it enables the intra-echelon transit links to be more fully utilized. Our results are supported by Van Hauwermeiren et al.'s [25] calculations that emissions from transportation dominate those associated with storage and processing for most of the plant-derived foods they study. Supply chains for foods that require more intensive cooling will have

Table 11
Energy and emissions by link and echelon, scenario D3.

D3: Long distance 3PL fulfillment via airfreight			Distance/time	Energy – MJ	Carbon – kg CO_2
WW > NVL	Transport	Midsize truck, diesel	29 km	1.05	0.08
NVL > FDX-CA	Transport	Midsize truck, diesel	75 km	2.71	0.20
FDX-CA > NWR	Transport	Air-LongHaul, JetFuel	4960 km	362.59	25.64
NWR > CU	Transport	Light truck, diesel	21 km	2.77	0.21
WW	Storage	None, electricity-US-Pacific	0 days	0	0
NVL	Storage	Cooler, electricity-US-Pacific	14 days	0.75	0.04
FDX-CA	Storage	None, electricity-US-Pacific	0 days	0	0
NWR	Storage	None, electricity-US-MidAtlantic	0 days	0	0
CU	Storage	None, electricity-US-MidAtlantic	0 days	0	0
			Total	369.88	26.17

Table 12
Energy and emissions by link and echelon, scenario D4.

D4: long distance 3PL fulfillment via rail					
WW > NVL	Transport	Midsize truck, diesel	29 km	1.05	0.08
NVL > FDX-CA	Transport	Midsize truck, diesel, cooler	75 km	2.72	0.20
FDX-CA > OAK	Transport	Midsize truck, diesel, cooler	50 km	1.81	0.13
OAK > NWK	Transport	Rail, diesel, cooler	5500 km	20.62	1.53
NWK > CU	Transport	Light truck, diesel, cooler	21 km	2.78	0.21
WW	Storage	None, electricity-US-Pacific	0 days	0	0
NVL	Storage	Cooler, electricity-US-Pacific	14 days	0.75	0.04
FDX-CA	Storage	Cooler, electricity-US-Pacific	0 days	0	0
OAK	Storage	Cooler, electricity-US-Pacific	0 days	0	0
NWK	Storage	Cooler, electricity-US-MidAtlantic	0 days	0	0
CU	Storage	None, electricity-US-MidAtlantic	0 days	0	0
			Total	29.72	2.19

different results. For instance, Venkat and Wakeland's [27] frozen food system requires more energy to store products than to deliver them and can be made more efficient by having less filled trucks making more frequent deliveries, to reduce the overall amount of inventory stockpiled at each echelon, and thus reduce usage of cold storage. Likewise, Van Hauwermeiren et al.'s [25] sample meat and dairy products result in comparatively more processing and storage emissions than transportation emissions.

The last 2 columns in Table 13 indicate the transport link in the scenario that contributes the most to emissions. Not surprisingly the cross-country transit link is responsible for the most emissions for all the long-distance scenarios. For most local scenarios the step linking the retailer to the consumer dominates. Even if the consumer effectively loads a standard gas car to full utilization (L1b) nearly half the emissions result from this segment. Only by eliminating this link, perhaps by having consumers walk, cycle or use efficient public transit, would emissions approach those of the local 3PL scenario.

4.11. *Caveats and limitations*

Researchers who have undertaken analyses similar to this one know that accurate and reliable data may not always be available for every input, requiring assumptions and estimates to be made. If these are inaccurate, results will be compromised. In our conversations with managers across the supply chain, we found that very few were comfortable with estimating the utilization and backhaul rates of inbound and/or outbound vehicles. As shown in Table 1, only the 3PL provider (New Vine Logistics) and the carrier (FedEx) provide information about either utilization or backhaul rates. While it seems safe to assume that negligible backhauling occurs in most local transport links, our assumption of a 100% utilization rate is, by definition, bound to be optimistic. To be consistent, we assume the same high utilization rate holds for all commercial vehicles. Were utilization rates significantly lower, our absolute per-unit emissions figures would increase. However, the relative ranking of the different scenarios would not be greatly affected, save for those that naturally lead to higher utilization for some links, such as scenarios that rely on retailer warehouses. As utilization rates drop, inserting a consolidation echelon would likely improve overall supply chain efficiency and emissions' profiles, even as mileage and lead-times increase.

Table 1 also shows that we were unable to have a conversation with a representative at the distributor tier. We thus assume that many of the characteristics of the retailer's regional distribution center would apply to the distributor echelon. If, say, the distributor contracts with a trucking company for different sizes of trucks for outbound distribution than we assume, our results would be compromised. Even more fundamental to our analysis is that CargoScope requires certain assumptions that may not hold universally, introducing some inflexibility into the modeling process. In particular, CargoScope assumes consolidated transit modes (ocean, rail and airfreight) have 100% utilization and 100% backhaul rates. Should significant inefficiencies exist for a particular case, CargoScope results would have to be adjusted manually.

Finally, it should be noted that our analysis is based upon a representative supply chain, but that no single winery's supply chain is likely to conform exactly to our sample. Wineries in more remote wine regions like Mendocino and Lake County will naturally incur more transportation emissions than our Sonoma Winery, especially as these wineries may not be convenient to delivery routes, such as the winery pickup service provided by New Vine Logistics Retailers with RDCs more remotely located than Cost Plus's Richmond facility will likewise result in higher emissions. By

Table 13
Ranked summary comparison of scenarios.

Scenario	Local or distant	Energy – MJ	Emissions-kg CO_2	Link with greatest emissions	Link's percent of total emissions
L4: local 3PL delivery	Local	5.83	0.42	NVL > FDX	48%
L1a: local 3-tier, standard scenario, with consumer using public transit or walking	Local	6.97	0.50	DW > RS	32%
L1b: local 3-tier, standard scenario, with consumer fully loading the car	Local	12.82	0.91	RS > CU	45%
L5c: consolidation run. consumer utilizes 100% of CargoScope of midsized pickup	Local	20.67	1.43	n/a	
L3b: winery self-distribution, via midsized truck	Local	27.2	1.89	RS > CU	89%
L1: local 3-tier, standard	Local	31.19	2.18	RS > CU	77%
D4: long distance 3PL fulfillment via rail	Distant	29.72	2.19	OAK > NWK	70%
L2: local 3-tier, with retailer warehouse	Local	32.28	2.25	RS > CU	74%
L3a: winery self-distribution, via light truck	Local	37.27	2.64	RS > CU	64%
D1: 3-tier distribution, Long Distance	Distant	48.61	3.62	DW-CA > DW-NJ	78%
D2: long distance 3PL fulfillment via truck	Distant	49.39	3.64	FDX-CA > ESS	77%
L5b: consumer drives a hybrid	Local	208.89	14.47	n/a	
D3: Long distance 3PL fulfillment via airfreight	Distant	369.88	26.17	FDX-CA > NWR	98%
L5a: consumer drives a regular car to the winery	Local	487.41	33.75	n/a	

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performing a detailed case study for a particular winery and its downstream network, we would be able to better estimate per-case emissions and address that winery's specific concerns.

5. Conclusions

Wine is an image-focused, luxury product that generates strong emotional ties with consumers. Wineries are concerned with attracting and retaining consumers and creating an image of sustainability. With the recent and growing focus on reducing greenhouse gas emissions, wineries face increasing pressure to demonstrate their commitment to minimizing their "carbon footprint." Many wineries are taking steps to reduce the energy usage associated with grape production and winery operations. For instance Cline Cellars, the winery that matches our model most closely, has solar panels on facility roofs to provide the majority of the winery's power needs. Other wineries are actively attempting to prevent soil erosion, reduce water usage and eliminate pesticide and herbicide usage. Some wineries even purchase credits to offset carbon emissions, as reported by Penn [17]. We propose that evaluating and redesigning the outbound supply chain will be considered as additional tool, as wineries typically have many options for downstream order fulfillment, and our results show that these options can have very different energy and emissions' profiles.

Wineries should focus more on transit than storage, as the latter contributes little to overall emissions. First, wineries can promote use of 3PLs for supporting direct-to-consumer sales, as this is very efficient for local delivery and can be comparable to 3-tier distribution for long distance fulfillment. For the latter, wineries should encourage clients to select ground rather than airfreight delivery and use 3PLs that provide temperature-controlled packaging to guard against spoilage on these longer journeys. Although small wineries are unlikely to have significant leverage with their supply chain partners, these wineries could favor supply chain partners who use rail instead of trucks for long distance deliveries.

While it would be naive to advise wineries to discourage tasting room visits, we recommend them to encourage wine club members to receive additional purchases via package delivery services by offering discounts on shipping. Another possibility would be for the winery to coordinate round trip van transport from club members from nearby cities for promotional winery events. Not only would such a service lessen the risk of inebriated drivers, but also it would allow the winery to better approach the efficiencies realized by the consolidation scenario L5c.

The high carbon intensity associated with consumer driving is troublesome from a policy perspective. This link is the least traceable and also the one a winery has least control over. Through positive informative campaigns, however, wineries could promote their involvement in reducing carbon emissions and, at the same time, nudge consumers to consider their own contributions. At the very least, volume discounts would encourage consumers to purchase more bottles at a time, leading to per-order emissions savings.

Our results also show that no single supply chain configuration is ideal for all wineries. Larger wineries that sell sufficient quantities to California retailers, where a typical delivery would fill a midsized truck, should consider self-distribution. Otherwise, a winery should rely on 3-tier distribution rather than self-distributing smaller volumes with light trucks or underutilizing midsized trucks. Similarly, if stores sell sufficient volumes to validate our assumption of fully utilized delivery vehicles, there is little value in adding the echelon of the retailer warehouse.

As previously noted, the emissions associated with delivering wine are a significant portion but still, only a portion of a winery's total carbon emissions. Likewise, carbon emissions are but one component of a company's overall environmental performance, and Lebel and Lorek [14] emphasize that a full life cycle assessment is often more appropriate than optimizing one single factor. In Point's [19] detailed life cycle assessment of the Nova Scotia wine region, contributions to global warming are but one of the 8 environmental factors examined. Even further, a fully complete CSR strategy for a winery would encompass more than ecological concerns, as grape harvesting typically makes heavy use of migrant laborers.

However, our isolated focus on logistics is justifiable because most aspects of the distribution process are independent of the winery's growing and operational processes. Thus, the delivery portion of supply chain can be evaluated separately by activities further upstream. We thus recommend wineries consider implementing this type of analysis as a part of their overall sustainability portfolio. Klassen and McLaughlin [12] show that companies often benefit financially from improving their environmental performance, especially in industries that are already categorized as environmentally friendly, as is the wine industry. Wineries could reap rewards from well-considered efforts. Attempting to document energy usage and carbon emissions using models such as those presented here would be a positive first step.

Speaking of first steps, we recognize that our model makes some generalizations and assumptions that may not apply universally. We plan next to undertake detailed case studies for specific wineries and their logistical networks. Such studies would allow the participants to better understand their supply chains and their options for improving efficiency. Comparisons between participating wineries would provide a better understanding of the commonalities within the wine industry and help us to better support generalizations about obtainable emissions' improvements.

Additionally, our research to date assumes that supply chain network decisions are made with existing products, facilities and equipment. We could extend our research to consider designing a supply chain with equipment and placement of facilities selected to minimize net energy usage and emissions. Evaluations of capital investments for new or existing firms may explicitly address sustainability issues in the future. These considerations would become even more probable were the U.S. to adopt a cap and trade emissions program similar to those found in the European Union. If so, emissions saved as a result of implementing a more efficient supply chain could then be credited to the winery. For instance, if the winery were able to ship more wine through efficient third party logistics providers in lieu of more energy-intensive delivery options or even redesign product packaging to be more compact and lightweight, overall emissions reduction could be calculated and applied as a credit towards a winery's emission budget. Modeling and analyzing such strategies, supported by use of tools such as CargoScope will help in quantifying the costs and benefits of different supply chain options and will support management decisions.

As a last word, we find that a winery can have an immediate and effective impact on emissions, even within our present limited scope. Wineries should focus on finding opportunities to make transport use more efficient, rather than focusing only on pure distances. They can support more direct-to-consumer sales through 3PL providers and ask supply chain partners to support long distance deliveries via rail rather than by truck and, most of all, avoid airfreight. Likewise, wineries with sufficient volume can consider routing deliveries though fewer echelons. Lastly, whenever possible, wineries should encourage their customers to consolidate purchases and otherwise minimize the highly emissions-intensive last link in the supply chain.

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