Journal of Transport and Supply Chain Management
ISSN: (Online) 1995-5235, (Print) 2310-8789

Enhancing brewery logistics with smart kegs: A simulation study

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Dates:
Received: 13 July 2024
Accepted: 21 Sept. 2024
Published: 13 Nov. 2024

How to cite this article:
Nettesheim, P.M., Burggräf, P. & Steinberg, F., 2024, 'Enhancing brewery logistics with smart kegs: A simulation study', *Journal of Transport and Supply Chain Management* 18(0), a1073. https://doi.org/10.4102/jtscm.v18i0.1073

Background: Supply chain optimisation is critical for companies in today's globalised world. Efficient supply chains ensure product quality and freshness in the food industry. For products like beer, efficiency extends beyond transportation and includes the management of logistics containers such as returnable kegs.

Objectives: This study investigated the impact of tracking logistics data on the efficiency of container logistics in a small regional brewery. The focus was reducing fleet size, processing times and pick-up distances.

Method: A simulation of a small brewery was used to analyse the impact of tracking logistics data. The study examined how kegs equipped with real-time tracking technology could improve logistics operations.

Results: The simulation showed that tracking logistics data significantly improved logistics processes. It led to a reduction in the fleet size, turnaround times and pick-up distances for empty kegs. These improvements were attributed to better resource allocation and more efficient management of reusable containers.

Conclusion: The study showed that smart kegs could reduce logistical inefficiencies in the brewing industry. The use of smart technologies in container logistics improves operational efficiency and sustainability.

Contribution: This research provides insights into how smart technologies can transform traditional logistics models. The results suggest that smart containers can revolutionise supply chains with efficient resource allocation, real-time tracking and automation. This shift towards smart logistics aligns with the broader adoption of the Industrial Internet of Things, offering a blueprint for future innovations in supply chain management. The implications extend beyond brewing, highlighting the potential for greater sustainability and a positive reduction in environmental impact in global supply chains.

Keywords: sustainability; smart solutions; supply chain; logistics; simulation; returnable transport item; brewing; optimisation.

Introduction

The growth of the global economy and the resulting increase in international trade have led to more frequent and complex logistic processes. Companies are facing increasing cost pressures in both production and supply chain because of growing competition (Cheng, Hai-Wei & Chen 2006). As a result, stable, cost-effective and efficient supply chains are crucial, because they are more globally networked than ever before (Blackhurst et al. 2005; Gani 2017). However, the smooth functioning of supply chains depends not only on the routes and means of transport but also on the containers used to transport goods.

The coronavirus disease 2019 (COVID-19) pandemic has highlighted the vulnerability of current supply chain mechanisms because of the absence of reusable transport containers, such as shipping containers. This shortage of transport containers has resulted in significant supply shortages across the world (Gray 2020). For instance, car manufacturers have had to halt production because of a lack of components, and companies have been unable to ship finished products (Ramani et al. 2022). Robust logistics processes are crucial in the food industry because of the specific product requirements. The perishable nature of produce means that delay can result in significant wastage and financial loss (Govindan 2018). This phenomenon is intensified by the strong seasonal demand for perishable goods, which strains the availability of transport containers.

The smooth operation of supply chains in the food industry is essential for sustainability (Li et al. 2014). Within the food industry, the brewing sector serves as an excellent example of the challenges involved because of its heavy reliance on the timely return of reusable containers, such as beer kegs and intermediate bulk containers (IBCs). These challenges, such as container shortages and inefficiencies in return processes, are reflective of broader issues faced across various industries but are particularly critical in the brewing sector, where the perishability of products and strict timing requirements intensify the impact of such disruptions. Delays in returning empty beverage kegs, including IBCs and bottles, can disrupt the entire production and delivery process as there is no suitable storage and transportation container available to deliver the beverage to the respective customer (Hariga, Glock & Kim 2016). This disruption not only provides a logistical inconvenience but also affects sustainability efforts. Breweries may need to limit production and bottling because of a shortage of transport containers or, in rare cases, have to dispose of beer, because the best-before date is no longer sufficient for further distribution to retailers, resulting in waste and financial losses (Cabras et al. 2023; Ina Verstl 2021; Patrick Cooley 2021).

There are several reasons for a shortage of kegs. Unforeseen peaks in demand because of inaccurate forecasting and the lack of data transparency and efficiency in the keg return process are key problems (Romer & Meißner 2019). The lack of data transparency with regard to the location and fill level of the kegs leads to significant logistical challenges. For example, breweries may struggle to accurately plan and coordinate the retrieval and redistribution of kegs, often leading to suboptimal loading of transport vehicles. As a result, more transports are required to move the same number of kegs, thereby increasing the frequency and distance of transports as well as the necessary fleet size (Yan & Yan 2019). This not only increases operational costs but also contributes to higher emissions and energy consumption, further exacerbating the environmental impact of the brewing industry.

Current research is making great strides in addressing these issues through the use of smart containers, such as smart IBCs and smart kegs, which are equipped with advanced sensors that monitor and transmit real-time data on location and fill levels. For example, smart IBCs can monitor critical parameters such as temperature, humidity, ethylene levels and microbial growth to ensure that perishable foods are transported in optimal conditions (Myintzaw et al. 2023). This technology not only facilitates real-time tracking but also enables proactive measures to prevent spoilage, thereby increasing food safety and customer confidence (Haass et al. 2015). In the brewing industry, smart kegs offer a practical application of this technology, allowing breweries to monitor external transport conditions and optimise logistics by reducing unnecessary transport and ensuring a more efficient keg return process. Despite these advances, the financial burden and data management complexities associated with implementing smart containers remain a significant challenge, particularly for small- and medium-sized enterprises (Astill et al. 2019; Burggräf et al. 2023a).

Solving the problem of inefficient keg returns needs a strategic overhaul of the keg return system. It requires increasing data visibility through smart kegs to optimise processes by introducing smart services for logistics planning to reduce unnecessary transportation, minimise environmental impact and ensure the sustainable operation of breweries.

Given the logistical inefficiencies, lack of data transparency and insufficient quality tracking, it is evident that current keg return systems in the brewing industry are inadequate. Previous research has predominantly focused on returnable transport items and sea containers in large, global networks, overlooking the specific challenges and potential of smart keg systems in smaller, more localised logistics networks. Designed to provide continuous information such as location and level, smart kegs have the potential to improve transparency, reduce the number of trips and minimise fleet size. However, there is a lack of scientific evidence quantifying the impact of improved data transparency on these key logistics factors in beer distribution. Filling this research gap is essential for understanding the impact of smart keg systems on transport frequency, fleet size and sustainability, especially for small breweries. Consequently, the central research question (RQ) is: *Can intelligent transport containers like smart kegs enhance the sustainability of the brewing industry by optimising the beer keg logistics through improved data transparency and reduced transport needs?* This investigation is not only about optimising logistic processes but also about contributing to the development of more sustainable supply chains in an era where environmental considerations are paramount.

To answer this question, the logistics processes of a small regional brewery distributing beer kegs directly to nine regional gastronomes were simulated. The carbon footprint was then calculated as a centralised sustainability score. The simulation results demonstrate positive effects on the supply chain sustainability by using smart kegs. The size of the keg fleet can be reduced, as well as the number of trips required for collection. Both indicate a positive impact of data transparency on sustainability in a brewery's supply chain.

The article is structured as follows: The 'Initial situation' section presents the initial situation. The 'Method' section introduces the method by detailing our simulation model. The 'Results' section presents our results of the simulation, while the 'Discussion' section discusses the effects of smart kegs in beer logistics. Subsequently, the 'Limitations & future work' section presents the limitations of our simulation and opens up approaches for further research activities. The 'Conclusion' section summarises the study and reflects the project results.

Initial situation

To answer the question, it is essential to comprehend the current state of the art in the field of smart containers and the return of empty containers. Understanding the field of smart containers provides a clear picture of data availability during circulation while comprehending the management of empty containers is necessary to understand the problem of container returns.

The logistics industry has been revolutionised using smart technologies, for example, in the area of smart shipping containers. This development is crucial for automation and digitisation of supply chains, leading to a reduction in costs and delivery times (Agrawal & Das 2011; Gnimpieba et al. 2015). A major advancement is the introduction of RFID technology, which increases efficiency and minimises errors (Abdullahi et al. 2024; Biswal, Jenamani & Kumar 2018).

Besides RFID, smart containers now incorporate Industrial Internet of Things (IIoT) technologies, making them active members of supply chains (Romer & Meißner 2019). These containers are equipped with sensors that provide real-time data on various conditions affecting the cargo, such as location, temperature and humidity, providing valuable insights for decision-making (Salah et al. 2020; Yingjun et al. 2010).

The trend of research towards more autonomous containers, including concepts of self-assessment and predictive maintenance, represents a remarkable leap in logistical possibilities (Burggräf et al. 2023b). The integration of cloud computing and big data analytics has given rise to a data-driven era in logistics management, enabling significant optimisation and efficiency gains (Chen et al. 2021; Strandhagen et al. 2017; Tran-Dang et al. 2020; Trappey et al. 2017).

In the food industry, smart containers can be used for maintaining optimal conditions for food safety and quality, as well as overcoming logistical challenges (Haass et al. 2015; Jedermann et al. 2014; Lang et al. 2011). Continuous monitoring of parameters such as temperature and humidity through advances in sensor technology is investigated for preserving perishable foods (Myintzaw et al. 2023). Research indicates that the use of smart container technologies, such as sensor-equipped beer kegs, in the beer industry has the potential to optimise product quality (BinaryBeer 2021). This not only ensures the best possible taste for the customer but also reduces costs for customer complaints because of incorrect handling by customers or carriers.

Nonetheless, companies encounter financial and operational challenges when implementing these technologies (Astill et al. 2019; Burggräf et al. 2023a). These challenges cannot be mitigated solely by increasing transparency in product quality. Therefore, it is crucial to develop smart services that leverage increased data transparency and allow companies to offset costs with savings or revenue streams of equal or greater value.

For instance, in the beer industry, the introduction of smart kegs leads to additional financial considerations. The costs associated with smart kegs are not only related to the transparency and improvement of product quality but it also requires the creation of additional smart services to cover the costs. These services must be designed to harness the increased data transparency, ultimately helping to offset the costs associated with smart keg implementation.

Empty container management is an area where a potential smart service can be implemented. The return of empty containers poses significant challenges in the interface between returnable intelligent transportation (RTI) and its automation, leading to inefficiencies that exacerbate sustainability issues (Cobb & Li 2022; Young Yun, Mi Lee & Seok Choi 2011). The current process is inefficient because of a lack of precise data on the location and readiness of empty containers for pickup, resulting in underutilisation of transport capacity (Soysal et al. 2023; Yildiz, Ravi & Fairey 2010). This inefficiency leads to unnecessary trips, increasing operational costs and contributing to increased carbon emissions, which undermines sustainability efforts in logistics.

As mentioned, sustainability challenges in industries often stem from a lack of transparency in supply chains, leading to inefficiencies that increase carbon emissions and operational costs (Matthess et al. 2022). The brewing industry exemplifies this issue, where smart kegs, as a specific kind of Returnable Transport Items (RTIs), offer a solution by providing real-time data on the location and condition of containers. This enhanced visibility allows for more efficient logistics, potentially reducing fleet size, associated carbon footprints, and operational costs through faster cycle times. At the same time, faster cycle times may increase transportation needs, leading to an increased carbon footprint and higher costs. This ambivalent situation highlights a critical juncture where broader implications of adopting smart keg technology must be considered. The expected outcome – a reduction in the brewery's overall carbon footprint through streamlined logistics and a minimised keg fleet – faces challenges from the potential increase in transport frequency. Transport frequency refers to how often transportation occurs, while transport distance denotes the length of each transport trip. Even if smart keg technology reduces the distance travelled per trip by optimising routes, an increased frequency of trips could strain logistics resources, potentially leading to unavailabilities of trucks. Thus, two hypotheses are formulated to reflect the dual potential of smart keg technology:

- **H1:** Smart keg technology, through its automation and data analytics capabilities, is hypothesised to reduce the necessary keg fleet size for a brewery. This reduction is expected to contribute to lower material and energy consumption, ultimately decreasing the brewery's carbon footprint.
- **H2:** Smart keg technology is anticipated to reduce the number of transports required for keg collection and positively impact the CO_2 footprint of brewery logistics. By optimising route planning and enabling more targeted pickups, breweries can achieve a more efficient logistics

operation, leading to a decrease in the carbon footprint associated with transportation. This hypothesis will be tested by simulating and comparing the carbon footprint of logistics operations, focusing on the number and frequency of transport trips before and after the technology's implementation.

These hypotheses challenge the assumption that improvements in one area of logistics – for example, a reduction in the keg fleet – inevitably lead to trade-offs in another area – namely, an increase in transportation frequency. They suggest that the positive and negative effects do not simply balance each other out but depend on how these logistics factors interact, particularly in terms of truck availability and overall operational efficiency.

Both hypotheses will be tested by simulating and comparing the carbon footprint of logistics operations, focusing on the number and distance of transport trips before and after the implementation of smart kegs.

Overall, they underline the importance of a holistic approach when assessing the environmental impact of intelligent technologies in logistics routes. Investigating these hypotheses will provide crucial insights into the complex interplay between technological innovation, operational efficiency and sustainability in the context of supply chains.

Method

To address the RQs and test the hypotheses, an agent-based simulation approach is employed. To substantiate the adoption of an agent-based simulation approach, it is crucial to acknowledge its capacity for modelling complex and dynamic systems, offering a practical means to evaluate various scenarios and their impacts without the inherent risks or expenses of real-world experimentation (Kondratyev & Garifullin 2009). Such an approach is especially pertinent in logistics and supply chain research, where the interplay of multiple factors and their outcomes can be systematically explored under controlled conditions (eds. Clausen, Langkau & Kreuz 2019; Sergeyev & Lychkina 2019). An experimental plan is devised with six scenarios, differentiated by two key parameters: the logistic concept of keg delivery and return, and the average customer demand. The logistic concept is relevant because of the different mechanisms of keg return between traditional and smart kegs. The average customer demand focuses on the scalability of the results to ensure that the reduction in the size of the keg fleet and the reduction in the number of transports are independent of the output. Each scenario is applied to a brewery simulation. Key indicators are calculated to show the impact of smart kegs on the sustainability and efficiency of the supply chain for the delivery and collection of kegs.

Simulation environment

The simulation model was created in Anylogic's established simulation environment. The model focuses on a small brewery with its production site located in Siegen, a city in North Rhine-Westphalia (Germany). The surrounding area is characterised by a mixture of urban and rural areas with a population of approximately 250 000. The brewery's annual output is up to 450 hL of only one type of beer. The beer is distributed in 50-litre kegs with a single truck to nine gastronomes based in Siegen and the surrounding area, without the intermediation of wholesalers or beverage distributors (see Figure 1). The total size of the keg fleet is 230.

The simulation mimics real-world pull ordering behaviour that corresponds to the average demand of these restaurants, providing a realistic and relevant context for our analysis. A simulation has been conducted for a 3-year period from 1 January 2024 to 31 December 2026.

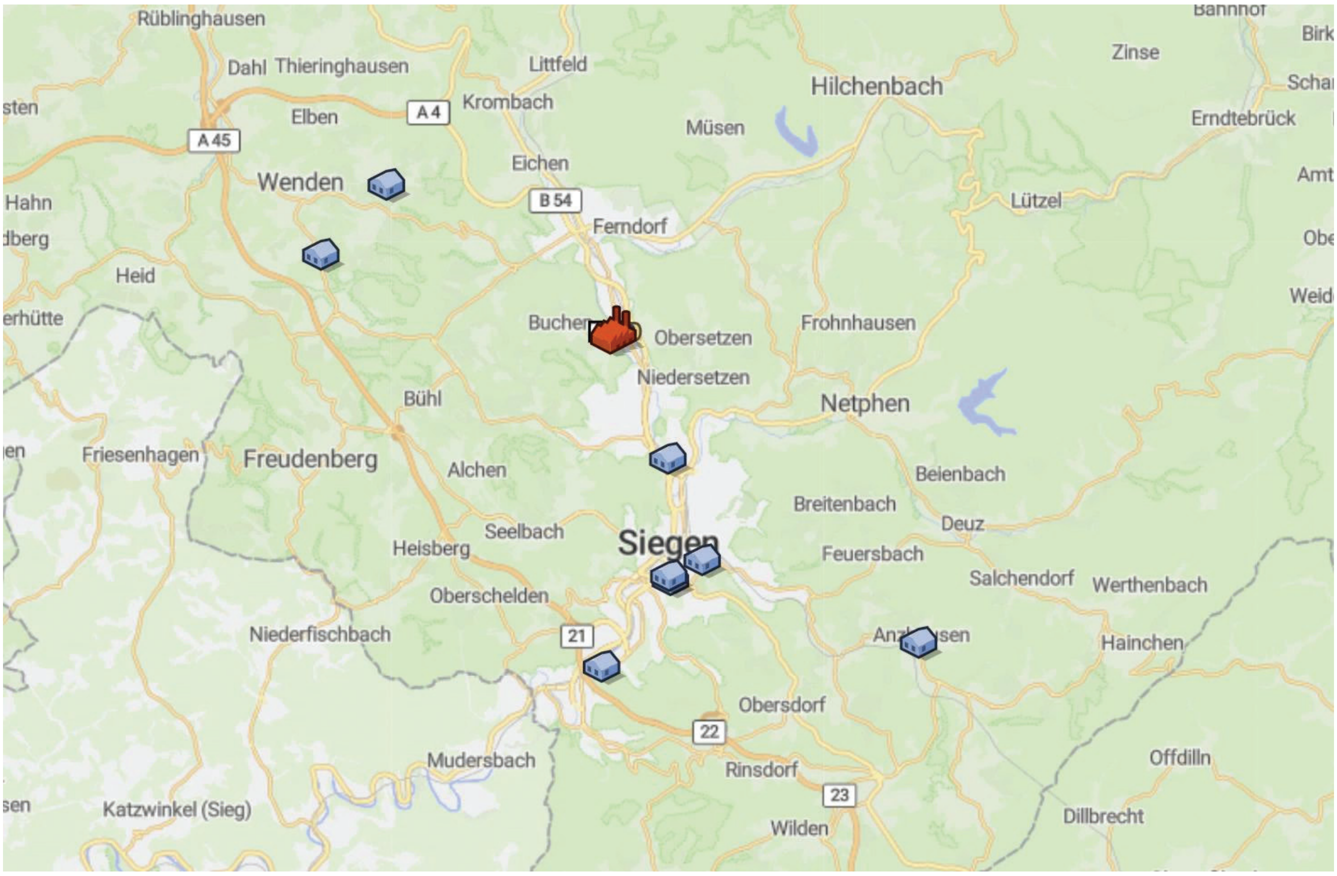
Experimental design

The study uses an agent-based simulation modelling approach to investigate the dynamics of keg returns within a brewery's supply chain. This approach models individual agents, such as breweries, kegs, trucks and restaurants, simulating their interactions based on defined rules. Each agent behaves autonomously, and their collective actions reveal complex system dynamics. By replicating real-world processes – like ordering, delivering, storing and returning kegs – the model provides insights into the overall supply chain efficiency. This method allows for the comparison of traditional and smart keg systems, capturing 3 years of logistical data in a short simulation period, ensuring objective analysis (Aslam & Ng 2010).

This approach facilitates the exploration of the RQs and hypotheses in a controlled and repeatable environment in a short period. Simulation is employed to determine key metrics such as required fleet size, keg turnaround time distributions and total transportation distances for both conventional and smart keg systems. The transport distances were calculated using geographic information system (GIS) data to ensure that the logistical aspects of the simulation accurately reflected real-world operations. These metrics serve as key indicators for a thorough assessment of the potential impact of smart keg technology on operational sustainability and supply chain efficiency.

A limitation of the simulation is that it was created with certain simplifications, such as excluding unpredictable spikes in demand because of single events and seasonal fluctuations, and assuming that deliveries of full kegs and collections of empty kegs do not coincide.

Methodical comparison of the results of traditional and smart keg logistics with identical simulated demand patterns aims to identify ways in which breweries can utilise technology to promote more sustainable operations and optimise fleet management and logistics planning. This methodological framework not only aligns with the research objectives but also highlights the opportunities that digital technologies present for enhancing sustainability in the brewing industry.



Note: The figure was generated using AnyLogic.

FIGURE 1: Overview of the brewery (red production site) and restaurants (blue houses) in the region of Siegen in North Rhine-Westphalia (Germany).

A full-factorial experimental design has been set up, consisting of two demand scenarios: 30 hL and 50 hL. These scenarios are based on the fluctuations in average annual beer demand by restaurants. Additionally, three logistics scenarios have been included, which are based on the options for collecting the empty kegs and enable a comparison between traditional and smart kegs to answer the RQ. The logistics scenarios for keg returns are described in detail below:

- **Traditional keg collection:** Here, restaurant agents periodically inform the brewery of empty kegs based on historical patterns and estimations, prompting the brewery to schedule collections. This method reflects the conventional approach where communication and logistics planning rely heavily on manual coordination and estimation.
- **Smart keg – individual collection:** In this innovative approach, smart kegs equipped with sensor technology automatically notify the brewery when they become empty. The decision to trigger collection upon accumulating 12 empty kegs at a single restaurant's location is strategically chosen. This threshold is based on the truck's maximum load capacity, ensuring that each trip is fully optimised in terms of cargo volume. This threshold is not arbitrary but is carefully selected to align with the logistical capacity and efficiency goals, ensuring that the transport resources are utilised to their maximum potential without exceeding the truck's carrying capacity.
- **Smart keg – route-based collection:** Expanding upon the smart keg technology, this scenario introduces a more advanced logistics optimisation by aggregating empty keg notifications along a predefined route involving three restaurants. The collection is initiated once a combined total of 12 empty kegs is reached across these locations. This method leverages the spatial distribution of restaurant agents to further enhance logistics efficiency, reducing the overall number of trips by consolidating pickups. This route-based approach represents a significant advancement in logistics planning, utilising real-time data and geographic considerations to minimise transportation distances and, consequently, the environmental impact. The simulation parameters and variables, including ordering patterns and return frequencies, were derived from the brewery's historical data, providing a grounded basis for our model. Transport distances were calculated using GIS data, ensuring the logistical aspects of the simulation closely mirrored real-world operations. However, the simulation was constructed with certain simplifications, such as excluding unpredictable demand spikes and seasonal variations, and assuming that deliveries of full and collections of empty kegs could not coincide.

Detailed state and flow diagrams were created to simulate this full-factorial test plan, tailored to each logistics scenario, mapping the brewery's keg delivery and collection processes. The three logistics scenarios included Traditional Keg Collection, Smart Kegs with Individual Collection and Smart Kegs with Route-Based Collection. Each scenario was customised for both 30 hL and 50 hL demand conditions.

Figure 2 shows an exemplary flowchart for all logistics and demand scenarios, illustrating the steps from the ordering of kegs by the restaurant agents to the reporting of empty kegs and subsequent collection. A truck agent ensures that only one delivery is made at a time. It travels at normal speed from the brewery to the restaurant and back again to reproduce realistic delivery behaviour. There are three different events in the restaurant agent flowchart. The first event named *Demand* starting the flowchart is the demand from the restaurant. Depending on the demand scenario, this triggers regular beer keg orders within a varying cycle time, which are collected in the *Keg_Collective_Order* queue. The event *Delivery* is then triggered at regular intervals of 14 to 21 days, and the ordered kegs are transported by truck to the respective restaurant, where they are first cooled. From there, the kegs are transferred to the dispensing system or, in a small percentage of cases, directly to the empty keg warehouse as rejects. All kegs are stored in the warehouse until collection, which is triggered by the Event *Keg_collection*, which varies depending on the collection mechanism.

In the traditional keg collection scenario, the event Keg_collection is triggered cyclically. For the low annual demand scenario from the restaurants, the collection takes place every 60 to 80 days, and for the higher demand scenario, the collection takes place every 25 to 35 days, based on the brewery's historical data.

Using smart kegs, the *Keg_collection* trigger is adapted to the automatic feedback from the kegs. The trigger initiates the collection of kegs when there are 12 kegs in a restaurant's empty keg warehouse, which is the maximum load capacity of the truck. The automatic feedback by the smart kegs eliminates delays caused by late manual feedback of the restaurant.

The third scenario analyses the route-based collection of empty smart kegs. For this, the restaurants are optimally assigned to three different routes, each with three restaurants. The event *Keg_collection* is then replaced by three events, each corresponding to one of the three defined routes. These three events are triggered as soon as a total of 12 kegs are ready for collection in the empty keg warehouses of the gastronomes on the predefined route.

Evaluation metrics

To quantify the sustainability impact of implementing smart keg technology in the brewing supply chain, the carbon footprint is calculated as a sustainability score (SS). The SS covers the aspects of operational efficiency and environmental sustainability by considering key metrics such as keg fleet size, keg turnaround times and transportation distances required for empty keg collection. By quantitatively assessing the efficiency of keg fleet utilisation, the speed of keg turnover and the environmental efficiency of transportation, the assertion that smart keg systems contribute to both operational optimisation and supply chain sustainability improvements is empirically tested. This methodological approach systematically investigates the expected benefits of smart keg technology and provides evidence-based insights consistent with fundamental research on the potential for sustainability improvements in brewery logistics and overall logistics through smart returnable transportation. The sustainability score is calculated by Equation 1:

$$SS = KFUE + EEoT. \qquad \text{[Eqn 1]}$$

The keg fleet utilisation efficiency (KFUE) as the first dimension of the SS is defined as Equation 2:

$$KFUE = KF \times \frac{CO_2}{Keg} \times \frac{TO}{120} \qquad \text{[Eqn 2]}$$

where:

- *KF* represents the size of the keg fleet, indicating how efficiently the physical assets are utilised and
- *TO* represents the number of turnovers of each keg during the simulated time.

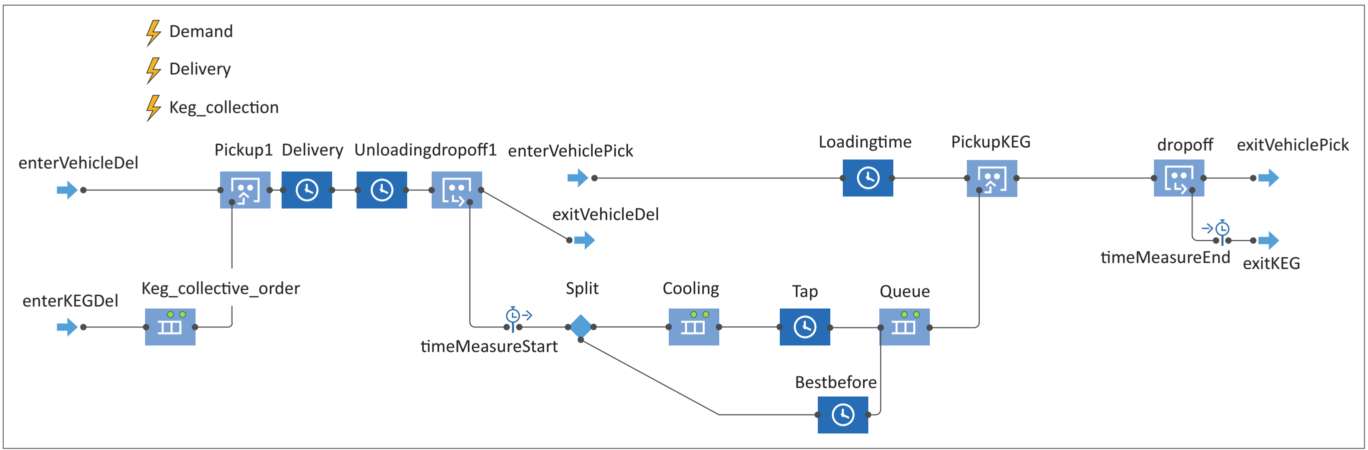


FIGURE 2: Flowchart for keg collection in AnyLogic.

KFUE assesses the effectiveness of the existing keg fleet in meeting demand while minimising idle times and the overall need for additional kegs by calculating the CO_2 emissions caused by the kegs during the simulated timespan. An optimised fleet size not only reduces the resources and emissions associated with producing new kegs (CO_2e/Keg) but also bolsters sustainability by ensuring efficient asset use. The typical weight of a 50-litre stainless steel keg is approximately 11.4 kg. As the production of stainless steel is associated with CO_2 emissions of approximately 3.1 kg per kilogram, it can be assumed that the production of a single keg emits approximately 35.34 kg CO_2e (BEIS 2022; BLEFA 2024). To take into account that the kegs are only used for a fraction of their lifespan during the simulated period, we multiply the CO_2 emissions for production by the fraction of the lifespan. For stainless steel kegs, this is typically 120 cycles (Thielmann 2024).

The environmental efficiency of transportation (EEoT) is the second dimension taken into account and is defined as Equation 3:

$$EEoT = TD \times \frac{CO_2}{km} \quad \text{[Eqn 3]}$$

where *TD* stands for the transportation distances in km required for collecting empty kegs, and CO_2e/km accounts for the carbon emissions per kilometre, together assessing the environmental footprint of logistics operations.

EEoT focuses on the ecological footprint of logistics. It considers the total transportation distances (TD) required for collecting empty kegs and the associated carbon emissions per kilometre (CO_2e/km). To calculate the CO_2 emissions per kilometre under standard conditions for the VW Crafter, a vehicle commonly used, the value of 0.199 kg/km is applied. Enhancing transportation efficiency – through reduced distances and CO_2 emissions per transport unit – not only elevates the sustainability score but also accentuates the environmental advantages of efficient logistic routes and cleaner transport methods. This aspect particularly targets the supply chain's environmental dimension, stressing the critical role of minimising greenhouse gas emissions to promote sustainable brewery operations.

Thus, SS is a multi-layered measure that can be used to assess both the environmental efficiency and operational efficiency of keg logistics in the brewing industry. Calculating SS aims to highlight and evaluate the different impacts of traditional and smart keg systems, especially under constant demand conditions, thereby addressing the RQ.

Taken together, cycle time, keg fleet size, empty keg return transportation distance and SS provide a comprehensive view of how keg logistics impact both the operational and environmental aspects of sustainability. Analysing these KPIs allows for a deeper understanding of how smart keg technology can optimise brewery supply chains and pave the way for a more sustainable future for the industry. Importantly, the evaluation of each category within the sustainability assessment, as well as the overall assessment itself, provides a direct answer to the hypotheses and RQ.

Results

After executing the experimental plan in the simulation and calculating the respective key indicators, the results are documented in Table 1.

The simulation data reveal that in a lower beer consumption scenario, traditional systems have a maximum keg fleet size of 157 kegs, which is marginally reduced in intelligent systems per restaurant to 156 kegs and more significantly in intelligent route-based systems to 29 kegs. When it comes to higher consumption rates, traditional systems utilise 180 kegs, while intelligent systems show a notable decrease, requiring only 160 kegs in intelligent systems per restaurant and 130 kegs for route-based systems. These figures underscore, that smart systems, regardless of the consumption rate, operate with fewer kegs in circulation than their traditional counterparts.

To compare traditional and smart keg systems, turnover time is also considered. Based on the scenario of an annual consumption of 30 hL per restaurant, traditional systems have an average keg turnover time of 102.2 days. With smart systems, this is reduced to 95.1 days for individual configurations and further to 65.5 days for route-based systems. The 50 hL/year scenario shows a similar pattern of improvement; traditional systems show a turnover time of 47.5 days, while smart systems show a significant reduction, with individual collection configurations achieving a turnover time of 41.8 days and route-based systems achieving a turnover time of 33.0 days. These empirical results imply an improvement in keg turnover time of up to 35.9% and 30.7% for the 30 hL and 50 hL scenarios, respectively. To illustrate these results more clearly and precisely, a bar chart is used to show the different turnover times for the different systems within

TABLE 1: Comparative analysis of fleet size, turnover times, transport distances and sustainability scores.

Consumption scenario	System and collection type	Fleet size	Average turnover time (days)	Distance (km)	Sustainability score (kg CO_2e)
30 hL/year	Traditional Keg	157	102.2	5366.5	1563.4
30 hL/year	Smart Keg – Individual Collection	156	95.1	3555.4	1236.6
30 hL/year	Smart Keg – Route-Based Collection	99	65.5	5715.3	1624.9
50 hL/year	Traditional Keg	180	47.5	11547.4	3518.8
50 hL/year	Smart Keg – Individual Collection	160	41.8	9126.0	3049.9
50 hL/year	Smart Keg – Route-Based Collection	130	33.0	14233.1	4102.2

hL, hectolitres.

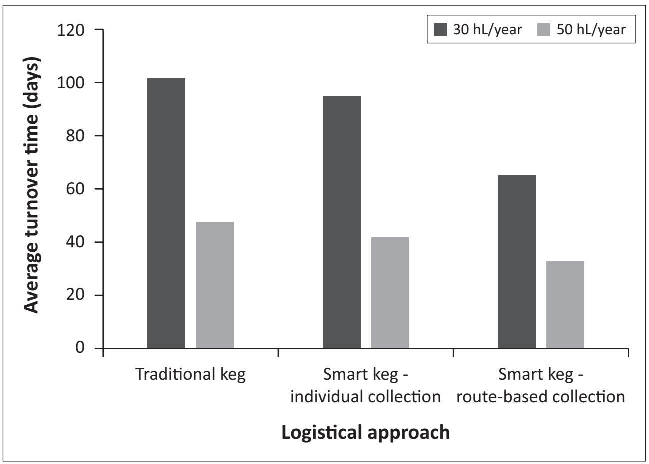


FIGURE 3: Comparative analysis of keg turnover times.

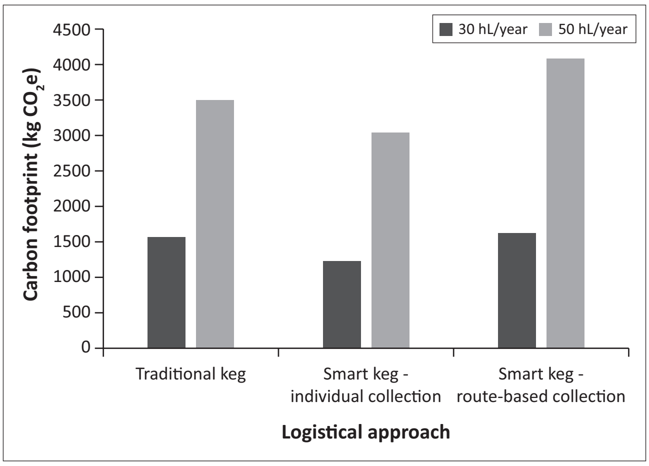


FIGURE 4: Comparative analysis of the carbon footprint.

each consumption class. As shown in Figure 3, the bar chart depicts the differences in turnaround times between the traditional and intelligent systems, effectively capturing the systematic improvements brought about by the intelligent configurations.

Truck utilisation also sees significant enhancement, with intelligent systems achieving full utilisation (100%) in all scenarios, compared to the traditional system's 66% in lower consumption and approximately 77.7% in higher consumption scenarios. Distance travelled by trucks during pickup reflects a reduction from 5366.5 km to 3555.4 km in the intelligent per gastronome system in the lower consumption scenario, but it increases to 5715.3 km for the intelligent route-based system. Conversely, in the higher consumption scenario, the distance is reduced to 9126 km for per gastronome systems, while the route-based system sees an increase to 14233.1 km.

The integration of smart keg systems has shown significant efficiency in reducing the maximum keg fleet size, with the route-based system showing the most significant reduction in both the 30 hL and 50 hL per year consumption scenarios. In addition, keg turnover times were significantly optimised in smart systems, with the route-based models showing the shortest turnover times, which could indicate improved operational efficiency. In addition, truck utilisation in intelligent systems has reached an optimal level of 100%, which is a significant improvement compared to traditional systems.

Looking at the sustainability scores shown in Figure 4, there is a clear relationship between the keg systems and their environmental impact. For the scenario of 30 hL per year per restaurant, the smart keg system with individual collection demonstrates a significant improvement in sustainability, with a lower score of 1236.65 kg CO_2e compared to the traditional system's higher score of 1563.42 kg CO_2e, as illustrated in the graph. However, the route-based smart system, despite its operational efficiencies, has a sustainability score of 1624.91 kg CO_2e, indicating an increase in CO_2 emissions because of longer transport distances.

In the 50 hL per year consumption scenario, Figure 4 shows that the smart individual collection system outperforms the traditional setup with a sustainability score of 3049.87 kg CO_2e, compared to 3518.77 kg CO_2e for the traditional system. However, the sustainability score of the route-based smart system reaches its peak at 4,102.22 kg CO_2e. This suggests that the advantages of reduced keg turnover times and full truck utilisation are outweighed by the environmental impact of increased transportation distances.

Discussion

Based on the detailed analysis of the sustainability scores and operational improvements in each dimension achieved by the introduction of smart keg systems, the focus is now on addressing the hypotheses and RQ set out at the beginning of this study.

In examining the impact of smart keg technology on the sustainability of the sample brewery's supply chain, the carbon footprint was utilised as a key metric to test the hypotheses proposed at the outset. Hypothesis 1 claimed that smart keg technology, through its automation and data analytics capabilities, would enable breweries to reduce their keg fleet, thereby lowering material and energy consumption and, consequently, the brewery's carbon footprint. This hypothesis was tested by simulating the necessary size of the keg fleet and calculating the total carbon footprint associated with the production and maintenance of the keg fleet before and after implementing the technology. The simulation results confirm this hypothesis, showing a significant reduction in fleet size from 157 to 156 and 99 kegs, respectively, for the lower demand scenario and from 180 to 160 and 130 kegs, respectively, for the higher demand scenario with smart systems, accompanied by an associated improvement in sustainability scores. Thus, Hypothesis 1 is accepted, supporting the claim that smart keg technology promotes more sustainable practices by rationalising resource and energy consumption.

Hypothesis 2 proposed that, despite initial assumptions, the implementation of smart keg technology could also reduce the number of transport trips required for keg collection. By optimising route planning and enabling targeted pickups, the technology was expected to lead to more efficient logistics operations, thereby reducing the carbon footprint associated with transportation and enhancing overall supply chain sustainability. This hypothesis was tested by simulating and comparing the carbon footprint of logistics operations, focusing on the number and frequency of transport trips before and after the technology's implementation. Contrary to the initial assumption that fleet reduction negatively correlates with the number of transports necessary for collection, the simulation results indicate an optimisation in the number of trips required for keg collection using smart kegs for both collection variants. Therefore, Hypothesis 2 is accepted even though it is noted that route-based collection leads to an increase in the required transport distances. The results overall confirm that smart keg technology has the potential to significantly improve the sustainability of the brewery's supply chain.

Having confirmed both hypotheses positively, the research now shifts to the central RQ: Can the use of intelligent transport containers enhance the sustainability of the beer keg logistics chain by reducing the transportation effort for the return of kegs, facilitated by improved transparency and efficiency?

The simulation results confirm that this question can be answered affirmatively. The keg fleet's maximum size has been significantly reduced, particularly through the route-based system in the two demand scenarios of 30 hL and 50 hL per year. Additionally, keg handling times have been optimised, resulting in optimal truck utilisation and a reduction in trips. These improvements not only demonstrate increased operational efficiency but also have a positive impact on sustainability, aligning with the core objectives of this study. However, when examining the sustainability scores based on the ecological footprint, a more nuanced picture emerges. On the one hand, the research confirms that data transparency through smart kegs leads to improved sustainability in the return of empty kegs. This is evidenced by the clear optimisation seen in the individual collection of smart kegs compared to traditional kegs. Contrary to the intended purpose, merging restaurants into a route-based pickup does not improve sustainability in the simulation environment. In fact, it has a negative effect, resulting in a worse sustainability score than traditional kegs. It is important to note that this statement cannot be generalised to other environments. It is possible that this effect is preferred by a small number of regional restaurants, but the opposite effect may occur with a larger number of regional restaurants or with clusters of restaurants at a greater distance.

In summary, the utilisation of smart keg systems, particularly with a focus on route-based tracking mechanisms, represents a significant advancement in the field of beer keg logistics. It contributes significantly to sustainability efforts by streamlining operational processes while reducing the environmental footprint of breweries' supply chain logistics. This development aligns with global sustainability goals and guides the brewing industry towards more sustainable practices.

The simulation results confirm that smart keg systems, especially those with route-based tracking, represent a significant advancement in beer keg logistics. These systems significantly reduce keg fleet sizes, with route-based models requiring up to 30% fewer kegs than traditional systems, regardless of beer consumption. In addition, keg turnaround times are improved by up to 35.9%, contributing to faster operations. Truck utilisation reaches 100% efficiency in all scenarios for smart systems, a significant improvement over traditional systems. However, the increased transport distances in route-based setups result in higher CO_2 emissions, highlighting a trade-off between operational efficiency and sustainability. This progress is in line with global sustainability goals and encourages the brewing industry to adopt more sustainable practices.

Expanding on the conclusions, the practical implementation of smart keg systems must be thoughtfully considered. The development of this technology must prioritise cost-effectiveness to ensure that breweries of all sizes can adopt it without facing financial strain. It is essential for the long-term viability and scalability of smart keg initiatives that they do not impose a heavy financial burden, especially on smaller breweries.

Additionally, the implementation of these intelligent systems should consider the current keg fleets. Retrofitting existing kegs with new technology would enable breweries to upgrade their equipment without having to replace their entire fleet, thus conserving resources and aligning with sustainable practices. The design of smart keg technologies should enable seamless integration with current operations, enabling breweries to make their kegs intelligent in-line, without significant production delays or disruptions.

In synthesising these considerations, it is evident that while the simulation's outcomes are favourable, the broader application of smart keg systems depends on creating accessible and easily integrated technologies. Meeting these challenges would enable the brewing industry to make significant strides in sustainability, aligning with broader environmental goals and setting an example for other sectors to follow.

Limitations and future work

While the study has illuminated several facets of operational efficiency and sustainability improvements, it is important to acknowledge the limitations inherent in the research methodology. Acknowledging these limitations not only anchors the findings within the framework of scientific rigour but also opens avenues for future research to enhance the understanding of smart logistics solutions in the brewing industry.

This discourse on limitations and subsequent research opportunities stems from a thorough examination of the scope and assumptions underlying the simulation, along with the extrapolation of its results to real-world contexts. Through this perspective, the parameters of the study are critically evaluated, and avenues for empirical validation and exploration beyond the current research boundaries are suggested.

The research provides insights into the efficacy of smart keg systems within the brewing supply chain. However, it operates within a limited framework, which must be acknowledged because of its limited applicability. The sustainability scores for the intelligent route-based collection may have been influenced by the simulation's constraints, such as servicing a limited number of restaurants in close proximity to the brewery. It should be noted that the findings may not be entirely objective because of the limitations of the simulation. The model indicates that a larger and more geographically diverse brewery network could enhance the sustainability performance of the route-based system. This is because the system could take advantage of scalable route optimisation to reduce CO_2 emissions more effectively. The simulation model may oversimplify supply chain dynamics by excluding seasonal variation and unpredictable events, which could lead to the omission of critical real-world operational challenges. Furthermore, the study's focus on a direct distribution model without intermediaries, such as wholesalers, limits its exploration to an idealised version of logistics for a small craft beer brewery, rather than an industrial brewery. The study's findings are limited to a small brewery that produces 450 hL per year and is connected to a regional on-trade network. Additionally, the route-based collection analysis used in the study does not consider the potential benefits of adaptive, intelligent routing mechanisms for logistical optimisation.

A limitation that has not been addressed yet is the absence of a technical solution for retrofitting smart kegs. Therefore, this study has not conducted a comprehensive economic evaluation of investing in smart kegs. This omission is because of the lack of available data on the costs associated with hardware as well as the effort required for the retrofit process. Without a concrete technical solution in place, estimating the economic impact, including potential savings or return on investment for breweries considering the adoption of smart keg systems, remains speculative.

Given these limitations, the path forward for scientific research into intelligent keg systems is both broad and varied. A key area of future research lies in the integration of distribution networks involving intermediaries, introducing a layer of complexity that reflects the multifaceted nature of beer distribution and keg collection. Expanding the scope of analysis to include large breweries with an extensive network of supra-regional publicans could provide invaluable insights into the scalability and adaptability of smart keg systems across different operational landscapes.

Crucially, the development of a cost-effective solution for monitoring keg fill levels is emerging as a paramount endeavour. Such technological advances promise to revolutionise brewery operations by ensuring optimal keg utilisation and facilitating a more environmentally sustainable logistics framework. This is not only in line with the industry's sustainability aspirations but also serves as a foundation for future logistics innovation.

Given the simulation-based findings of the study, the need for empirical validation through real-world experimentation cannot be overstated. Conducting experimental trials to corroborate the simulation results would not only strengthen the credibility of the findings but also provide a concrete basis for the practical implementation of smart keg systems. This empirical approach would serve to bridge the gap between theoretical modelling and operational reality, thereby enriching the academic discourse on smart logistics within the brewing sector and beyond.

Conclusion

The rigorous analysis and simulation conducted in this study demonstrate that the implementation of smart RTIs, specifically smart keg systems, significantly improves the operational efficiency and sustainability of brewery supply chains. The empirical data derived from the simulations clearly show a significant reduction in the required fleet size and a significant improvement in keg turnaround times, highlighting the key role of smart technologies in optimising supply chain logistics.

Additionally, the use of intelligent RTIs has been shown to extend beyond mere operational improvements and offers profound environmental benefits through optimised transport logistics and reduced carbon emissions. The findings from the brewing industry serve as a compelling case study for the broader applicability of smart logistics solutions across multiple industries. Smart IoT, with its inherent capabilities for real-time data collection and analysis, represents a transformative opportunity for industries to move towards more sustainable and efficient supply chain practices.

The implications of the research suggest a paradigm shift in logistics management across multiple industries. The integration of smart technologies into RTIs has the potential to revolutionise traditional supply chain models by promoting adaptive, data-driven logistics strategies. This transition to intelligent logistics systems is not limited to the brewing industry but is applicable to a wide range of industries, including other beverage industries, pharmaceuticals, food industries and manufacturing industries, among others. Each can benefit from the increased data visibility provided by smart RTIs, which enables more sustainable management of returnables and represents a critical advancement in improving supply chain sustainability, particularly in the area of empties logistics. This suggests that smart RTIs could play a critical role in reducing environmental impact while improving efficiency.

Overall, the study contributes to the burgeoning field of smart logistics by illustrating how smart keg systems can serve as a model for the adoption of smart RTIs across different industrial landscapes. It can be shown that the strategic integration of these technologies will not only advance the brewing industry but also usher in a new era of supply chain management characterised by enhanced sustainability, efficiency and adaptability.

Acknowledgements

Competing interests

The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.

Authors' contributions

P.M.N. contributed to conceptualisation, draft preparation, methodology, simulation, analysis, visualisation and editing. P.B. and F.S. were responsible for conceptualisation, supervision, review and editing. All authors have read and agreed to the published version of the manuscript.

Ethical considerations

This study did not involve human or animal subjects. The research was determined to be non-human subjects research and was exempt from ethical review.

Funding information

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Data availability

Data sets generated during this study are available from the corresponding author upon reasonable request.

Disclaimer

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