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ENERGY-EFFICIENCY AND SUSTAINABILITY IN CROSS-DOCKING SUPPLY USING E-VEHICLES

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Abstract:
Manufacturing and service companies in different sectors are trying to green their supply chains in two ways: by optimizing processes and by using green technologies such as electric vehicles. Cross-docking offers a good solution for optimizing supply chain processes. The aim of this research is to investigate how cross-docking supply with electric vehicles can lead to energy efficient solutions and emission reduction. The scientific novelty of this research is the integration of a process improvement solution and the application of advanced technology through optimization. The presented functional model, mathematical model and its solution algorithm are suitable to demonstrate the economic feasibility of applying a cross-docking facility and solving the transportation tasks with e-trucks for a conventional supply chain. Based on the numerical studies presented, it can be concluded, that the proposed solution can significantly contribute to the optimization of local and global supply chains, reducing the ecological footprint of supply chains both locally and globally. As the analysis of case studies shows, it is possible to reach an energy efficiency improvement of about 40%, which can also lead to a significant GHG emission up to 30%.

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1. INTRODUCTION

Energy efficiency is playing an increasingly important role today, as a company can only be a successful player in the market if it can implement its processes in an energy-efficient way. This is particularly true for supply chains, where it is essential to design and operate processes and technologies that increase the energy efficiency of transportation, materials handling, and warehousing processes while significantly reducing the environmental impact [1].

In particular, cross-docking offers a solution to global supply challenges with large geographical distances, which can greatly reduce the cost of the supply process, increase the availability, efficiency, flexibility, and transparency of supply, and reduce the environmental impact through reduced energy consumption. When designing a cross-docking supply, there are several design challenges to be addressed [2], such as:

- Design of the macro-layout of the cross-docking supply, which involves the determination of the number of tiers and the number and location of cross-docking terminals in each tier.
- Design of the cross-docking terminal layout.
- Optimization of the door strategy, which is a link between scheduling inbound, outbound, and internal materials handling operations.
- Design of in-plant materials handling processes for the cross-docking terminals.
- Scheduling of inbound and outbound.

As the Cross Docking Services Market Report of Transparency Market research shows [3], the cross-docking market is expected to realize a CAGR of 6% between 2020 and 2030, and the global cross-docking facility-based supply chain solutions are expected to reach 342 Bn USD by 2030.

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Dudukalov et al. concluded in their research [4], that a 1% improvement in logistics operations of cross-docking facilities can lead to a warehousing cost reduction of about 32%, and the efficiency of distribution processes can also be improved by 35%.

Within the frame of this article, the author focuses on the macro-layout design problems of cross-docking supply using a novel methodology to compare conventional and cross-docking supply solutions from an energy efficiency and environmental impact point of view.

The outline of this paper is as follows. Section 2 presents a short literature review, which summarizes the main research results in the field of design of cross-docking supply. Section 3 describes the evaluation model, which makes it possible to evaluate and compare different types of cross-docking supply solutions from an energy efficiency, emission, and material handling performance point of view. Section 4 describes the numerical results of the scenario analyses. Conclusions, future research directions, and managerial impacts are discussed in Section 5.

2. LITERATURE REVIEW

The biggest problem of supply chains today is that the complexity of supply chains can lead to many disruptions. Cross-docking terminals represent reasonable solutions to solve and avoid the problems that arise from these disruptions [5]. As Esmizadeh et al. [6] concluded, the different types of supply chains (hub-and-spoke network, cross-docking, pick-up and delivery network) offer different potential to avoid the negative impact of disruptions. Still, the optimal solution is the integration of these basic models.

The next potential design aspect of cross-docking supply is the scheduling of inbound and outbound operations. Theophilus et al. [7] suggested an evolutionary algorithm to solve the transportation processes of cold supply chains as a mixed integer programing problem.

Important design problem of cross-docking supply is the vehicle routing problem. As Cota el al. [8] proposed, the efficient solution of open vehicle routing problems supports the efficient management of logistic solutions in cross-docking supply solutions.

Integrated approaches are focusing on the design of cross-docking supply focusing on the integrated optimization of facility location, inventory optimization, vehicle routing, time-window management, supplier evaluation and selection, and allocation of orders. Tavana et al. [9] proposed a mixed-integer linear programming model for the integrated design of closed-loop cross-docking supply using fuzzy goal programming in the General Algebraic Modeling System (GAMS).

The truck pool of cross-docking supply solutions is generally heterogeneous. In this case, the routing and scheduling tasks are complex optimization problems, where capacity utilization plays a vital role in multi-objective optimization [10].

The application of Industry 4.0 technologies significantly increases the efficiency of cross-docking supply chains because IoT solutions make it possible to perform real-time optimization. In the case of conventional supply chain solutions, upgrading with Industry 4.0 technologies can improve system performance, efficiency, and flexibility [11].

The cooperation strategy can significantly increase the efficiency of cross-docking supply. As Santos et al. [12] concluded, the players of the value chain (retailers, third-party logistics providers, manufacturers, users) can choose different collaboration strategies, and these strategies allow the producers to cross-dock their cargo at the depot of another entity to increase the flexibility or plasticity of the supply chain.

The optimization models of cross-docking design include a wide range of models and methods. Dulebenets suggested a delayed start parallel evolutionary algorithm for just-in-time truck scheduling at a cross-docking facility in his work [13], where the truck scheduling problem was defined as a mixed integer linear programming (MILP) model, minimizing the service costs of truck services. This model focuses on cost optimization, but sustainability aspects and the potential advantages of e-vehicles are not considered. As Monemi et al. [14] concluded, a machine learning-based branch-cut-and-benders for dock assignment and truck scheduling problem in cross-docks can significantly increase the success rate of the design of cross-docking supported supply chain solutions.

Gelareh et al. compared and analyzed the existing cross-dock door assignment problems [15]. They start their work from the standard quadratic formulation of the problem and derive 11 nonstandard linear mixed integer programming (MIP) models. This research shows that cross-docking design includes a wide range of design problems, and their models can differ depending on the environment and operation strategies.

Dulebenets focused on truck scheduling problems at cross-docking terminals and analyzed different mechanisms in evolutionary algorithms focusing on mutation [16]. As this work showed, the suitable model is only the first part of a successful optimization process because the convergence of the solution algorithms is significantly influenced by the optimization parameters, which is especially important in the case of heuristics and metaheuristics.

The research work of Rostami et al. [17] shows that cross-docking terminals play an important role in multi-level supply chain solutions, where the uncertainties of the environment can lead to the application of stochastic models.

Teophilus et al. [18] showed the most important design aspects of truck scheduling at cross-docking terminals and concluded the importance of terminal shape, doors, door service modes, pre-emption, internal transportation mode used, temporary storage capacity, resource capacity, objectives, and adopted solution algorithms.

Cross-docking terminals are used in a wide range of supply chains for the distribution of products, including cold supply chains for perishable products [7], supermarket supply using split pick-up and delivery operations [10], overseas supply for the automotive industry [19], oilfield services [20], pathology health-care service provider [21], retail or reverse logistics [22].

In today's economy, the sustainability aspects play important role in supply chain solutions, as shown in researches focusing on the following topics: sustainable freight transportation networks with cross-docks [23], sustainable closed-loop supply chain network [24], sustainable truck scheduling in a rail-road Physical Internet cross-docking hub [25] and integrated design (routing and facility locations) in a sustainable supply chain of perishable goods [26].

The consequences of the literature review are the followings:

- The articles that addressed the optimization of cross-docking facility based maintenance strategies are focusing on different cost-related aspects, but only a few of them discusses the potentials of e-vehicles and e-trucks to improve the sustainability and reduce the environmental impact of cross-docking facility-based supply chain solutions.
- A wide range of research articles discuss the optimization of cross-docking facility-based supply chain solutions, but they are generally focused on process optimization, and the impact of the different electricity generation sources is out of scope; therefore, this research topic still needs more attention and research.
- Mathematical models and solution algorithms are essential tools for optimizing cross-docking logistics, which can lead to increased cost-efficiency, availability, flexibility, efficiency, sustainability, and transparency. According to that, the main goal of this research is to propose a novel mathematical model to support the optimization of e-vehicle-based cross-docking solutions.

3. MATERIALS AND METHODS

The energy efficiency-related analysis of different cross-docking supply solutions includes the following main steps:

- Defining the general structure of cross-docking supply solutions,
- Defining the typical system parameters of the general structure of cross-docking supply solutions,
- Defining a suitable mathematical model for the energy efficiency-related evaluation and comparison of different cross-docking supply, defining suitable evaluation functions,
- Energy efficiency-related evaluation of cross-docking supply by comparing different types of solutions focusing on conventional, single-tier, and multi-tier supply using fuel-powered trucks and e-trucks.

Fig. 1 shows the general structure of a multi-tier cross-docking supply including a set of suppliers, a set of TIER1 and TIER2 cross-docking facilities [27], and a set of users or manufacturers.

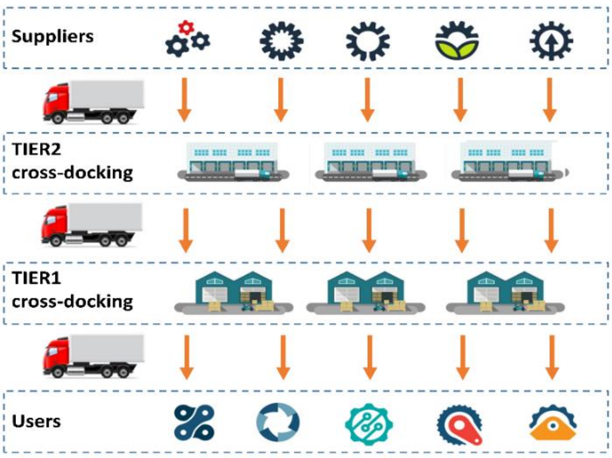

Fig. 1. Structure of a multi-tier supply chain including suppliers, users, and two levels of cross-docking facilities

Tiers are always numbered from the users to the suppliers, the cross-docking facilities closest to the users are TIER1 cross-docking facilities. In the case of direct supply, there is a direct link between suppliers and users; in the case of single-tier cross-docking supply, there is a set of TIER1 cross-docking facilities, while in the case of a multi-tier cross-docking supply, there are two sets of cross-docking facilities (TIER1 and TIER2).

The input parameters of the cross-docking facility-based supply chain can be defined as shown in Table 1.

Table 1. Description of variables

Variable	Description
l_i^{Sx}, l_i^{Sy}	location of supplier *i*, $i = 1...i_{max}$
l_j^{Ux}, l_j^{Uy}	location of user *j*, $j = 1...j_{max}$
$l_{k,z}^{Cx}$, $l_{k,z}^{Cy}$	location of cross-docking facility *z* at TIER *k*, $k = 1...k_{max}$
$d_{j,p}$	demand of user *j* for products *p* in [LU] (loading unit)
a_p	potential supplier of product *p*, $a_p = i$ means, that product *p* is supplied from supplier *I*, $p = 1...p_{max}$
$c_{v,w}$	loading capacity of the truck used in *v*–*w* relation in [LU], where $v, w \in (S, U, C1, C2)$, *S* is for suppliers, *U* is for users, *C1* is for the cross-docking facility at tier 1 and *C2* is for the cross-docking facility at tier 2,
$\sigma_{v,w}$	specific energy consumption of truck used in *v*–*w* relation in [l/100km] in the case of fuel, and in [kWh/100km] in the case of e-truck
$\mu_{v,w,b}$	specific GHG emission of truck used in *v*–*w* relation in [g/l] in the case of conventional fuel-driven trucks or in [g/kWh] in the case of e-trucks.

The evaluation function of the different scenarios is the total energy consumption of the supply chain process within a specific time window. We can define these evaluation functions for the analyzed three scenarios as follows:

- In the case of a conventional supply chain without a cross-docking facility, the material supply from the suppliers to the users is uninterrupted and has relations only among suppliers and users:

$$EC^{M1} = \sum_{j=1}^{j_{max}} \sum_{p=1}^{p_{max}} \left\lceil \frac{d_{j,p}}{c_{S,U}} \right\rceil \cdot d_{a_p,j} \cdot \sigma_{S,U} \cdot \quad (1)$$

- In the case of a single-tier cross-docking facility-based supply chain the users' demands are transported from the suppliers to specific cross-docking facilities at TIER1, and from these TIER1 cross-docking facilities are the demands transported to the users, therefore the evaluation function has two main parts describing the transportation process from the suppliers to cross-docking facilities and from cross-docking facilities the users:

$$EC^{M2} = EC_{S.C1}^{M2} + EC_{C1,U}^{M2} \cdot \quad (2)$$

where

$$EC_{S,C1}^{M2} = \sum_{z1=1}^{z1_{max}} \sum_{j=1}^{j_{max}} \sum_{p=1}^{p_{max}} \left\lceil \frac{d_{j,p} \cdot g_{j,p,1,z}}{c_{S,C1}} \right\rceil \cdot \quad (3)$$
$$\cdot d_{a_p,x_{j,p,1}} \cdot \sigma_{S,C1}$$

$$EC_{C1,U}^{M2} = \sum_{z1=1}^{z1_{max}} \sum_{j=1}^{j_{max}} \left\lceil \sum_{p=1}^{p_{max}} \frac{d_{j,p} \cdot g_{j,p,1,z}}{c_{C1,U}} \right\rceil \cdot \quad (4)$$
$$\cdot d_{x_{j,p,1},j} \cdot \sigma_{C1,U}$$

- In the case of multi-tier cross-docking facility-based supply chain the users' demands are transported from the suppliers to specific cross-docking facilities at TIER1, and from these TIER1 cross-docking facilities are the demands transported to specific TIER2 cross-docking facilities, and from here to the users, therefore the evaluation function has three main parts describing the transportation process from the suppliers to TIER1 cross-docking facilities, from TIER1 cross-docking facilities to TIER2 cross-docking facilities, and from to TIER2 cross-docking facilities to the users:

$$EC^{M3} = EC_{S.C1}^{M3} + EC_{C1,C2}^{M3} + EC_{C2,U}^{M3} \quad (5)$$

where

$$EC_{S,C1}^{M3} = \sum_{z1=1}^{z1_{max}} \sum_{j=1}^{j_{max}} \sum_{p=1}^{p_{max}} \left\lceil \frac{d_{j,p} \cdot g_{j,p,1,z}}{c_{S,C1}} \right\rceil \cdot . \quad (6)$$
$$\cdot d_{a_p,x_{j,p,1}} \cdot \sigma_{S,C1}$$

$$EC_{CD1,CD2}^{M3} =$$
$$\sum_{z1=1}^{z1_{max}} \sum_{z2=1}^{z2_{max}} \left\lceil \sum_{j=1}^{j_{max}} \sum_{p=1}^{p_{max}} \delta_{z1,z2,j,p} \right\rceil \cdot \quad (7)$$
$$\cdot d_{x_{j,p,1},x_{j,p,2}} \cdot \sigma_{C1,C2}$$

$$\delta_{z1,z2,j,p} = \frac{d_{j,p} \cdot g_{j,p,1,z1} \cdot g_{j,p,2,z2}}{c_{C1,C2}} \quad (8)$$

$$EC_{C2,U}^{M3} = \sum_{z2=1}^{z2_{max}} \sum_{j=1}^{j_{max}} \left\lceil \sum_{p=1}^{p_{max}} \frac{d_{j,p} \cdot g_{j,p,2,z2}}{c_{C2,U}} \right\rceil \cdot d_{x_{j,p,2},j} \cdot \sigma_{C2,U} \quad (9)$$

and $g_{j,p,\alpha,z}$ is a binary variable, which defines, that demand p of user j is assigned to cross-docking facility z at tier α: if $x_{j,p,\alpha} = z$ then $x_{j,p,\alpha,z} = 1$, otherwise $x_{j,p,\alpha,z} = 0$ and in this case $\alpha = 1$. In the equations, $\lceil r \rceil$ is the ceiling function, which links *r* to the least integer greater than or equal to *r*.

This research work focuses on the evaluation of the different supply chain solutions, but in the case of an optimisation approach, the evaluation functions can be transformed into objective functions, while decision variables and constraints must also be defined [28]. The decision variables of a multi-tier cross-docking supply are the following:

- a_p is the assignment vector of products and suppliers, where $a_p = i$ defines that product p is assigned to supplier i,
- $x_{j,p,\alpha}$ is the assignment hypermatrix of demands, users, and cross-docking facilities, where $x_{j,p,\alpha} = z$ defines that demand *p* of user *j* at cross-docking tier α is assigned to cross-docking facility z.

Within the frame of this article, the decision mentioned above variables are assumed to be known, which means that we are talking about evaluation and not optimization. In the chapter, the proposed evaluation framework will be analyzed using a numerical analysis of a scenario.

4. RESULTS AND DISCUSSION

This chapter aims to demonstrate the efficiency of multi-level cross-docking solutions. For this analysis, the above-described methodology is used to illustrate the advantages of multi-tier cross-docking supply from an energy efficiency point of view and show the impact of e-trucks on energy efficiency and greenhouse gas emission. The analysis focuses on the following three models: (1) conventional supply chain without cross-docking facility (direct supply), (2) single-tier cross-docking supply (indirect supply), and (3) multi-tier cross-docking supply (indirect supply). The input parameters of the models are the following:

- The layout of the supply chain with the location of 10 suppliers, 10 users, and 1 cross-docking facility per tier.
- Users' demand for 20 different products in [LU].
- Parameters of available vehicles for each level of the supply chain (capacity in [LU], fuel consumption for fuel-driven trucks in [l/100km] and energy consumption for e-trucks in [kWh/100km]).
- Optimal assignment of users' demands to suppliers, and in the case of cross-docking supply to cross-docking facilities.
- Specific GHG emission of trucks in [g/l] in the case of conventional fuel-driven trucks or in [g/kWh] in the case of e-trucks.

Based on the numerical analysis of the scenarios, the following can be concluded:

- The application of cross-docking facilities can lead to a decreased number of required trucks because cross-docking supply makes it possible to increase the capacity utilization of trucks through batch transportation of users' demands.
- In the case of indirect supply using cross-docking facilities, although transportation distances per product increase, the total transportation distance decreases significantly due to the increase in vehicles' utilization. The reduction of the total delivery distance compared to conventional direct supply without cross-docking is 71% for single-tier cross-docking supply and 73% for multi-tier cross-docking supply.
- The application of e-trucks can lead to significant environmental impact because the greenhouse gas emission has significantly decreased, depending on the source of electricity generation source.
- In the case of e-trucks, the emission reduction can be calculated as a virtual emission because e-trucks have no emission. Still, electricity production has measurable greenhouse gas emission, depending on the electricity generation source (fuel, lignite, coal, oil, natural gas, photovoltaic, biomass, nuclear, water, wind).
- The electricity generation source significantly influences the virtual GHG emission. As the scenario analysis of the multi-tier cross-docking facility-based supply chain shows, the CO_2 emission reduction is between 40% and 99% depending on the electricity generation source. In the case of lignite-based electricity generation, it is possible to save 11443 kg of CO_2 emission compared to fuel-based transportation. The wind-based electricity generation leads to a CO_2 emission reduction of 18912 kg compared to fuel-based supply (see

Fig. 2). The proposed methodology makes it possible to analyze the impact of different energy mixes (for example, natural gas – photovoltaic sources). This analysis has practical importance because electricity generation is based in practical cases on more sources, therefore, the energy mix-related approach is important to analyze the environmental impact of e-truck-based supply chain solutions.

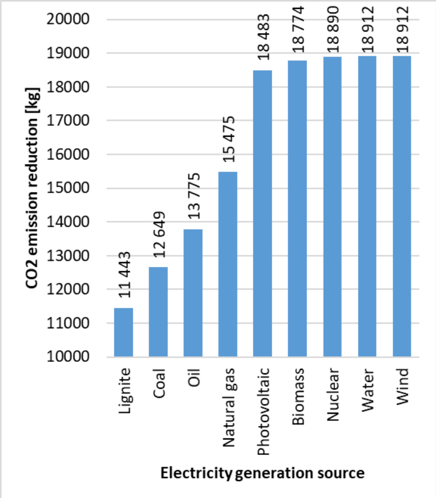

Fig. 2. Impact of electricity generation source on CO_2 emission reduction in the case of multi-tier cross-docking supply

- The logistics resources are important influencing factors because their increasing performance indicators can lead to more efficient and green supply chain solutions. Fig. 3 shows an example of this impact. Based on the analysis of the impact of the maximum loading capacity of e-trucks and the layout of the supply chain, it can be concluded that higher capacity e-trucks lead to lower CO_2 emission, while the average distance of users and the TIER 1 cross-docking terminals are also a significant influencing factor of GHG emission parameters.

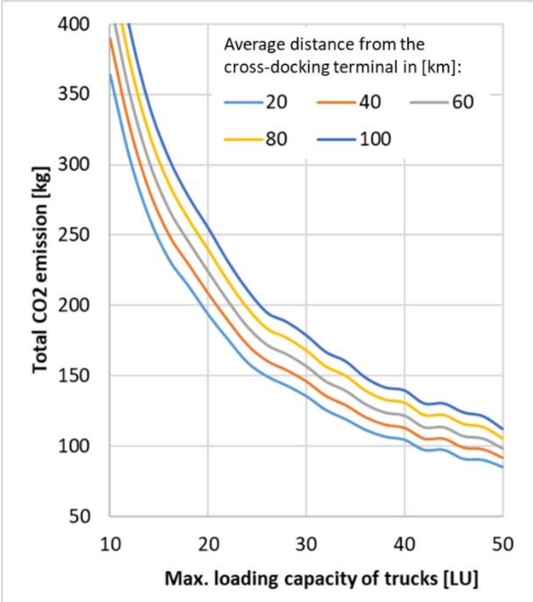

Fig. 3. Impact of e-truck capacity and average distance of users and TIER 1 cross-docking terminals on virtual CO_2 emission in the case of multi-tier cross-docking supply

The numerical results of the analysis of the three scenarios comparing distances, fuel/energy consumptions, and GHG emission parameters in the case of direct and indirect supply solutions with and without cross-docking terminals are shown in Table 2.

Table 2. Results of the comparison of the different scenarios

Parameters	Model 1		Model 2		Model 3	
	fuel	e-truck	fuel	e-truck	fuel	e-truck
total length of route [km]	26486		7701		7265	
fuel consumption [l]	9270	-	2695	-	2543	-
energy consumption [kWh]	-	66215	-	19253	-	18164
required trucks [pcs]	98		44		66	
CO_2 emission [kg]	69631	13216	20247	3843	19101	3625
SO emission [kg]	2.12	0.42	0.62	0.12	0.58	0.12
CO emission [kg]	58.27	11.07	16.94	3.22	15.98	3.04
HC emission [kg]	31.78	6.04	9.24	1.76	8.72	1.66
NO emission [kg]	315.18	58.96	91.65	17.14	86.46	16.17
PM emission [kg]	2.65	0.50	0.77	0.15	0.73	0.14

As Table 2 highlights, the indirect multi-tier cross-docking supply led to shorter transportation routes (27% of direct supply), while the fuel consumption of conventional trucks and energy consumption of e-trucks also significantly decreased. The emission rate was also decreased.

5. CONCLUSION

Cross-docking offers an opportunity for energy-efficient and environmentally friendly design of complex supply chain processes, which can give supply chain members a significant market advantage. The study carried out in this research work shows that, compared to conventional supply chains, cross-docking supply can significantly reduce the number of transportation resources required and increase energy efficiency through better capacity utilization. In the case of long-distance partners and partner networks, multi-tier cross-docking supply is particularly beneficial. Using e-trucks can further increase the energy efficiency of the supply chain and further reduce the environmental impact, especially if electricity is generated from "greener" sources.

The optimization of this challenging decision problem can be solved using advanced optimization algorithms in the future. Research works focusing on the design and control of logistics and supply chain solutions also applied a wide range of applied optimization algorithms, and these applications significantly highlight the effectiveness of these methods, as discussed in the case of a self-adaptive fast fireworks algorithm for effective large-scale optimization [29], metaheuristic algorithm for the vehicle routing problem with a factory-in-a-box in multi-objective settings [30], diffused memetic optimization for reactive berth allocation and scheduling at marine container terminals [31] or ant-based pheromone spaces for generation constructive hyper-heuristics [32].

The practical significance of this research is that the results of the theoretical analysis presented here can be used to provide concrete data to support strategic decisions on the design of a supply chain. A possible further direction of research could be the development of models and methods that consider environmental uncertainties.

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