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Green last-mile route planning for efficient e-commerce distribution

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ABSTRACT

This study aims to design vehicle routes based on cost minimisation and the minimisation of greenhouse gasses (GHG) emissions to help companies solve the vehicle routing problem with pickup and delivery (VRPPD) via particle swarm optimisation (PSO). An effective metaheuristics search technique called particle swarm optimisation (PSO) was applied to design the optimal route for these problems. Simulated data from Li and Lim (2001) were used to evaluate the PSO performance for solving green vehicle routing problems with pickup and delivery (Green VRPPD). The findings suggest that green vehicle routing problems with pickup and delivery should be used when distributing products to customers living in a specific area called a cluster. However, the design of vehicle routes by Green VRPPD costs more when used to distribute products to customers living randomly in a coverage service area. When logistics providers decide to use Green VRPPD instead of VRPPD, they need to be concerned about possible higher costs if an increase in the number of vehicles is needed. PSO has been confirmed for solving VRPPD effectively. The study compared the results based on the use of two different objective functions with fuel consumption from diesel and liquefied petroleum gas (LPG). It indicates that solving VRPPD by considering the emissions of direct greenhouse gases as an objective function provides cleaner routes, rather than considering total cost as the objective function for all test cases. However, as Green VRPPD requires more vehicles and longer travel distances, this requires a greater total cost than considering the total cost as the objective function. Considering the types of fuels used, it is obvious that LPG is more environmentally friendly than diesel by up to 53.61 %. This paper should be of interest to a broad readership, including those concerned with vehicle routing problems, transportation, logistics, and environmental management. The findings suggest that green vehicle routing problems with pickup and delivery should be used when distributing products to a cluster. However, the design of vehicle routes by Green VRPPD costs more when used to distribute products to customers living randomly in a coverage service area. When logistics providers decide to use Green VRPPD instead of VRPPD, they need to be concerned about possible higher costs if an increase in the number of vehicles is needed.

KEY WORDS

last-mile, routing, green, particle swarm optimisation, e-commerce

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Introduction

Environmental concerns are a serious issue in most developed countries. Transportation is one of the primary sources of GHG emissions. The Inventory of US Greenhouse Gas Emissions and Sinks under the United Nations Framework Convention on Climate Change (UNFCCC) is issued annually. According to Greenhouse Gas Emissions and Sinks 1990–2017 (EPA 2019), light-duty vehicles were the largest category source of GHG emissions in the

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transportation sector, followed by medium-duty and heavy-duty trucks with about 59 % and 23 %, respectively. The GHG emissions created by the transportation sector include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These emissions result from fossil fuel combustion.

In the last decade, the e-commerce business growth rate has increased significantly in most parts of the world. Online retail markets have changed rapidly. The US was the largest e-commerce market in the world before it was overtaken by China in 2013. In today's fiercely competitive business environment, online sellers need to adapt to outperform their business competitors. The literature on e-commerce generally considers issues addressing the interrelations between e-commerce companies and logistics providers, investigating solutions and measures in the e-commerce environment, and evolutionary applications in solving e-commerce problems (Zhang et al., 2020; Tsang et al., 2021; Mutinda Kitukutha, Vasa & Oláh, 2021; Al-Tit, 2020; Federko et al., 2018; Florek-Paszkowska, Ujwary-Gil & Godlewska-Dzioboń, 2021; Gulc, 2021). E-commerce for logistics service providers has faced the challenge of delivery service reliability that can serve the customised requirements of larger e-commerce enterprises while maintaining low-cost operations (Yu et al., 2020). Liu, Zhang, Chen, Zhou, and Miao (2018) suggested that logistics initiatives are among the main factors e-commerce businesses can use to leverage operational performance. Logistics initiatives have accelerated the speed with which order volumes move both up and down the supply chain. Numerous researchers have focused on topics related to online shopping behaviour (Fu et al., 2019; Rita et al., 2019; Zhou et al., 2020), customer experiences (Lemke, 2016; Yuen et al., 2019; Chen & Yang, 2021), online marketing (Gregory, 2017), the design of smart locker banks (Faugère & Montreuil, 2018), and last-mile delivery (Vakulenko et al., 2019; van Lopik et al., 2020; Qin et al., 2021). Researchers have focused on these topics because good products and efficient services are essential factors driving demand and, therefore, boosting revenue in e-commerce businesses. E-commerce businesses generate revenue for online businesses and also create opportunities for other service businesses in the supply chain. One type of supply chain business is known as a last-mile delivery service. The Capgemini Research Institute (2018) reported that 74 % of satisfied customers intended to increase their spending by 12 % with preferred retailers that provide great last-mile delivery service.

The purpose of a last-mile delivery service is to deliver products to customers as fast as possible. Therefore, various technologies have been developed to enhance the efficiency of last-mile delivery services. Examples of such technologies include drones, autonomous vehicles, delivery by car, and self-service lockers or smart lockers. The use of such varied technologies implies that last-mile delivery has become another key customer expectation in this era. However, last-mile delivery also impacts the environment due to increased GHG emissions.

Although many researchers have published studies on the concept of last-mile delivery, the optimal green route design for last-mile delivery has not been addressed. The last-mile delivery concept coupled with green route optimisation can transform ordinary last-mile delivery to be a much more efficient delivery method. The main idea of green route optimisation is to minimise total GHG emissions, delivery cost, and delivery time by considering several factors, such as the location of the depot and customers, the vehicles' capacity and number.

Subsequently, this study aims to propose an optimisation search technique called particle swarm optimisation (PSO) that can be used to design optimal green routes for the delivery of products to online shoppers. The remainder of this paper is organised into four sections. Theory and experimental research are presented in Section 2. This section describes a PSO algorithm used to solve green vehicle routing problems with pickup and delivery. Computational results and discussion are presented in Sections 3 and 4, respectively. Lastly, conclusions and future research recommendations are discussed in Section 5.

1. Literature review

The vehicle routing problem (VRP) is a generalisation of the travelling salesperson problem (TSP). The VRP is considered a combinatorial optimisation and integer programming problem. It is an NP-hard problem that is time-consuming when solved using exact algorithms, such as branch and price, branch and cut, and branch price and cut methods (Yu et al., 2019). However, such problems could be solved using metaheuristics approaches. Simulated annealing (SA) and genetic algorithm (GA) were applied to green vehicle routing with a heterogeneous fleet, including reverse logistics in the form of collecting returned goods. The experimental results showed that the proposed algorithms were able to find the near-opti-

mal solutions for large instances. SA achieved relatively better results in terms of solution quality, while GA spent less computational time for all-sized test problems (Foroutan et al., 2020). A hybrid genetic algorithm (GA) was successfully developed to determine multi depot capacitated vehicle routing problem with split delivery and vehicle selection (Mehlawat et al., 2019). A hybrid genetic algorithm with variable neighbourhood search was developed to solve the problem multi-depot vehicle routing problem under the time-varying road network. It was found that the Hybrid genetic algorithm was effective for solving VRP (Fan et al., 2021).

The green vehicle routing problem with pickup and delivery is an extended version of the vehicle routing problem with a time window (VRPTW). Vehicle routes are commonly designed to visit each location on the route that requires pickups and deliveries, and the addition of this requirement transforms the VRPTW problem into the vehicle routing problem with pickup and delivery. Practical applications of VRPPD include postal deliveries, school bus routing, and urban newspaper distribution (Créput et al., 2004; Gupta et al., 2021). VRPPD can also include the problem of on-demand delivery service where customers pick up a product at a specific location (e.g., a convenience store or smart locker). A solution to the VRPPD problem involves designing a set of routes by minimising total routing cost while meeting the following requirements:

- Each route starts and ends at the depot.
- A pickup, and its corresponding delivery customer, is visited by exactly one vehicle.
- The total demand of any vehicle route does not exceed the capacity of the vehicle assigned to the route.
- The total duration of any route does not exceed the pre-set route duration bound.
- Time windows specified by the customer are satisfied.

PSO is one of the most famous optimisation search techniques for solving NP hard problems. PSO was inspired by the social behaviour of animals, such as bird flocking and fish schooling (Shi and Eberhart, 1998). Numerous researchers have successfully adopted PSO to solve the VRPs (Belmecheri et al., 2013; Goksal et al., 2013; Chen et al., 2016; Norouzi et al., 2017; Lagos et al., 2018; Zhu et al., 2019; Harbaoui Dridi et al., 2020; Bansal & Wadhawan, 2021).

The concept is to determine the solution by letting each particle search for the solution randomly. The solution of each particle is then compared with its own neighbour. The velocity and position of each particle is then updated according to its own best experience and the global best experience to reach the best solution.

The PSO algorithm consists of the following steps:

- The PSO algorithm starts by initialising an array of particles with random position and velocities on d dimensions.
- Initialise the inertia weight.
- Evaluate the objective function. [The objective function is to determine vehicle routing problems with pickup and delivery requests by minimising the emissions of greenhouse gases including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) in d variables.]
- Compare the particle's fitness evaluation with the particle's pbest (previous best). If the current value is better than pbest, then set the pbest value equal to the current value and set the pbest location equal to the current location in d-dimension space.
- Compare the fitness evaluation with the population's overall previous best. If the current value is better than gbest (global best) then set gbest to the current particle's array index and value.
- Adjust the velocity and position of the particle according to Equations (20) and (21), respectively.
- Loop back to step 2 until a stopping criterion is met. A stopping criterion is usually a sufficiently good fitness or a maximum number of iterations (generation).

2. Research methods

The following section presents a mathematical model for VRPPD, including the input parameters and variables used in the model.

Input parameters consist of the set of pickup nodes and delivery nodes. These nodes are defined as $P = \{1, \dots, n\}, D = \{n+1, \dots, 2n\}$, respectively, where n is the number of requests.

H_i represents the penalty cost when request i is not served.

$i \in P, K$ represents the set of all vehicles $|K| = m$.

C_k denotes the capacity of the vehicle $k, k \in K$.

f_k is the fixed cost of the vehicle $k, k \in K$ if it is used.

τ_k is the start node of the vehicle $k, k \in K$.

τ'_k is the end node of the vehicle $k, k \in K$.

All nodes are set as $V = N \cup \{\tau_1, \dots \tau_m\} \cup \{\tau'_1, \dots \tau'_m\}$. A denotes the set of arcs from node i to node $j(i,j)\ i,j \in V$. While $d_{ij}$is the nonnegative distance from node i to node $j, i, j \in N$, t_{ij}represents the nonnegative travel time from node i to node $j, i, j \in N$. In cases where travel time is included, the travel time must satisfy the triangle inequality where $t_{ij} \leq t_{il} + t_{lj}$ for all $i.j.l \in V$. S_i is service time spent for loading and unloading vehicles at node i. The time windows are represented by $[a, b]$ for node i, and a visit to node i can only occur in this time interval. The quantity of goods loaded onto a vehicle at node i is represented as q_i when $i \in P$ and $q_i = -q_{i-n}$ for $i \in D$. Lastly, an emissions factor for each GHG is represented as ε where ε_{CO_2} denotes the emissions factor for CO_2, ε_{CH_4} represents the emissions factor for CH_4, and ε_{N_2O} refers to the emissions factor for N_2O.

Decision variables are explained below.

$x_{ijk} = \{1\ if\ edge\ between\ node\ i\ and\ j\ is\ used\ by\ vehicle\ k;\ 0\ otherwise.$

$S_{ik}$is a nonnegative integer that represents the service start time of the vehicle k at the location $i \in V, k \in K$.

$Q_{ik}$is a nonnegative integer that represents the upper bound on the amount of goods on the vehicle k after servicing node i where $i \in V, k \in K$.

$z_i = \{1\ if\ the\ request\ is\ placed\ in\ the\ request\ bank;\ 0\ otherwise, i \in P.$

According to the assumptions above, green VRPPDP can be explained with a mathematical model as follows:

Minimise

$$\alpha \sum_{k \epsilon K} \sum_{(i,j)} d_{ij} x_{ijk} (\varepsilon_{CO_2} + \varepsilon_{CH_4} + \varepsilon_{N_2O}) \quad (1)$$

Subject to

$$\sum_{k \in K} \sum_{j \in N_k} x_{ijk} + z_i = 1 \forall i \in P \quad (2)$$

$$\sum_{j \in V} x_{ijk} - \sum_{j \in V} x_{j\,n+i\,k} = 0 \forall i \in K, \forall i \in P \quad (3)$$

$$\sum_{j \in P \cup \{\tau'_k\}} x_{\tau_k jk} = 1 \forall k \in K \quad (4)$$

$$\sum_{i \in D \cup \{\tau_k\}} x_{i\tau'_k k} = 1 \forall k \in K \quad (5)$$

$$\sum_{i \in V} x_{ijk} - \sum_{i \in V} x_{jik} = 0 \forall k \in K, \forall j \in N \quad (6)$$

$$x_{ijk} = 1 \Rightarrow S_{ik} + s_i + t_{ij} \leq S_{jk} \forall k \in K, \forall (i,j) \in A \quad (7)$$

$$a_i \leq S_{ik} \leq b_i \forall k \in K, \forall j \in V \quad (8)$$

$$S_{ik} \leq S_{n+i\,k} \forall k \in K, \forall j \in V \quad (9)$$

$$x_{ijk} = 1 \Rightarrow Q_{ik} + q_i \leq Q_{jk} \forall k \in K, \forall (i,j) \in A \quad (10)$$

$$Q_{ik} \leq C_k \forall k \in K, \forall i \in V \quad (11)$$

$$Q_{\tau_k k} = Q_{\tau'_k k} = 0 \forall k \in K \quad (12)$$

$$x_{ijk} \in \{0,1\} \forall k \in K, \forall (i,j) \in A \quad (13)$$

$$z_i \in \{0,1\} \forall k \in P \quad (14)$$

$$S_{ik} \geq 0 \forall k \in K, \forall i \in V \quad (15)$$

$$Q_{ik} \geq 0 \forall k \in K, \forall i \in V \quad (16)$$

The goal of green VRPPD is to design a vehicle route by minimising three GHG emissions (CO_2, CH_4, and N_2O) from the transportation vehicle, as presented in Equation (1). This minimisation ensures that the pickup and delivery orders are performed by the same vehicle, and the orders are implemented in Equations (2) and (3). The confirmations for the conditions that each vehicle departs from its starting terminal and stops at its ending terminal are performed in Equations (4) and (5). Equation (6) ensures that consecutive paths between τ_k and τ'_k are used for each vehicle. Equations (7) and (8) guarantee that S_{ik} is set correctly along the paths within a particular time window. Further, these two equations are used to make sure that sub-tours will not be generated. Equation (9) ensures that each pickup takes place before the corresponding delivery. Equations (10) to (12) confirm that load variability is precisely set along the path and confirm the use of vehicle capacity constraints. Lastly, the nature of the decision variables is set up in Equations (13) to (16).

Various researchers have studied the alternative fuel for Green VRP by considering the GHG emission (Xu et al., 2019; Bruglieri et al., 2019; Sruthi et al., 2019). GHG emissions are calculated by multiplying fuel consumption by the emissions factor of GHG for each fuel type. The distance travelled is one of the most significant influencing factors for calculating GHG emissions. Consequently, GHG emissions are calculated by multiplying the travel distance by a distance-based emissions factor. The emissions factor for CO_2 relies on several factors such as fuel heat content, fraction of oxidised carbon in the fuel, and the carbon content coefficient, which is somewhat difficult to obtain. Therefore, only vehicle travel distance (distance-based approach) is applied for calculating GHG emissions in this study. The calculations of GHG emissions are divided into two main processes. In the beginning, data is collected for travel distance, in terms of freight distance (e.g., ton-

Tab. 1. Approximation of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions factors for a 10-ton capacity truck

STATE OF VEHICLE	WEIGHT LADEN (%)	FUEL CONSUMPTION (LITRE/100 KM)	CO_2 FUEL CONVERSION FACTOR FOR DIESEL (KG CO_2/ LITRE)	CO_2 FUEL CONVERSION FACTOR FOR LPG (KG CO_2/ LITRE)	CH_4 FUEL CONVERSION FACTOR FOR DIESEL (KG CH_4/ LITRE)	CH_4 FUEL CONVERSION FACTOR FOR LPG (KG CH_4/ LITRE)	N_2O FUEL CONVERSION FACTOR FOR DIESEL (KG N_2O/ LITRE)	N_2O FUEL CONVERSION FACTOR FOR LPG (KG N_2O/ LITRE)	CO_2 EMISSIONS FACTOR FOR DIESEL (KG CO_2/KM)	CO_2 EMISSIONS FACTOR FOR LPG (KG CO_2/KM)	CH_4EMISSIONS FACTOR FOR DIESEL (KG CH_4/KM)	CH_4 EMISSIONS FACTOR FOR LPG (KG CH_4/KM)	N_2O EMISSIONS FACTOR FOR DIESEL (KG N_2O/KM)	N_2O EMISSIONS FACTOR FOR LPG (KG N_2O/KM)
Empty	0	29.6	2.6569	1.5301	0.0009	0.0007	0.0191	0.0018	0.786442	0.45291	0.000266	0.000207	0.005654	0.000533
Low Load	25	32							0.850208	0.489632	0.000288	0.000224	0.006112	0.000576
Half Load	50	34.4							0.913974	0.526354	0.00031	0.000241	0.00657	0.000619
High Load	75	36.7							0.975082	0.561547	0.00033	0.000257	0.00701	0.000661
Full Load	100	39							1.036191	0.596739	0.000351	0.000273	0.007449	0.000702

mile), for different vehicle types, sizes, and types of fuel used. The approximated freight distance is then converted into GHG emissions. The GHG emissions are determined by multiplying the freight distance by a distance-based emissions factor, as explained in the equations below:

$$CO_2\ Emissions = Distance\ Travelled \times \times\ Emissions\ Factor\ for CO_2 \quad (17)$$

$$CH_4\ Emissions = Distance\ Travelled \times \times\ Emissions\ Factor\ of\ CH_4 \quad (18)$$

$$N_2O\ Emissions = Distance\ Travelled \times \times\ Emissions\ Factor\ of\ N_2O \quad (19)$$

The energy consumption (in litres/100 km) is approximated according to Ubeda et al. (2014). However, the fuel conversion factor for diesel and LPG ($kgCO_2$/litre) is obtained from DEFRA (2013). The approximation of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions factors for diesel and LPG are presented in Table 1.

2.1. The particle swarm optimisation (PSO) algorithm for green VRPPD

The PSO algorithm is initialised with random position, velocity, and inertia weight. The velocity is constantly adjusted according to the particle's experience, and its group's experience, to move towards the better solution, as described in the following equations:

$$v_{id} = w^*v_{id} + C_1 rand(\,)^*(p_{id}-x_{id}) + C_2 rand(\,)^*(p_{gd}-x_{id}) \quad (20)$$

$$x_{id} = x_{id} + v_{id}^*\Delta t \quad (21)$$

where

v_{id} is the velocity of the i^{th} particle in the d^{th} dimension.

w is the inertia weight.

p_{id} is the best previous position (the position giving the particle's best fitness value) of the i^{th} particle in the d^{th} dimension.

p_{gd} is the best previous position (the position giving the swarm's best fitness value) of the i^{th} particle in the d^{th} dimension.

x_{id} is the position of the i^{th} particle in the d^{th} dimension.

C_1, C_2 is equal to 2.

$rand(\,)$ is a uniform random number generated within (0,1).

As shown in Equation (21), the velocity of the i^{th} particle in the d^{th} dimension consists of three terms. The first term is the momentum of the part of the particle. The inertia weight (w) represents the degree of the momentum of the particle's previous velocity. It is a control parameter used to control the influence of the previous velocity on the current velocity of the particle. A larger inertia weight would pressure the movement of particles towards global exploration (searching for a new area) because the particle can fly in large areas. In contrast, a smaller inertia weight would move the particle in a smaller search area. The suitable selection of the inertia weight should provide a balance between the global and local search areas.

The computation of PSO depends on population size, inertia weight, maximum velocity, maximum and minimum positions and a maximum number of iterations. The initial population size was chosen so that it was large enough to cover the search space

within the iteration limit based on the trial runs and literature. The population size of 50 was then selected. The maximum number of iterations and other parameters were also initialised by using the same rationales. They should ensure that the search spaces are never violated and the solutions obtained are always valid. The same parameter settings were used for all datasets.

In this experiment, the performance of PSO for solving Green VRPPD based on a different value of inertia weight with the range from 0.1 to 0.9 and the inertia weight started from 0.9 and gradually decreased to 0.4 to balance the global and local exploration based on a linear function of time (iteration) for improving convergence rate (Kennedy, 1997) were tested and compared. It was found that when inertia weight is set to be a large value, it is difficult for particles to perform global exploration during the beginning of the search process. Then, the inertia weight value is gradually decreased so that the good region found can be found by the search process to provide the best searching performance.

The second term in Equation (21) is called the "cognition part" because the distance between the particle's previous best and current position $(p_{id}\text{-}x_{id})$ would provide a path for the particle to return to its best value achieved so far. The third term in Equation (21) is called the "social part" because the difference between the swarm's previous best and current position $(p_{gd}\text{-}x_{id})$ provides a path for the swarm to return to their best value.

C_1 and C_2 are positive constants called "acceleration coefficients". They are used to determine the relative "pull" of *gbest* and *pbest*. The higher the constant, the greater the acceleration toward the position it is multiplying. In this case, C_1 and C_2 are set to 2 for all PSO runs to balance the impact of its own trajectory with its neighbours' trajectory.

Also, *rand( )* is a random number uniformly distributed within the range (0,1). *rand( )* makes the system less predictable and more flexible so that each particle is stochastically accelerated towards its own previous position and the global best position.

Furthermore, v_{id} is limited to keep the computer from overflowing. This limit makes it more realistic to simulate the incremental changes of human learning and attitude change. The limit also determines the search of the problem space. Next, v_{id} is set to be within the boundary of $[-v_{max}, v_{max}]$ so that the search space of each particle is limited, and the particle cannot move out of this range. If v_{id} is greater than v_{max} , then set v_{id} equal to v_{max}. But, if v_{id} is less than $-v_{max}$, then set v_{id} equal to $-v_{max}$. The v_{max} parameter is important because it determines the resolution with which the regions around the current solutions are searched. If v_{max} is too high, then the PSO facilitates a global search, which means that particles might fly past good solutions. However, if v_{max} is too small, then the PSO facilitates a local search, which means that particles may not explore beyond locally good regions. In case of maximum and minimum positions of the variables in each dimension, they were chosen to represent the suitable search space, which is problem dependence.

The positions of particles in the equation are updated based on their movement over a discrete-time interval (Δt), with Δt usually set to 1 as depicted in Equation (21).

3. Research results

The experiment was conducted by using simulated data from Li and Lim (2001). One hundred task instances were used as a benchmark to evaluate the performance of the PSO for solving green vehicle routing problems with pickup and delivery. Each task is either for a pickup or a delivery. Four different types of datasets (LC1, LC2, LR1, LR2) were used to test the proposed model. The first set of problem instances (LC problems) represent customers located in clusters that are distributed in the coverage service area. This kind of distribution is similar to customers located in a town or in a city. Numerous people stay in certain areas forming clusters. The second set of problem instances (RC problems) represents customer locations that are randomly distributed in the coverage service area. This kind of distribution is similar to customers that live in rural areas. The LC1 and LR1 problems have a long scheduling horizon, while LC2 and LR2 problems have a shorter scheduling horizon. Next, the PSO parameter settings of the experiment are explained. The acceleration coefficients (C1 and C2) were equally set at 2 to balance the impacts of exploratory and exploitative learning experiences. The inertia weight (w) was set to linearly decrease from 0.9 to 0.4. This decrease allowed the particles to perform global searches at the beginning of the search and then gradually decrease the scope of the search space to the good region. The population size and the maximum number of iterations were set at 50 and 500, respectively. These parameter settings

Tab. 2. Comparison of results from two different objective functions for the cluster-distributed customer dataset

Instance	Minimising cost		Minimising GHG emissions		Distance increase (%)
	Distance	NV	Distance	NV	
LC101	828.94	10	989.91	12	19.42
LC102	828.94	10	828.94	10	0
LC103	827.86	10	827.86	10	0
LC104	861.95	9	903.85	9	4.86
LC105	828.94	10	828.94	10	0
LC106	828.94	10	828.94	10	0
LC107	828.94	10	828.94	10	0
LC108	827.61	10	827.61	10	0
LC109	827.82	10	827.82	10	0
LC201	591.56	3	591.56	3	0
LC202	591.56	3	591.56	3	0
LC203	591.17	3	591.17	3	0
LC204	590.60	3	590.60	3	0
LC205	588.88	3	588.88	3	0
LC206	588.29	3	588.49	3	0.04
LC207	588.29	3	588.29	3	0
LC208	588.32	3	588.32	3	0
				Average	**1.43**

Tab. 3. Comparison of results from two different objective functions for the randomly distributed customer dataset

Instance	Minimising cost		Minimising GHG emissions		Distance increase (%)
	Distance	NV	Distance	NV	
LR101	1543.38	17	1650.80	19	6.96
LR102	1361.93	13	1555.64	17	14.22
LR103	1071.23	10	1329.99	13	24.16
LR104	1013.99	9	1080.51	10	6.56
LR105	1295.14	12	1393.35	14	7.58
LR106	1221.29	12	1293.30	12	5.90
LR107	1174.83	11	1257.08	12	7.00
LR108	1085.18	10	1204.41	11	10.99
LR109	1263.96	12	1563.00	13	23.66
LR110	1135.66	10	1224.67	12	7.84
LR111	1156.54	11	1179.63	11	2.00
LR112	1151.38	11	1159.13	11	0.67
LR201	1266.25	4	1266.57	4	0.03
LR202	1162.40	4	1316.46	4	13.25
LR203	934.53	3	1153.83	3	23.47
LR204	912.40	2	1025.59	3	12.41
LR205	1118.70	3	1248.82	4	11.63
				Average	**10.49**

were set based on trial-and-error methods. The algorithms were coded using the C# version of Visual Studio 2019. The comparison of the results based on cost minimisation and GHG emissions minimisation for the LC and LR problems are presented in Tables 2 and 3, respectively.

Table 2 presents the results of the PSO for designing vehicle routes from 17 benchmark instances where customers are cluster-distributed. The PSO was applied to design vehicle routes by considering the minimum total cost as the objective function (VRPPD). The PSO was then applied to design the optimal route by considering the minimum GHG emissions as the objective function (Green VRPPD). The results from the two different objective functions were compared using the per cent increase of distance. The reason is that the travel distance is directly proportional to the total cost. The results reveal that designing the vehicle routes by using VRPPD and Green VRPPD are comparable when customers are

cluster-distributed. The number of vehicles used for delivering products to customers using VRPPD or Green VRPPD is the same in most cases. However, the percentage difference of benchmark instance LC101 is 19.42, which is quite high when compared to two other benchmark instances: LC104 and LC206. On average, the Green VRPPD requires a travel distance that is 1.43% greater than that of VRPPD. It is suggested that Green VRPPD should be used for designing vehicle routes in the last mile of delivery when customers' locations are cluster-distributed.

Vehicle routes were designed by the PSO using 17 benchmark instances for problems where customers are randomly distributed. In this case, the location of customers is randomly dispersed around the service area. The experimental results in Table 3 show that vehicle route planning based on minimising GHG emissions requires a greater number of vehicles and greater travel distances than route planning based on minimum total cost as the objective function in most cases.

These results reveal that Green VRPPD requires travel distances that are 10.49% greater than those required by VRPPD on average. Furthermore, 11 out of 17 cases require a greater number of vehicles to deliver products to customers. Tables 4 and 5 presents the comparison of the results from the best-known solution and PSO for the cluster-distributed customer dataset and randomly distributed customer dataset, respectively. It found that the results from PSO are comparable to the best-known solution for LC1, LC2, and RC1. However, the results of PSO for solving RC2 problems are not as good as the best-known solution.

Tab. 4. Comparison of results from the best-known solution and the results from PSO for the cluster-distributed customer dataset

Instance	Minimising cost		Best-known solution		References	Deviation of distance (%)
	Distance	NV	Distance	NV		
LC101	828.94	10	828.94	10	Li & Lim (2001)	0.00
LC102	828.94	10	828.94	10	Li & Lim (2001)	0.00
LC103	827.86	10	1035.35	9	Bent & Van Hentenryck (2003)	-20.04
LC104	861.95	9	860.01	9	Hasle & Kloster (2007)	0.23
LC105	828.94	10	828.94	10	Li & Lim (2001)	0.00
LC106	828.94	10	828.94	10	Li & Lim (2001)	0.00
LC107	828.94	10	828.94	10	Li & Lim (2001)	0.00
LC108	827.61	10	826.44	10	Li & Lim (2001)	0.14
LC109	827.82	10	1000.6	9	Bent & Van Hentenryck (2003)	-17.27
LC201	591.56	3	591.56	3	Li & Lim (2001)	0.00
LC202	591.56	3	591.56	3	Li & Lim (2001)	0.00
LC203	591.17	3	591.17	3	Bent & Van Hentenryck (2003)	0.00
LC204	590.6	3	590.6	3	Bent & Van Hentenryck (2003)	0.00
LC205	588.88	3	588.88	3	Li & Lim (2001)	0.00
LC206	588.29	3	588.49	3	Li & Lim (2001)	-0.03
LC207	588.29	3	588.29	3	Li & Lim (2001)	0.00
LC208	588.32	3	588.32	3	Li & Lim (2001)	0.00

Tab. 5. Comparison of results from best-known solution and the results from PSO for the randomly distributed customer dataset

Instance	Minimising cost		Best-known solution		References	Deviation of distance (%)
	Distance	NV	Distance	NV		
LR101	1543.38	17	1650.8	19	Li & Lim (2001)	-6.51
LR102	1361.93	13	1487.57	17	Li & Lim (2001)	-8.45
LR103	1071.23	10	1292.68	13	Li & Lim (2001)	-17.13
LR104	1013.99	9	1013.39	9	Li & Lim (2001)	0.06
LR105	1295.14	12	1377.11	14	Li & Lim (2001)	-5.95
LR106	1221.29	12	1252.62	12	Li & Lim (2001)	-2.50
LR107	1174.83	11	1111.31	10	Li & Lim (2001)	5.72
LR108	1085.18	10	968.97	9	Li & Lim (2001)	11.99
LR109	1263.96	12	1208.96	11	Hasle & Kloster (2007)	4.55
LR110	1135.66	10	1159.35	10	Li & Lim (2001)	-2.04
LR111	1156.54	11	1108.9	10	Li & Lim (2001)	4.30
LR112	1151.38	11	1003.77	9	Li & Lim (2001)	14.71
LR201	1266.25	4	591.56	3	Li & Lim (2001)	114.05
LR202	1162.4	4	591.56	3	Li & Lim (2001)	96.50
LR203	934.53	3	591.17	3	Hasle & Kloster (2007)	58.08
LR204	912.4	2	590.6	3	Hasle & Kloster (2007)	54.49
LR205	1118.7	3	588.88	3	Li & Lim (2001)	89.97

Tab. 6. Comparison of GHG emissions from both diesel and LPG fuel

Instances	Diesel emissions	LPG emissions	Difference of GHG emission (%)
LC101	101.43	58.55	53.61
LC102	97.84	56.48	53.60
LC103	103.4	59.69	53.60
LC104	93.27	53.84	53.61
LC105	69.23	39.96	53.61
LC106	49.98	28.85	53.61
LC107	181.23	104.62	53.60
LC108	86.5	49.93	53.61
LC109	125.58	72.49	53.61
LC201	119.93	69.23	53.61
LC202	92.72	53.52	53.61
LC203	301.41	173.99	53.61
LC204	202.55	116.92	53.61
LC205	117.44	67.8	53.60
LC206	162.08	93.56	53.61
LC207	187.54	108.26	53.60
LC208	148.5	85.72	53.61
LR101	51.85	29.93	53.61
LR102	105.24	60.75	53.61
LR103	79.31	45.78	53.61
LR104	47.13	27.2	53.63
LR105	61.39	35.44	53.60
LR106	150.54	86.9	53.61
LR107	143.72	82.96	53.61
LR108	147.21	84.98	53.60
LR109	124.78	72.03	53.60
LR110	139.27	80.4	53.60
LR111	74.23	42.85	53.60
LR112	114.39	66.03	53.61
LR201	300.71	173.58	53.61
LR202	97.76	56.43	53.61
LR203	580	334.81	53.60
LR204	181.81	104.95	53.61
LR205	473.12	273.11	53.61
LR206	260.5	150.37	53.61
LR207	342.92	197.95	53.61
LR208	536.67	309.8	53.60
LR209	226.6	130.81	53.60
LR210	249.36	143.94	53.61
LR211	312.26	180.25	53.61
		Average	**53.61**

Considering greenhouse gases emissions, the results indicate that the use of liquefied petroleum gas (LPG) fuel is more environmentally friendly than the use of diesel fuel. Table 6 presents the comparison of GHG emissions from both diesel and LPG fuels. The data show that LPG fuel emits 53.61 % less GHG emissions than does diesel fuel.

4. Discussion of the results

Particle swarm optimisation (PSO) was applied to determine optimal vehicle routes based on two different objective functions. The first objective function is to design vehicle routes by minimising the total cost. Next, then PSO was applied to design vehicle routes by minimising GHG emissions as the objective function. Three main GHGs were considered in this study: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Two different types of customer locations were tested. The first type of customer location is cluster-distributed, where the location of customers in the coverage service area are clustered in villages, towns, or cities. The results reveal that vehicle route design based on Green VRPPD is comparable to that of VRPPD, as presented in Table 2. Only three out of seventeen cases show that designing vehicle routes by considering GHG emissions requires more travel distance than by considering minimum total cost as the objective function. The results for Green VRPPD instance LC101 require 19.42 % more travel distance than the results for VRPPD. The increased travel distance is because the computational result from Green VRPPD requires two more vehicles to deliver products to customers. The average difference in travel distance is equal to 1.43 %, which does not have much effect on the total cost. Therefore, Green VRPPD is recommended for designing vehicle routes when the location of customers is cluster-distributed in the coverage service area.

The second type of customer location is randomly distributed around the coverage service area. The results presented in Table 3 show that Green VRPPD requires more travel distance compared to VRPPD. The average travel distance difference is equal to 10.43 %. Green VRPPD for three instances, LR103, LR109, and LR203, require 20 % more travel distance compared to VRPPD. When considering GHG emissions, most of the instances require more vehicles to service customers than when considering the total cost as the objective function. The implication is that environmental concerns would cost 10.49 % more for transportation. Fuel selection is another option that companies can use to provide more environmentally friendly transportation. The computational results indicate that the use of LPG fuel emits 53.61 % less GHGs than does diesel fuel.

The results reveal that Green VRPPD is suitable for the situation that the customer location is clustered. Generally, cluster-distributed customer location can save both transportation costs and time for the delivery of the product to the customers. Further, this would lead to the reduction of GHG from transportation. It also causes less local air pollution to use LPG as the fuel rather than using petrol gasoline or

diesel. However, Green VRPPD is suitable for designing the route of vehicles in some cases when the customer location is randomly distributed around the coverage service area because it would require more travel distance to be travelled.

Conclusions

The purpose of this study is to design a green last-mile route that supports efficient e-commerce distribution. A metaheuristics approach called particle swarm optimisation (PSO) was applied to design the route for last-mile delivery. This study used 34 benchmark instances from Li and Lim (2001) to test the performance of the search technique. First, the PSO was developed to solve VRPPD for transportation cost minimisation. Then, the PSO was applied to design vehicle routes based on GHG emissions minimisation (Green VRPPD).

Two different types of customer location distributions were evaluated. The LC datasets contain clusters of customers, whereas the LR datasets contain customers that are randomly distributed. The results of this study reveal that the use of Green VRPPD is very suitable for LC problems because the total distances and the number of vehicles used are the same whether considering GHG emissions or minimum total cost as the objective function in most cases. For RC problems, the decision of vehicle routing should depend on the logistics provider's situation because a design based on Green VRPPD is more expensive and requires more vehicles than a design based on VRPPD in most cases.

This study also looks at the use of two different fuel types. The study compares GHG emissions from LPG fuel and diesel fuel. It was found that using LPG appears to be more environmentally friendly than using diesel fuel.

The limitations of this work are the problem instances. It would be more realistic to use real data from third-party logistics providers. However, it is somewhat difficult to get such data because most logistics companies consider this data to be confidential information. Suggested future research would be to improve the metaheuristics technique used to design routes for delivering products to customers.

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Long-term trend of electric vehicle sales in Thailand

Thanwadee Chinda

ABSTRACT
This research study aims at examining the long-term trend of EV sales in Thailand, utilising the system dynamics (SD) modelling approach. This approach is commonly used to model complex systems with causal relationships among key factors within the system. The developed SD model consists of five key factors affecting electric vehicle (EV) sales, namely, the environment, economy, charging infrastructure, government support, and battery maintenance. The simulation results show the increase in EV sales by ten times in the next 20 years with implementation plans related to the five key factors. The government support factor is the most important in enhancing EV sales in the short term. Several government support plans should be initiated to attract more EV consumers, such as subsidies and tax reductions. The environment and charging infrastructure factors are crucial to increasing EV sales in the long term. The enforcement of the CO_2 tax and the provision of charging stations all around the country should be established to achieve a sustainable EV market in the long term. This research study contributes to the Thai government and automotive industry to better understand the complex relationships among key factors affecting EV sales. The related sectors may use the study results to plan for EV campaigns to promote the use of EVs and achieve a sustainable EV market.

KEY WORDS
electric vehicle, system dynamics modelling, trend, Thailand

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Introduction

Global warming is a critical global issue with transportation as a major contributor. Transport emissions account for 11.9 % of the total global emissions in 2020 (Ritchie & Roser, 2020). Transportation is responsible for carbon dioxide (CO_2) emissions and PM2.5 problems, causing severe harm to human health in the long term. The Thai government has implemented several policies to support alternative energy used in transportation, including electric vehicles

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(EVs). The EV campaign was first launched in 2015 to promote the use and manufacture of EVs in Thailand. A number of charging stations were built by the public and private sectors. Currently, over 230000 EVs represent a 20 % increase from 2020. Out of 700 charging stations, 34 % have fast chargers (EVAT, 2021). By 2030, 750000 EVs are planned to be manufactured in Thailand out of the total of 2.5 million cars, accounting for 30 % of all car sales (BO, 2015; Bangkok Post, 2021).

Although the EV market in Thailand is growing, it is still small compared with the market of internal combustion engine vehicles, as there are several factors affecting consumer purchasing decisions. Thananusak et al. (2017), for example, mentioned five key factors affecting the intention to purchase EVs in Thailand, including vehicle performance, infrastructure, finances, environmental concerns, and price premium factors. The study results revealed the vehicle performance, environmental concerns, and price premium as crucial factors in making EV purchasing decisions. Mendoza (2018) agreed that vehicle performance, financial aspects, and government incentives played major roles in EV purchasing decisions. Key concerns focus on safety issues, maintenance costs, and tax incentives. Dolcharumanee (2018), on the other hand, concluded that technology advancement, information provision, aftersales service, and supportive government policies were the key factors used by Thai consumers in making EV purchasing decisions. Vongurai (2020) examined factors affecting brand preference towards electric vehicles in Bangkok, Thailand, and concluded that social influence has a significant effect on environmental concerns, as well as a positive effect on attitude. The consumer attitude towards environment-friendly products then affected the encouragement of brand preference, which largely depends on individual opinion.

A long-term plan for the EV market requires understanding complex relationships among key factors affecting EV sales in Thailand. Vongurai (2020) stated that the better fuel efficiency of EVs, the lesser harm and better preservation of the environment. This, in turn, leads to a positive attitude towards EVs. Tonpradit (2017) examined causal relationships among key factors affecting EV purchase intention in Thailand using the structural equation modelling approach. The study results revealed that perceived ease of use, perceived usefulness, consumer innovativeness, and consumer's degree of greenness affects the attitude, which influences the purchase intention.

Therefore, this study aims to examine trends of EV sales in the long term utilising the system dynamics (SD) modelling approach. Causal relationships among key EV factors are used as input in the developed SD model to reflect complex relationships of the EV market and the plan for EV strategies to support EV sales in the long term.

This study conducted a literature review to understand the global and Thai EV markets and identify key factors influencing EV sales. SD modelling approach is then reviewed, and relevant data are collected to be used in the SD model development. The developed SD model is separated into five sub-models, representing five key factors affecting EV sales in Thailand. The developed model is simulated and validated using the sensitivity analysis method. The conclusion is finally presented with the contributions and limitations.

1. Literature review

Many research studies attempt to identify key factors affecting the EV purchasing decision and the EV market in Thailand. Mendoza (2018), for example, concluded five key factors involved in the uptake of EVs in Thailand, namely vehicle performance, financial aspects, government incentives, user personality, and buyer demographics. Kumnerdpetch (2020) pinpointed product and price aspects as key marketing factors, while perceived usefulness, perceived ease of use, and perceived risk aspects were indicated as crucial for the technology acceptance factor. Promphat and Deebhijarn (2019) concluded that the customers' purchasing decision was influenced by customer perception, subjective norms, marketing mix, external environment, and attitude. Selvakkumaran et al. (2018) stated four factors affecting the benefits of EV transition in Thailand, namely, economic, social, policy and technological factors. Thananusak et al. (2021) explored the development of EV charging stations in Thailand, as it mainly affects the purchasing decision. It was suggested that the government set up a national EV policy committee to accelerate the EV adoption and EV charging stations in Thailand. According to Bangkok Post (2021), to enhance the EV market in Thailand, the government has to ensure that the drivers have convenient access to power sources, i.e., charging stations.

In this study, five key factors affecting EV sales in Thailand are extracted from the literature and are used in the development of the system dynamics (SD) model. They include 1) environmental, 2) economic, 3) charging infrastructure, 4) government support, and 5) battery performance factors.

- The environmental factor focuses on using EVs to reduce global warming and CO_2 emission. Martz et al. (2021) mentioned that EVs are a promising option for greenhouse gas (GHG) mitigation in the transport sector, especially when the fast decrease in CO_2 emissions from electricity provision is considered. Toyota Motor Corporation (2017) stated that EVs emit less CO_2 than conventional vehicles, with a difference of more than 60 grams/km. This reduces the CO_2 tax the consumers have to pay, leading to a higher EV demand in the future.
- The economic factor focuses on energy saving from the use of EVs (Szkutnik & Jakubiak, 2012; Goncalves et al., 2020). CAA (2021) stated that EVs require less fuel consumption and emit less GHG than conventional vehicles. Controlling electricity prices could stimulate the use of EVs. Mendoza (2018) maintained that electricity cost subsidies could be one of the government policies to stimulate the use of EVs in Thailand.
- The charging infrastructure factor focuses mainly on the availability of charging stations to support the use of EVs. The installation of charging stations is crucial to fulfilling the charging demand at different locations, maintaining the minimum negative impact on the power system (Pal et al., 2020). Thananusak et al. (2017) added that charging stations should be adequately provided as an EV battery still has a low range per charge.
- The government support factor focuses mainly on the vehicle price subsidy for EVs to attract more consumers. According to Shao et al. (2020), government support, especially subsidies, helps expand the EV market. The subsidy scheme in this study follows the first-car scheme implemented in Thailand in 2012, where the consumers were repaid no more than THB 100000 as tax rebates one year after the purchases (Bangkok Post, 2012).
- The battery maintenance factor is reflected by the low maintenance cost of an EV battery. Issues related to the battery cost and its maintenance should be considered individually, as the battery accounts for about half of the EV manufacturing cost (Konig et al., 2021). Krupa et al. (2014) stated that low battery and maintenance costs stimulated the EV market.

Five key factors affecting EV sales are used in the SD model development to examine the trend of the EV market in Thailand in the long term.

2. Research methods

2.1. System dynamics modelling approach

The long-term trend of EV sales in Thailand is examined utilising the SD modelling approach. This method was first introduced for modelling and analysing the behaviour of complex social systems, particularly in the industrial context. It has been widely used in research studies where feedback loops are dynamic and critical to understanding the interrelationships (Rodrigues & Bowers, 1996). SD modelling has the following advantages:

- Both policies and processes can be included in the model to address problems with policies. An example is the subsidy policy from the government to stimulate the EV demand.
- The SD model considers cause and effect interrelationships among system variables, making the outcome realistic. The government's support policies help reduce the vehicle price and increase the EV demand. More EVs reduce CO_2 emissions, raise the environmentally friendly perception, and increase the EV demand. More EVs, however, raise the electricity demand, which may result in high electricity prices. This, in turn, may discourage the use of EVs.
- Qualitative (such as causal loop diagrams) and quantitative (such as flow rates and beginning stock) data can be used as the model input for equations development. Examples include the subsidy policies, the fuel and electricity prices, the increasing rate of the vehicle price, the CO_2 tax, and the EV demand.

The SD methodology provides a good basis for making decisions. It allows the interrelationships among important variables affecting a problem, providing a better understanding and possible solutions.

A number of research studies have been conducted utilising the SD modelling approach. Feng et al. (2013), for example, developed an SD model to examine the future energy demand and CO_2 emissions in Beijing, China. Nhim (2015) developed an SD model to identify sources of drought resilience at household and commune levels and find possible ways to improve it in Cambodia. The results show that access to irrigation is the most important source of resilience at both household and community levels as it can help maintain stability and continuous development of rice production over time. Doan & Chinda (2016) exam-

Tab. 1. SD model components

Component	Icon	Explanation
Stock		A stock represents a part of a system whose value at any given instant in time depends on the system's past behaviour that accumulates
Flow		A flow represents the rate at which the stock is changing at any given instant. It either flows into a stock (causing it to increase) or out of stock (causing it to decrease)
Converter		A converter is used to take input data and convert it into output
Connector		A connector is used to transmit input and information

ined the feasibility of a construction and demolition waste recycling programme in Bangkok, Thailand, using the SD modelling technique. The results revealed that the investment return for the recycling programme takes 14 years. Nghia & Chinda (2018) examined the profit of residential projects in Ho Chi Minh City, Vietnam, in the long-term using five key profit factors, including the urban population, buyer capacity, housing supply, housing economics, and housing finance. Simulation results revealed that the average profit of residential projects in Ho Chi Minh City, Vietnam, in the next 20 years is 35 %, with a minimum and maximum profit of 19 % and 41 %, respectively.

This study utilises the Structural Thinking Experimental Learning Laboratory with Animation (STELLA) software in the SD model development. It provides a graphically oriented front end for the development of SD models. The stock and flow diagrams used in the SD model development are directly supported with a series of tools supporting model development. Equations are written using dialogue boxes accessible from the stock and flow diagrams. The graphical depictions of the SD model, and the ability to quickly adjust a model and run it on the software, have proven to be an excellent discussion medium for model enhancement (Isee Systems, 2021). The model consists of four key components: stock, flow, converter, and connector, see Table 1 (Tang & Vijay, 2001).

2.2. Data collection

Data related to five key factors affecting the EV demand are collected using several literature sources as input in the SD model development (Table 2). For example, EV maintenance costs amount to around THB 26731 for 100000 kilometres (Best Auto Sales,

Tab. 2. Data used in the SD model development

Factor	Data	Reference
Environment	• CO_2 tax: 483 Baht/ton CO_2, • CO_2 reduction: 205871.083 tonnes CO_2 per 1 % increase in EVs/total vehicles ratio, • Initial EVs: 231682 units, • Initial total vehicles: 10.5 million units, • The maximum increasing rate of total vehicles in Thailand: 6.39 % per year, • The minimum increasing rate of total vehicles in Thailand: 1.83 % per year, • The increasing rate of EV sales in Thailand: 5.46 % per year, • Average EV price: THB 2.48 million/unit (THB 33.75 = USD 1)	Doan & Chinda (2016); EPPO (2021); EVAT (2021); Thananusak et al. (2021); Kaeo-tad et al. (2021)
Economy	• Average fuel consumption: THB 1.68 /kilometre, • Average electricity consumption for EVs: THB 0.85 /kilometre, • Average driving distance: 20000 kilometres/year	BCP (2021); Hearst Autos (2021)
Charging infrastructure	• The number of EVs per charging station: 1739, • The initial number of charging stations: 276, • Consumer purchasing decision based on charging stations: 7 %	Sutabutr (2019); Kaewtatip (2019); ITL (2020); EVAT (2021); GPSC (2021); F&L Asia (2021); Thananusak et al. (2021)
Government support	• EV increasing rate following the first-car scheme: 18.2 % until 2023 and 16.1 % until 2026	Svasti (2012); Department of Land Transport (2019); CEIC (2021); Statista (2021)
Battery maintenance	• Maintenance cost of an EV: 50 % of a conventional vehicle, • Average maintenance cost of an EV: THB 5346/year	Best Auto Sales (2020); Consumer Reports (2021)

2020). Hearst Autos (2021) stated that the average mileage of an EV per year is 20 000 kilometres. This leads to average EV maintenance costs of THB 5346 per year. Consumer Reports (2021) stated that EV drivers save an average of 50 % on maintenance and repairs over the vehicle's life compared to owners of gas-powered cars.

This results in the maintenance cost savings of THB 5346 per year for an EV. The initial number of charging stations in Thailand is 276 (without shopping centres, restaurants, and property developers). It is expected to reach 690 stations with a total of 1.2 million EVs by 2036 (Sutabutr, 2019; Kaewtatip, 2019). This brings an average of 1739 EVs required for a charging station location. EVs have about half lower electricity costs and higher motor efficiency than conventional vehicles.

2.3. SD model of EV sales in Thailand

The SD model of EV sales in Thailand consists of six sub-models, namely, the environment, economy, charging infrastructure, government support, battery performance, and total EV sub-models (Fig. 1). Details are provided below.

2.3.1. Environment sub-model

Every 1 % increase in EVs/total vehicles ratio brings the reduction of 205871.083 tonnes in CO_2 emissions (Sutabutr, 2019; EPPO, 2021). Less CO_2 emission results in a lower CO_2 tax, thus attracting more green consumers to purchase EVs. In this study, the increase in the EV demand based on the environmental factor (EVEN) is achieved by dividing the savings of CO_2 tax (SVCO) with the average selling price of an EV of THB 2.48 million (Eqs. 1–3).

$$RTEV = IF\ CTY > 0 \quad THEN\ (HISTORY(RATIO_{EV}, CTY) - -HISTORY(RATIO_{EV}, CTY - 1))\ ELSE\ 0 \tag{1}$$

$$SVCO = RTEV \times 205871.083 \times 483 \tag{2}$$

$$EVEN = ROUND(SVCO/2480000) \tag{3}$$

Where

RTEV = Increase in EVs/total vehicles ratio

CTY = Count year

$RATIO_{EV}$ = Ratio of EVs/total vehicles each year

SVCO = Savings of CO_2 tax (THB/year)

EVEN = Increase in the EV demand from the environment factor (vehicles/year)

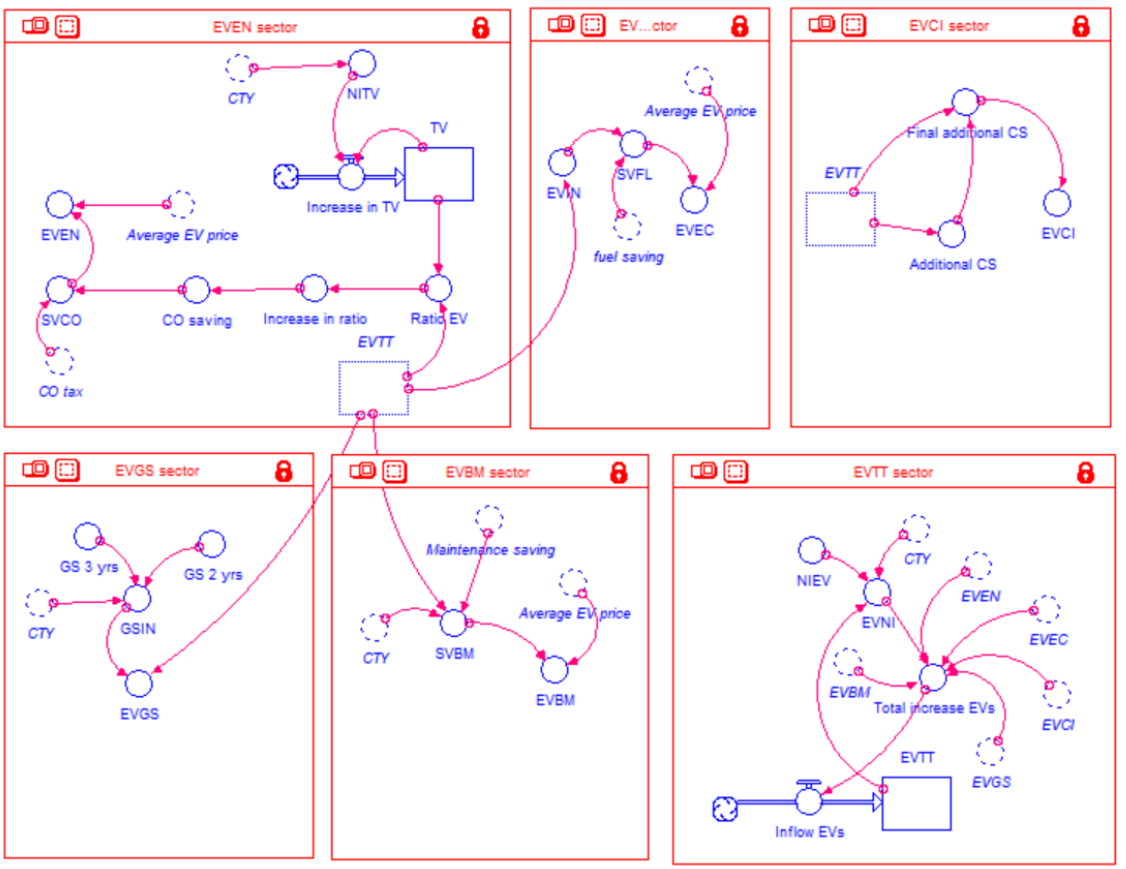

Fig. 1. SD model of EV sales in Thailand

2.3.2. Economic sub-model

The average fuel consumption of conventional vehicles is 1.68 THB/kilometre, while EVs cost about 0.85 THB of electricity/kilometre (BCP, 2021; Hearst Autos, 2021). This results in the saving of 0.83 THB/kilometre. With an average driving distance of 20000 kilometres/year, this yields the saving of 16600 THB/EV/year. The increase in the EV demand based on the economic factor (EVEC) is achieved by dividing the savings of fuel consumption (SVFL) by the average selling price of an EV (Eqs. 4–6).

$$EVIN = EVTT - DELAY(EVTT, 1) \quad (4)$$

$$SVFL = 16600 \times \text{EVIN} \quad (5)$$

$$EVEC = ROUND(SVFL/2480000) \quad (6)$$

Where
EVIN = Increased number of EVs (vehicles/year)
EVTT = Total EVs (vehicles/year)
SVFL = Savings of fuel consumption (THB/year)
EVEC = Increase in the EV demand from the economic factor (vehicles/year)

2.3.3. Charging infrastructure sub-model

Thailand currently has 276 charging station locations with a capacity to service up to 479964 EVs (1739 EVs require one charging station). One additional charging station could attract 7 % of green consumers to purchase EVs (Kaewtatip, 2019; Thananusak et al., 2021). The increase in EV demand based on the charging infrastructure factor (EVCI) is then achieved, as shown in Eqs. 7–8.

$$CIAD = IF\ EVTT < 479964\ THEN\ 0\ ELSE\ ROUND((EVTT - DELAY(EVTT, 1))/1739) \quad (7)$$

$$EVCI = CIAD \times 1739 \times 0.07 \quad (8)$$

Where
CIAD = Additional charging stations (stations/year)
CHTT = Total charging stations (stations)
EVCI = Increase in the EV demand from the charging infrastructure factor (vehicles/year)

2.3.4. Government support sub-model

It is expected that the government policy to subsidise the first-car to be an EV will help increase the share of EVs by 18.2 % in the next two years (until 2023) and by 16.1 % three years after, i.e., until 2036 (Svasti, 2012; Department of Land Transport, 2019). The increase in the EV demand based on the government support factor (EVGS) is achieved by multiplying the increasing rate from the government support (GSIN) with the total number of EVs each year (EVTT) (Eqs. 9–10).

$$GSIN = IF\ CTY \leq 2\ THEN\ 0.182\ ELSE\ (IF\ 3 \leq CTY \leq 5\ THEN\ 0.161\ ELSE\ 0) \quad (9)$$

$$EVGS = GSIN \times EVTT \quad (10)$$

Where
GSIN = Increasing rate of EVs from the government support
EVGS = Increase in EV demand from the government support factor (vehicles/year)

2.3.5. Battery maintenance sub-model

EV battery maintenance costs comprise only half of the maintenance costs of conventional vehicles (Consumer Reports, 2021). This is equivalent to the savings in maintenance costs of 5346 THB/EV/year. The increase in the EV demand based on the battery maintenance factor (EVBM) is then achieved, as shown in Eqs. 11–12.

$$SVBM = 5346 \times \text{EVIN} \quad (11)$$

$$EVBM = ROUND(SVBM/2480000) \quad (12)$$

Where SVBM = Savings of battery maintenance costs (THB/year)
EVBM = Increase in the EV demand from the battery maintenance factor (vehicles/year)

2.3.6. Total EV sub-model

The average increase of the EV number amounts to 14.45 % per year (EVAT, 2021). The additional EV demand from five key factors, i.e., the environment, economy, charging infrastructure, government support, and battery maintenance factors, are also added to achieve the total EVs (EVTT), see Eqs.13–15.

$$EVIN = EVEN + EVEC + EVCI + +EVGS + EVBM + EVNI \quad (13)$$

$$EVNI = DELAY(EVTT, 1) \times 0.0546 \quad (14)$$

$$EVTT = EVIN + DELAY(EVTT, 1) \quad (15)$$

Where
EVNI = Increase in the EV demand from the normal increasing rate (vehicles/year)

3. Research results

3.1. Simulation results

The SD model of EV sales is simulated for a 20-year period to examine the trend of EV sales in the long term. The simulation results are shown in Fig. 2 and Table 3.

The results show that the number of EVs will increase from 231682 vehicles to over 2 million vehicles in the next 20 years with the implementation of the five key factors affecting EV sales. This represents an average increasing rate of EVs of 41.4 % per year.

These simulation results are consistent with Sutabutr (2019), claiming that the number of EVs are expected to be over 1.2 million vehicles in 2036.

Closer examination (Fig. 3) reveals that the EV demand mainly increased due to the government support factor (EVGS) in the first five years of simulation. The increase followed the first-car scheme implemented in 2012, resulting in more than 100000 new registered vehicles (Svasti, 2012; Statista, 2021). Therefore, the government may offer a subsidy programme to attract more EV consumers, such as a tax rebate of up to THB 100000 per vehicle per person. This programme, however, should be implemented for a short period to promote the use of EVs. Fig. 3 also shows that the additional EV demand from the environmental factor (EVEN) is crucial in enhancing EV sales in Thailand by reducing the CO_2 tax that attracts more green consumers.

The EV demand from the charging infrastructure (EVCI) is zero in the first four years of simulation. This is because the current number of charging stations (276) is adequate to service up to 479964 EVs. As the number of EVs increases, more charging stations are built, reflecting the availability of charging stations and attracting more EV consumers.

Tab. 3. Numerical results of the SD model of EV sales in Thailand

Simulation time	Year	Total EV (vehicles/year)	Increased EV demand (vehicles/year)
Initial	2021	231682	0
1	2022	286998	55316
2	2023	369540	82542
3	2024	471176	101636
4	2025	598404	127228
5	2026	767012	168608
6	2027	860148	93136
7	2028	929786	69638
8	2029	994393	64607
9	2030	1060424	66031
10	2031	1130180	69756
11	2032	1204536	74356
12	2033	1284028	79492
13	2034	1369012	84984
14	2035	1459818	90806
15	2036	1556789	96971
16	2037	1660412	103623
17	2038	1771105	110693
18	2039	1889294	118189
19	2040	2015429	126135
20	2041	2150114	134685

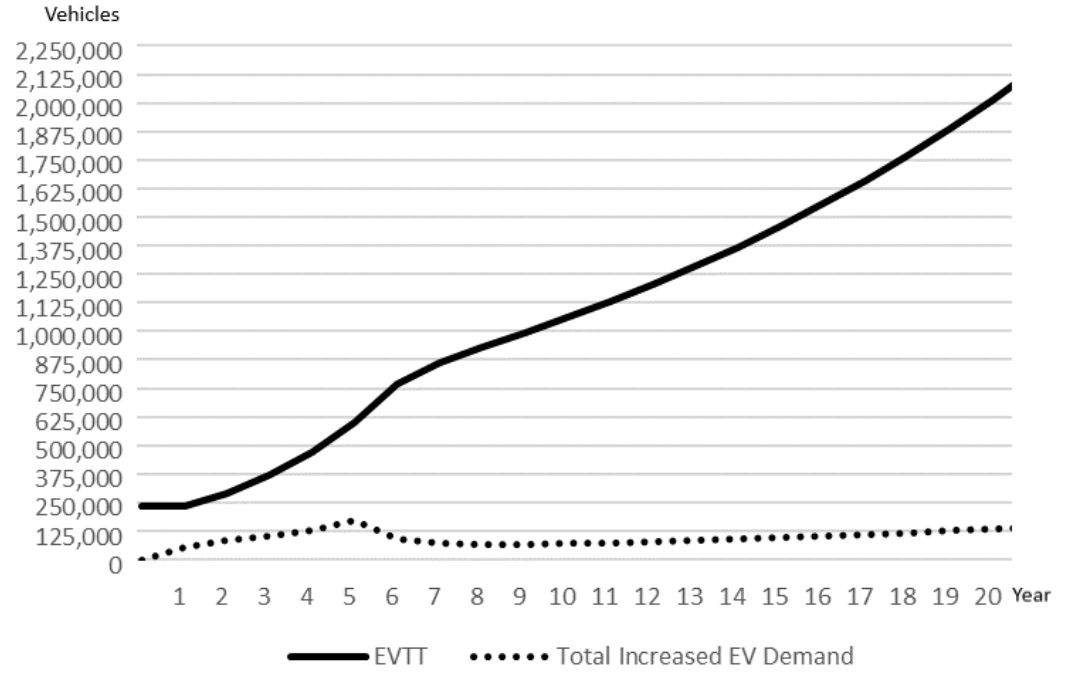

Fig. 2. Graphical results of the SD model of EV sales in Thailand

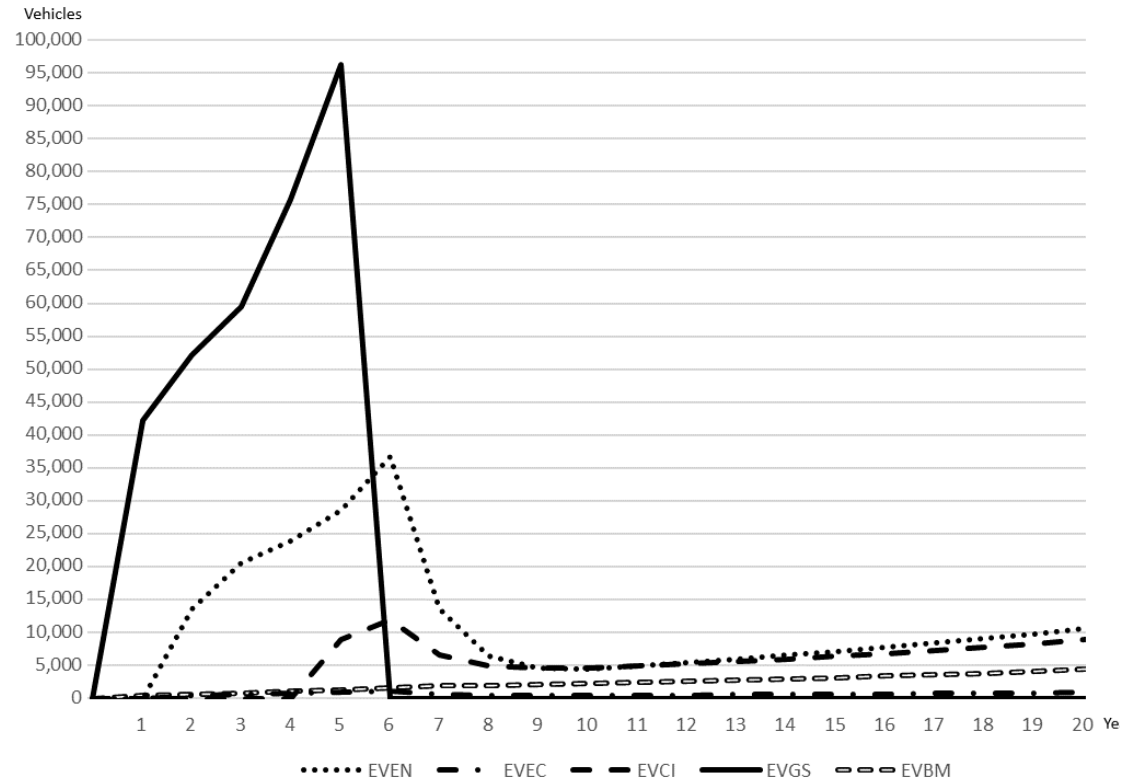

Fig. 3. Increased EV demand from five key factors affecting EV sales

3.2. Model validation

The developed SD model of EV sales in Thailand must be validated to ensure its use in practice and ascertain whether plausible shifts in model parameters can cause the model to fail behaviour tests that were passed previously (Balas et al., 2007). One of the common model validation tests is sensitivity analysis, or so-called policy analysis. It is used to reveal the degree of robustness of the model behaviour and indicate the degree to which policy recommendations may be influenced by uncertainty in parameter values.

This study performed the sensitivity analysis by varying the values related to government support, environment, and charging infrastructure factors, representing the highest additional EV demand (Fig. 3). In the government support factor, the increasing rate of EV sales from year 3 to year 5 (the last three years of the government subsidy programme) varied from 16.1 % to 18.2 % (Svasti, 2012; Statista, 2021). The simulation results (Fig. 4) show that the developed SD model of EV sales is robust, as the model

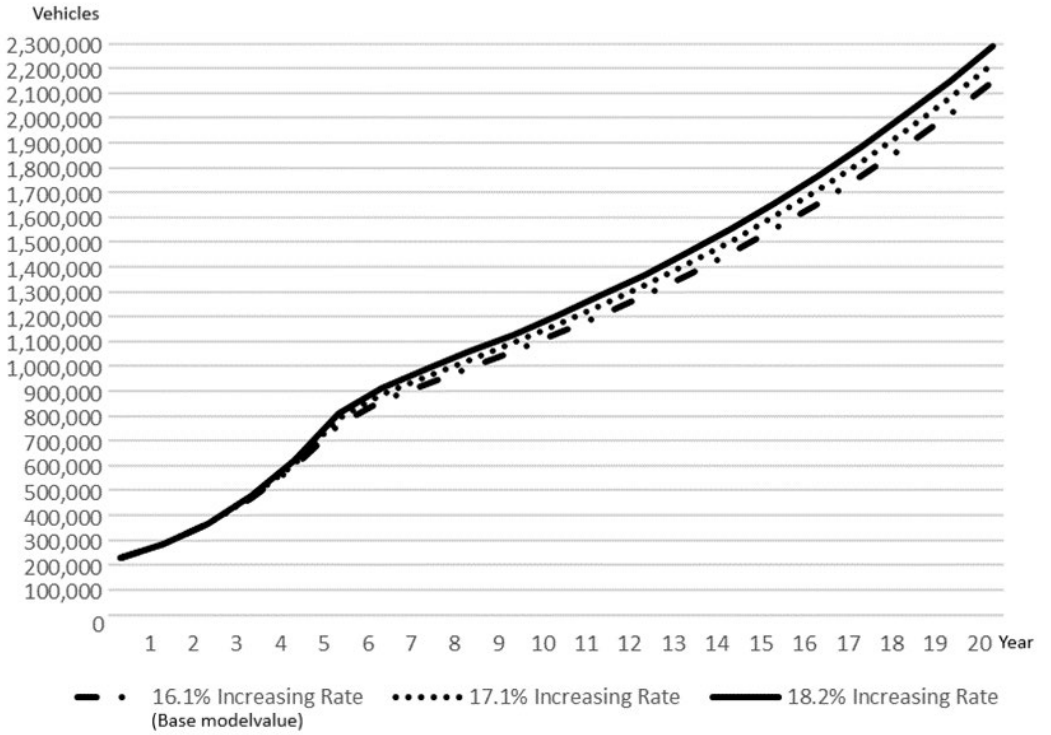

Fig. 4. Sensitivity analysis results when the increasing rate of the EV sales from the government support factor is changed

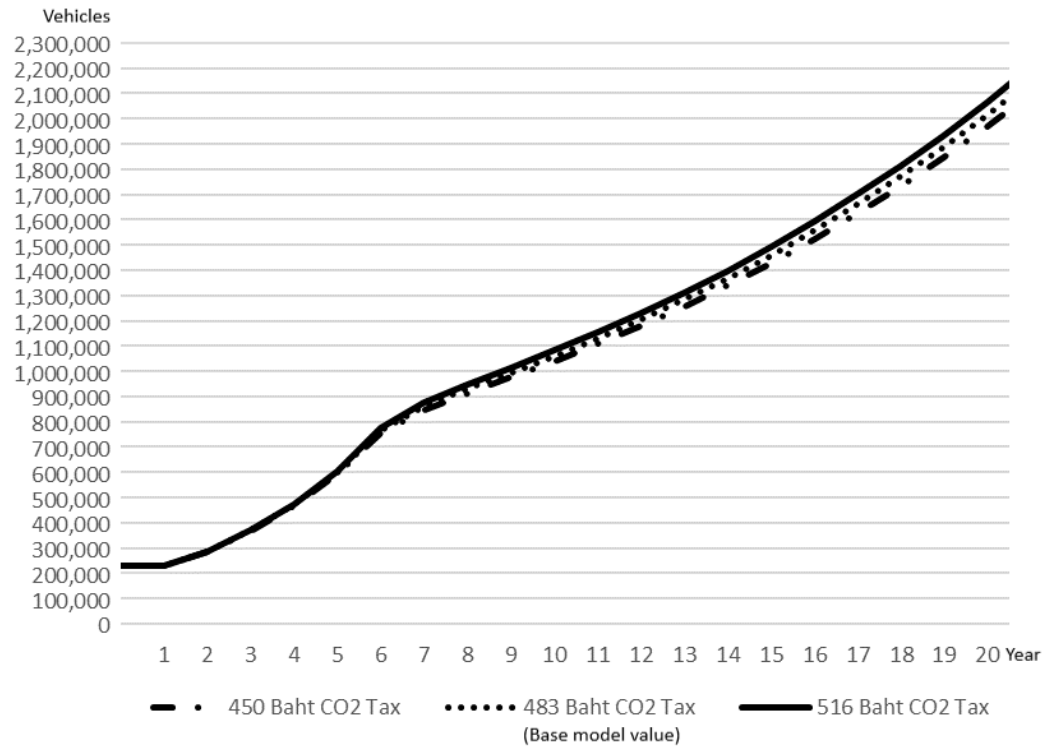

Fig. 5. Sensitivity analysis results when the CO_2 tax from the environment factor is changed

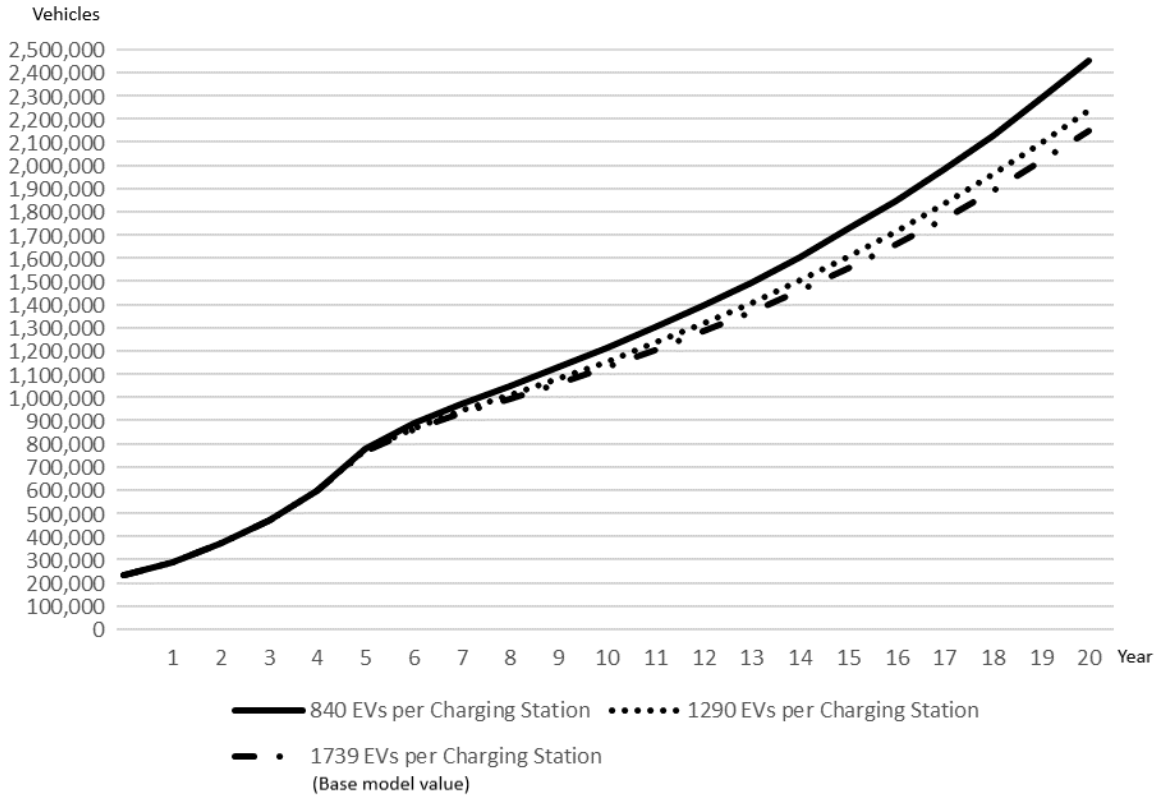

Fig. 6. Sensitivity analysis results when the number of EVs per charging station from the charging infrastructure factor is changed

behaviour has not changed. This validates the developed SD model to be used in real situations.

Fig. 4 shows that a higher increasing rate from the government support factor gives higher EV sales. Therefore, the government may support the EV manufacturers and consumers with various subsidy programmes, such as tax reduction and incentives and start-up programmes to encourage the EV production and EV market in Thailand in the long term.

The sensitivity analysis is also performed with the environmental factor by varying the CO_2 taxes from 450 to 500 THB/ton CO_2 (Doan & Chinda, 2016). Fig. 5 shows that a higher CO_2 tax results in higher savings from the CO_2 tax and more EVs purchased. This finding is consistent with Thananusak et al. (2017) that reduction in CO_2 emission helps enhance the EV sales in Thailand in the long term.

The sensitivity analysis in the charging infrastructure factor is performed by varying the number of EVs from 840 to 1739 vehicles per charging station (EVAT, 2021). The simulation results in Fig. 6 confirm that more charging stations attract more EV consumers and enhance the EV market in the long term.

4. Discussion of the results

The SD model of EV sales in Thailand is simulated for 20 years to examine the long-term trend of EV sales in Thailand. The simulation results reveal that the number of EVs increases from about 0.23 to 2.1 million vehicles in 20 years, representing an average increasing amount of about 100000 vehicles per year or an average increasing rate of 44 % per year.

These results follow the previous Thai government's first-car scheme that produced more than 100000 new registered vehicles per year (or a 50 % increase in the rate per year) (Statista, 2021). Therefore, it is crucial that the Thai government provides a number of supporting campaigns to enhance the EV market in the long term, as follows:

- Set up the subsidy campaign following the first-car campaign of 2012. The campaign provides EV consumers with a tax rebate through EV purchases. It could be implemented at the early stage to boost the EV market in Thailand (Bangkok Post, 2012). Based on the simulation results, this

campaign could grow the number of EVs by over 300000 vehicles in the next five years.
- Enforce the CO_2 tax regulation to reduce the CO_2 emission and control the global temperature increase to not exceed 1.5 °C following the Conference of the Parties (COP) 26 (BBC, 2021). The simulation results reveal that the reduction of CO_2 emission could enhance the EVs by almost 240000 vehicles in the next 20 years.
- Have an adequate number and distribution of charging stations. Private companies may cooperate in providing charging stations at specific locations, such as supermarkets, shopping centres, and restaurants (EVAT, 2021). In this study, adequate charging stations could raise the number of EVs by almost 120000 vehicles in the next 20 years.
- Control electricity prices to motivate the use of EVs.
- Provide skills training for EV battery manufacturing to reduce production and maintenance costs. A comprehensive set of incentives should be provided to cover all major aspects of the EV supply chain, focusing on battery EVs and local production of critical parts (BOI, 2017).

Conclusions

EVs are a possible solution in response to the increasing concerns for climate change and global warming. The SD model of EV sales is developed based on five key factors, namely, the environment, economy, charging infrastructure, government support, and battery maintenance factors, to examine the trend of EV sales in Thailand in the long term. The simulation results revealed that strategies and campaigns related to the five key factors could help raise the number of EVs by almost ten times in the next 20 years. Some strategies are suggested to be implemented in the early years, while others aim at a longer period. The government support through tax rebates, for instance, could be established at the early stage to promote the use of EVs. Import taxes for key EV components, especially the electric battery, should be subsidised to support the local EV manufacturing.

The government should also have a long-term plan to increase the number of charging stations to cover the charging demand of the country. Electricity costs for vehicle charging should be controlled to attract more EV consumers. Moreover, the government should add electric battery and EV manufacturing modules in vocational study programmes to supply an adequate number of skilled workers in the market in the long term.

Short- and long-term plans related to the five key factors could help stimulate the EV demand and enhance EV sales. The public and private sectors should cooperate to achieve a sustainable EV market in Thailand in the long term.

This research study contributes to the government and automotive industry as follows:
- It considers the long-term trend of EV sales in Thailand utilising the SD modelling approach.
- Five key factors affecting EV sales, their complex relationships and the link with the EV demand. The developed SD model clearly depicts these relationships to better understand the EV sales trend in the long term.
- The Thai government plays a vital role in successfully growing the EV market in Thailand. Various supports should be initiated, both short-and long-term, to enhance EV sales. Such supports are tax reduction, subsidies, charging infrastructure provision, skills training, and promotion campaigns.

This research study has some limitations. Data used in the SD model development have been obtained from the literature on developed and developing countries and are not specific to the Thai context. Expert interviews may be performed to collect specific data, such as CO_2 emissions, energy consumption, and related-infrastructure plans for the SD model development. The EV sales achieved from the developed SD model should be compared with the real data when available.

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Order picking and loading-dock arrival punctuality performance indicators for supply chain management: a case study

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ABSTRACT
Supply chain activity control is an essential part of Supply Chain Management (SCM), ensuring compliance with customer requirements. This paper presents a case study into the control of SCM activities. The study analysed two areas involving two different SC links associated with order picking, and outsourced truck freights, respectively. The studied company had problems with these links. An approach based on developing a KPI (Key Performance Indicator) was proposed to address the issues. Consequently, different affected processes were analysed and characterised, considering the relevant data for defining a KPI. Then, strategies and methods were devised for data collection and processing regarding the system's current state. Finally, tools were designed to facilitate the interpretation of the system's current state and thus, pave the way for the decision-making process on corrective measures.

KEY WORDS
supply chain management, key performance indicators, control, logistics, operations management

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Introduction

Supply Chain Management (SCM) is one of the key elements of a successfully operating business in today's world (Lambert & Cooper, 2000; Sangwan, 2017). It must be effective and efficient, accomplishing Supply Chain (SC) goals and reducing the usage of resources (Bieńkowska, 2020; Osadolor et al., 2021). The SCM function has gained preponderance within company systems, becoming an essential management activity in generating added value

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(Carter & Rogers, 2008; Bukowski, 2019; Komza, 2017). The main support activities provided by the SCM system must encompass the planning of inter-organisational and intra-organisational operations to meet customer demands (Ivanov et al., 2017; Shiri et al., 2020). Supply chain management is responsible for balanced supply and demand along the entire value-added chain (Christopher, 2011).

Even though plans for the Supply Chain (SC) consider the anticipated conditions, the real-world events may impact the behaviour of various agents (internal and/or external) differently than expected, affecting the efficiency of the plans (Ivanov, 2018). These effects should be minimised to maintain efficiency at expected levels (Makris et al., 2011). To achieve this, operations must be controlled by using the information on the system's state for taking corrective measures to avoid unwanted results (Broz et al., 2018). Managers and supply chain members must spend at least half of their working time handling uncertainties and risks. Consequently, as the natural feedback channel between planned and real processes, the control function has become increasingly more important (Ivanov et al., 2017).

Process control ensures that real and planned operations concur by evaluating the current process and necessary actions to be implemented to achieve the proposed objectives (Neely et al., 1997; Gunasekaran & Kobu, 2007; Nurakhova et al., 2020). Indicators are created to determine whether the proposed objectives are being met and to measure the degree of their achievement (Kucukaltan et al., 2016). Action plans can be designed to control the indicators and lead the organisation back to the initially established strategy by obtaining information about the real state of decision areas that affect the company's performance (Lohman et al., 2004).

These implemented indicators mainly aim to provide a quantifiable vision for senior management and a measure to identify business success, frequently assessing the evolution of the process and constantly developing ideas that contribute to increased performance (Rafele, 2004; Parmenter, 2015). Therefore, indicators must be formulated along with objectives to show their success or failure, progress or delay, and the causes allowing or preventing their achievement to identify maintaining or corrective actions (Neely, 2007; Sujová et al., 2019).

This paper addresses two problems of a Supply Chain case study carried out in a German company and developed during an improvement project. The company manufactures and markets household vacuum cleaners. The studied company's problems affect two SC links: the logistics of the carriers (suppliers and customers) and the assembly of customer orders. Regarding the first problem, the main drawback is the failure to meet deadlines and lead times planned by carriers, exacerbating the activities that follow the loading or unloading of trucks. The second problem is related to the customer's order picking, where errors in quantity and product types are significant. This implies extra costs from the logistics of recovering wrongly shipped products and sending the right items.

These problems are addressed by developing Key Performance Indicators (KPIs). This approach allows gathering and processing all the data regarding the system's current state and presenting it in an easily interpretable manner. The information visualisation of using graphics was an important part of the project. The developed KPIs enable the company's managers to address the problems directly and achieve a significant improvement with planning at the Supply Chain Department.

The rest of the article is organised as follows. Section 2 introduces materials and methods used in this study. Section 3 describes the development of the KPIs and presents the results. Section 4 discusses the results obtained applying the KPIs. Finally, Section 5 provides conclusions.

1. Materials and methods

Regardless of the business characteristics, every management system is composed of a set of complex functions providing it with a structure and facilitating operations (Vollmann et al., 2005). A suitable management strategy is required to ensure coordinated operation of these functions to accomplish the system's objective (Steiner, 2010; Jabilles et al., 2019). Good management must comply with the plan; thus, the system's control constitutes a primary administrative stage allowing managers to verify the actual situation in the organisation by employing a mechanism for checking its alignment with set objectives (Maulina & Natakusumah, 2020; Marziali et al., 2021). Control systems evaluate performance against the existing plan (Colledani & Tolio, 2011).

Management control is a dynamic and important system for achieving the organisational goals set in the planning process. The control function should focus on assessing the behaviour of the critical factors that influence the fulfilment of the strategy. It should

be flexible and continuously adjust to changing strategies of the organisation (Gunasekaran & Kobu, 2007). One way to manage and implement a control system is by developing indicators. The indicators will measure attributes of the business or industry processes and provide relevant information for making decisions against deviations from the plan (Parmenter 2015).

1.1. Key performance indicators

KPIs measure the level of process performance, focusing on the "how" and indicating its state. Key performance indicators are measurements used to quantify objectives that reflect the organisation's performance, generally included in the strategic plan (Neely et al., 1997; Lohman et al., 2004). They are necessary for improving operations since what is not measured cannot be controlled, and what is not controlled cannot be managed (Kucukaltan et al., 2016). KPIs are "vehicles of communication" in the sense that they allow top-level executives to convey the company's mission and vision to the lower hierarchical levels and directly involve all employees in achieving the strategic objectives (Parmenter, 2015).

Although they vary from company to company, the most common KPIs aim to evaluate work productivity, product and service quality, business profitability, deadlines, process effectiveness, lead times, resources utilisation, growth, cost control, level of innovation and performance of technological infrastructure (Neely, 2007; Sangwan, 2017; Florek-Paszkowska et al., 2021; Mandal, 2016).

However, defining a sound set of KPIs has its complexities since the real challenge is to select the indicators that help meet budget goals and, more importantly, those in perfect tune with the company's strategic goals (Rafele, 2004).

Fig. 1 schematises the central idea: the KPI value is plotted on the Y-axis, and the X-axis shows the evolution of the controlled process. The maximum point is defined as the goal to be achieved in terms of the KPI value. Then, different states of the controlled process are identified, allowing different corrective actions to be implemented to reach the desired level of the KPI.

1.2. KPI system implementation

During the project for the creation and implementation of indicators, the logistics team of the studied company's Supply Chain Department considered it necessary to create systems of indicators with specific characteristics.

The system comprised the indicator, the baseline level, the current level, the goal, and the traffic light or the RAG rating system for performance evaluation. These elements facilitate the interpretation of the results obtained from the measurement of an indicator, allowing to know the initial situation of the indicator, its variations and the degree of progress towards the proposed goal.

Baseline level refers to the initial measurement or the standard level taken for the indicator and represents the performance achieved before the effect of strategic improvement initiatives.

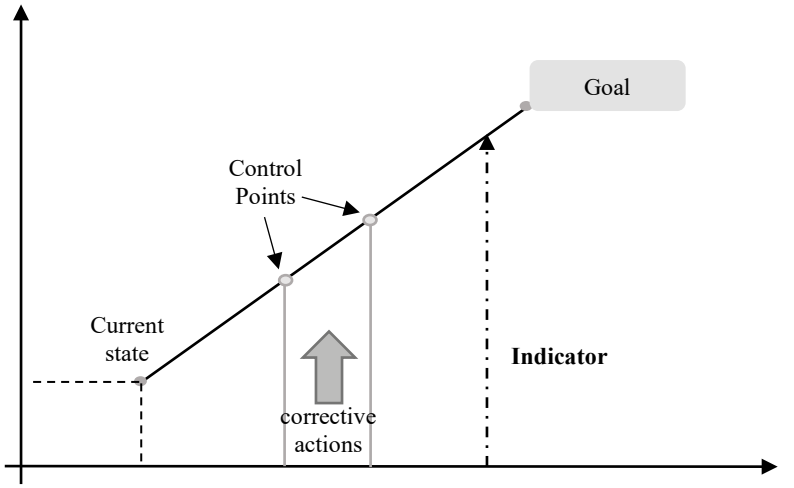

Fig. 1. Relationship between the business objective and the indicator

The current level represents the indicator measurements period by period as influenced by the effects of strategic initiatives.

The goal is the expected level of the indicator that the organisation wishes to achieve after successfully executing the improvement actions.

A traffic light rating system, traffic light or RAG (red, amber, green) is used to easily observe the indicator's performance level, where green represents expected performance, amber (yellow) — worrying performance, and red indicates unacceptable performance.

1.3. Problem description

This case study is based on a supply chain of vacuum cleaners with the manufacturer and the main parts of the chain located in Germany. The manufacturer distributes its finished products from its headquarters in Germany by freight train and trucks. The company owns the freight train, wagons and access railway tracks to the cargo sector of the warehouse facilities. The trucking services are outsourced; thus, the company does not own the vehicles used to distribute final products. However, the outsourced services do not include distribution logistics, remaining under the care of the SC Department's logistics team. The delivery service is outsourced to several transportation companies (thirteen in total). Orders placed by clients or retailers are handled at the Finished Product Warehouse. The whole supply chain is illustrated in Fig. 2. Grey stars in Fig. 2 indicate the problems considered in this study. These stars are placed on SC links that present logistic problems. "Problem 1" refers to the punctuality of trucks arriving at the loading dock, i.e., the company has problems with the outsourced logistic systems as trucks fail to provide services on time. However, no issues exist with delivery by trains. "Problem 2" refers to picking finished products, i.e., some orders have issues with the quantity, the product mix or the quality.

1.4. Related KPIs

As explained in the previous section, the problems addressed in this article occurred in different links of the Supply Chain; besides, each problem involves different responsibilities as the truck transport is outsourced and the order preparation is performed by the company's labour. This feature prevents the company from using usual supply chain indicators, such as OTIF (Order in Time, In Full) for Problem 1 and POR (Perfect Order) for Problem 2 (Chae, 2009; Maestrini et al., 2017), because they have a wider scope than required for the case study. If the OTIF indicator was used for Problem 1, then the part of the indicator related to "in full" would be constantly 1, which does not make much sense. And, if a wider KPI, such as OTIFEF (Order in Time, In Full, Error Free), was used for considering the two problems together, its value would mix the responsibilities.

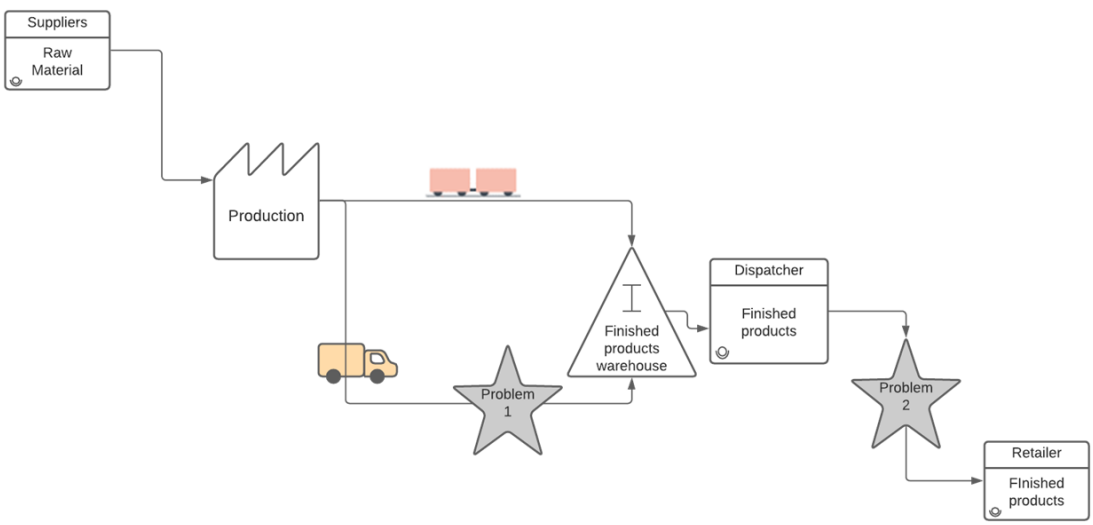

Fig. 2. Supply chain illustration: grey stars indicate links with addressed problems

Consequently, if the trucks were punctual but the dispatching centre was wrong, OTIFEF would flag this situation but would not indicate the problem directly. Besides, since both problems represent different supply chain partners and consequently, different contracts, it would be much easier to execute penalisation by having a clear indicator for each partner or responsible group. Thus, newly tailored indicators are proposed, enabling to include the poor performance causes.

2. Results: KPI development and outcomes

This section presents the system of indicators for different KPIs, specifying the reasons that led to its proposal, explaining how they are measured, where the information is obtained and providing the results.

It is worth mentioning that at the time of starting this control project using KPIs, the company had already begun with primary developments required for its implementation. Consequently, the standard control project phases aimed at institutional diagnosis and the identification of key processes had already been completed. The participation of researchers in the project consisted mainly of developing the indicator systems for key processes aiming to measure their attributes and set the basis to perform corrective measures.

2.1. KPI-I: punctuality of trucks

The company distributes its finished products from its headquarters in Germany by freight train and trucks. The company owns the freight train, wagons and access railway tracks to the cargo sector of the warehouse facilities.

The trucking services are outsourced; thus, the company does not own the vehicles used to distribute final products. However, the outsourced services do not include distribution logistics, remaining under the care of the SC Department's logistics team. The delivery service is outsourced to several transportation companies (thirteen in total).

The recurrent problems with the punctuality of arriving trucks at the depot necessitated the control of this variable. The first step consisted of digitising the forms used to record the arrival of the trucks, including information on arrival time (planned and actual), destination, outsourced owner of the truck, numbers of loaded products and loading time, etc. This information is used to monitor different outsourced companies, keep track of the number of trucks that are loaded and dispatched as planned and take corrective actions for product lines that frequently experience punctuality problems. Also, the obtained data is used to generate a new table to measure the performance of the parameter month by month, recording the percentage of trucks that are on time, regardless of the expedition or the transportation company.

Several meetings were held with the managers and leaders of the Supply Chain Department to develop the indicator system. Therefore, the values were set for baseline, current and desired levels and intervals required to apply the traffic light rating system. These values were set based on historical records provided by the same department. Table 1 shows the main attributes of this system.

2.1.1. KPI-I: indicator development procedure

At this point, the procedure will be detailed, from the initial moment of data collection to obtaining the results and graphs showing the performance of the indicator.

The first step is to digitalise forms containing information on truck arrival, including data, such as

Tab. 1. KPI-I system: truck punctuality

Truck punctuality KPI: indicator system	
Baseline level	The first measurement of the indicator taken in June of 2018 is considered the baseline level
Current level	The value obtained from the monthly measurement of the indicator is considered the current level
Goal	The proposed goal for this indicator is 90 % of punctual trucks obtained during a year
Traffic light rating system	The indicator limits are set using the traffic light rating system. The upper limit is 100 % (the maximum value of the indicator). The lower limit is 80 % of trucks on time, below which the situation is considered critical and requires corrective actions

arrival time (planned and actual), destination, owner of the truck, the quantity of product loaded (in the number of pallets) and loading time. A spreadsheet was used to prepare Table 2.

The information to complete Table 2 is obtained from the registration forms available in the loading area, which are completed manually by the personnel assigned to truck loading. The information in the table is updated weekly, on the last business day of the week.

The "Expedition" column holds information on the load destination and the loaded vehicle owner. For example, the destination is Berlin, and the vehicle owner is ABC Transport (fictitious name), the column "Expedition" should say "Berlin — ABC Transport". The "Status" column must indicate either "Punctual" or "Unpunctual", depending on the difference between the actual and planned arrival times. This column has a drop-down list with the two available options.

A two-hour margin in the difference between actual and planned arrival times is used as a tolerance range for determining the expedition status. Thus, if the truck arrives within two hours after or before the scheduled time, it is considered on time. Other parameter values of the indicator and the range for punctuality were determined by the leader of the logistics team, based on his knowledge regarding the delays in the arrival of trucks and the accuracy required by the rest of the process.

Table 3 shows the complete truck arrival record for the first half of June 2018. This month's values were taken as the indicator's baseline level since it was the first control. The information obtained during June and recorded in forms similar to the one shown in Table 3 was used to create two new tables with information relevant to the truck punctuality indicator. The first form records the number of trips that have complied with the arrival time for each expedition (Table 4); and the second form shows the KPI performance throughout the investigated period (Table 5). Each of the mentioned tables corresponds to a graph that helps visualise the data.

Table 4 presents the status (punctuality or unpunctuality) of the trips made for each expedition during a specific month. It helps to analyse the problems of truck punctuality in relation to each expedition, thus allowing to apply corrective actions to problematic expeditions.

The automatically completed Table 5 uses data from Table 4. Both tables are linked by spreadsheet formulas, reducing the user workload by not having to manually input the data.

Table 6 is the last table with information related to this KPI. It shows how the information related to the truck punctuality indicator is recorded and pro-

Tab. 2. Truck arrival and loading information form

Date	Expedition	Arrival time		Status	Loading time	Quantity of loaded pallets
		Planned	Actual			

Tab. 3. Example of Table 2 filled out in June 2018

Date	Expedition	Arrival time		Status	Loading time	Quantity of loaded pallets
		Planned	Actual			
6 Jun	A	7:00	8:00	Punctual	1:15	34
	B	9:00	8:45	Punctual	1:15	33
	C	7:00	7:30	Punctual	1:00	32
7 Jun	A	7:00	8:30	Punctual	1:45	53
	D	7:00	9:15	Unpunctual	1:00	33
8 Jun	A	7:00	8:00	Punctual	1:30	34
11 Jun	A	7:00	9:00	Punctual	1:15	34
	E	13:00	10:15	Punctual	0:45	33
	D	7:00	7:15	Punctual	1:00	33
12 Jun	A	7:00	7:30	Punctual	1:30	34

Tab. 4. Punctuality of trucks by expedition for all expeditions of June 2018

Expedition	Total	Status	
		Punctual	Unpunctual
A	15	14	1
B	8	7	1
C	2	2	0
D	2	1	1
E	3	2	1
F	2	1	1
G	3	2	1
H	1	1	0
I	1	1	0
J	1	0	1

Tab. 5. Percentage of punctuality per expedition in June 2018

Expedition	Punctuality %
A	93.33 %
B	87.50 %
C	100.00 %
D	50.00 %
E	66.67 %
F	50.00 %
G	66.67 %
H	100.00 %
I	100.00 %
J	0.00 %

Tab. 6. KPI-I performance: truck punctuality, an example of June 2018

Date	6 Jun	7 Jun	8 Jun	11 Jun	12 Jun
Number of trucks	3	2	1	3	1
Punctual	3	1	1	3	1
Percentage	100%	50%	100%	100%	100%
Goal	90	90	90	90	90
Lower limit	80	80	80	80	80
Upper limit	100	100	100	100	100

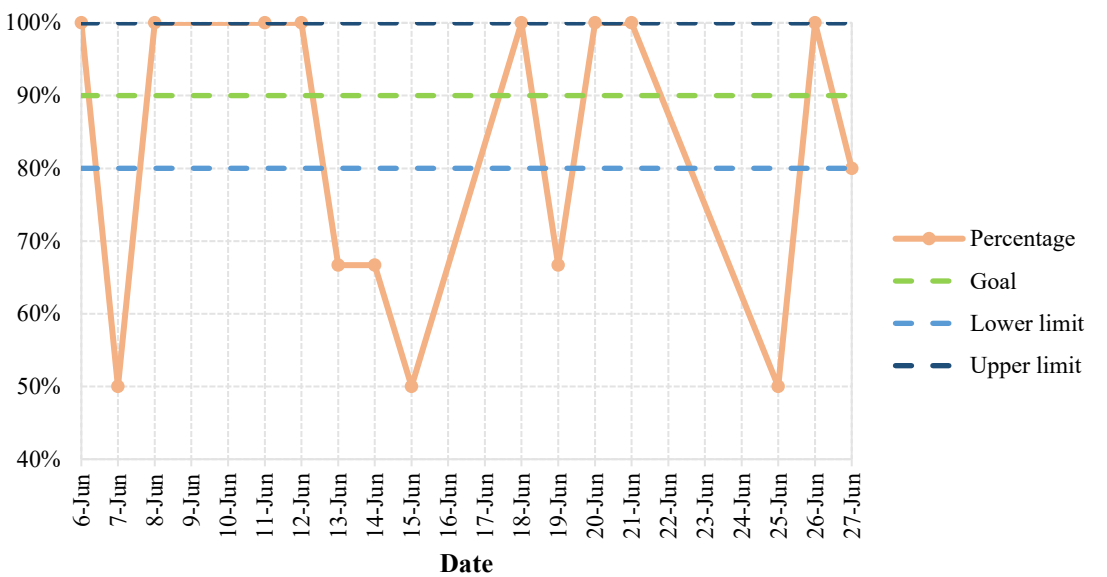

Fig. 3. KPI performance: truck punctuality (June 2018)

vides detailed information for some days of June 2018 as an example. The table lists the number of trucks that made deliveries and arrived at the company's warehouse on time for each working day of the month.

Also, it calculates the percentage of punctual over the total number of trucks for each day. However, Table 6 does not account for expedition codes since it shows the overall performance of the indicator, for which the goal for trucks arriving on time was established at 90 %, with lower and upper limits of 80 % and 100 %, respectively. Finally, for the first indicator, Fig. 3 is obtained from Table 6.

The information from Table 6 is clearly and simply shown in Fig. 3, where the percentage of trucks on time is indicated for each day of the month. It simultaneously displays the level established as a goal for the indicator and the lower and upper limits.

2.2. KPI-II: order picking errors

The logistics team of the Supply Chain Department is responsible for the delivery of finished products from the company's warehouse to different destinations.

The trip logistics include planning and decision-making on delivery frequencies, the quantity and variety of sent products, the outsourced carrier etc. Thus, as this team is responsible for sending the finished products, it receives and must process all documentation related to the dispatched merchandise, including delivery receipts.

In cases where the shipped products do not match (in terms of the quantity, product type or quality) the documents, the products are returned to the company along with the corresponding freight claim.

This indicator was initiated due to repeated problems and complaints regarding rejected deliveries or disagreements. It aims to determine the most frequent errors when preparing shipments made by trucks to apply corrective actions and avoid extra costs generated in the process.

Three types of errors were detected when preparing the orders:

- Picking incorrect products, i.e., others than indicated in the order. Although the company only produces vacuum cleaners, more than 300 different product variants are available.
- Picking correct products in wrong quantities, i.e., orders are delivered in greater or lesser quantities than ordered.
- Picking correct products and quantities but with defective quality, i.e., products that do not meet the corresponding quality requirements.

In addition to the mentioned errors, the possibility is considered that several different errors can be made in one order, i.e., all possible combinations of the basic errors are considered.

The information necessary to obtain the KPI-II indicator comes from the documentation that accompanies the delivery receipts signed in disagreement and freight claims. Due to the time required to receive and process these documents, it was decided to update the indicator monthly.

Tab. 7. KPI-II system: order picking errors

Order picking errors KPI: indicator system	
Baseline level	The first measurement of the indicator for May 2018 is taken as the baseline level. The measurement was taken during June since the required information was obtained over the past month
Current level	The value obtained from the monthly measurement of the indicator is considered as the current level
Goal	To be aligned with the "zero defects" policy adopted by the company, the goal for this indicator was proposed to ensure no errors in the order picking process for the shipments of finished products made by trucks
Traffic light rating system	Although the delivery receipts signed in disagreement indicated errors in order preparation, the information was not digitised. Therefore, no previous knowledge of the amount and types of errors made in preparing orders for shipment was available prior to the development and implementation of this indicator. Consequently, the results of the first indicator measurements are necessary to establish the parameter values for the traffic light rating system

2.2.1. KPI-II: indicator development procedure

Different possible errors in preparing orders are provided in Table 8 to clarify the indicator development. Errors and their combinations were coded to make the indicator record completion easier. Error E02 "Defective quality" is used when products to be reprocessed get dispatched as ready products. A clear example is packaging damaged during the process.

Table 9 presents a record in which the data about erroneously picked orders is entered on a monthly basis from the documentation that accompanies the order delivery receipts of the previous month.

The first step is to complete the "Date" column with the business days of the month. Then, the copies

Tab. 8. Types of order picking errors and their codification

Code	Type of error
E01	Wrong product
E02	Defective quality
E03	Wrong quantity
E04	Wrong product and quantity
E05	Wrong product and defective quality
E06	Defective quality and wrong quantity
E07	Wrong product, wrong quantity and defective quality

Tab. 9. Order picking errors for deliveries made by truck

Date	Code	Type of error	Quantity
Total			

Tab. 10. Order picking errors made in deliveries by truck for May 2018

Date	Code	Type of error	Quantity
2 May			
3 May			
4 May			
7 May			
8 May			
9 May			
14 May	E04	Wrong product and quantity	60
15 May			
16 May	E01	Wrong product	72
17 May			
18 May			
22 May			
23 May			
24 May	E02	Defective quality	24
25 May			
28 May			
29 May			
Total			**156**

Tab. 11. Truck order picking errors expressed in percentage and ppm for May 2018

Total amount of delivered units	Type of error	Quantity	%	ppm (1 % = 10 000 ppm)
39622	E01: Wrong product	72	0.18 %	1817.17
	E02: Defective quality	24	0.06 %	605.72
	E03: Wrong quantity	0	0.00 %	0.00
	E04: Wrong product and quantity	60	0.15 %	1514.31
	E05: Wrong product and defective quality	0	0.00 %	0.00
	E06: Defective quality and wrong quantity	0	0.00 %	0.00
	E07: Wrong product, wrong quantity and defective quality	0	0.00 %	0.00

of the delivery receipts of the same month are selected, and those with order picking errors are set apart. For each erroneously picked order, the information in the row corresponding to the date is completed as follows:

- In the "Code" column, the corresponding error code is entered from Table 8. This column has a drop-down list with seven error options.
- The "Type of Error" column is automatically completed based on the code selected in the "Code" column.
- The column "Wrong quantity" must indicate the quantity of finished product units that was wrongly picked in the order.

The procedure is repeated for all incorrect orders of the month. If one business day has picking errors in more than one order, a row is added for each wrong order, with the corresponding information (including the date).

Finally, the spreadsheet automatically calculates the monthly total of the "Wrong quantity" column, i.e., the sum of all incorrectly picked quantities.

Table 10 shows the complete record with the information for May 2018. The values obtained for that month were taken as the baseline level of the indicator.

Table 11 is derived from the information in Table 10, it calculates the proportion of truck order picking errors in percentage and in parts per million (ppm). Table 11 is automatically generated using formulas of the conditional sum type (for the "Quantity" column); while the percentage and ppm columns are automatically completed using multiplication and division formulas. These two columns calculate the percentage and parts per million of units that have been erroneously picked over the total units dispatched. The user must only enter the value of the first column, which indicates the total number of units delivered by truck during the month. The value is obtained by adding up the quantities of each shipment of the month.

3. Discussion

This section discusses the results obtained for each KPI. First, KPIs are presented, explaining their development and the results obtained during the evaluation period and then, their efficacy and relevance are analysed.

3.1. KPI-I (punctuality of trucks): analysis and discussion of results

The analysis of results requires considering Tables 4–6 and Fig. 3. Tables 4 and 5 show the results according to the expeditions, and Table 6 and Fig. 3 show the overall performance of the indicator throughout the studied month.

Based on Tables 4 and 5, expeditions A, B, C, H and I present a percentage of punctuality that is within the acceptable range (80–100 %). However, expeditions E and G with 66.67 % and D and F with 50 % are well below the lower limit. Finally, expedition J presents a 0 % punctuality (because the only delivery they made in June 2018 was behind schedule). Therefore, in the following months of evaluation, special attention should be paid to expeditions E, G, D, F and J, and their performance should be closely assessed in terms of punctuality. If the unpunctuality

problem persists, it will be necessary to take action and improve the situation.

On the other hand, Fig. 3 shows the overall performance of the indicator without considering the expedition variable. Of the 15 business days of the studied month, six days had the percentage of on-time trucks outside the expected limits. Of the remaining evaluated days (those that fall within the established range), eight of them have a 100 % punctuality, exceeding the target set of 90 %, while only one is below the goal, with a percentage of 80 % (the value equal to the lower limit).

As these values were obtained from the first evaluation of the indicator, they are considered the baseline levels. In the following measurements, the performance of the indicator will be re-evaluated to establish whether it maintains stable values, shows improvements or performs worse.

3.2. KPI-II (order picking errors): analysis and discussion of results

This subsection analyses the results obtained from the first measurement of the KPI-II associated with errors in the order picking process. The values from this first evaluation will be considered the baseline level for the indicator, proceeding in the same way as for the previous indicator.

Table 11 is required to analyse the indicator during the studied month (May 2018) as it shows the picking order errors in parts per million (ppm). Of the seven types of errors that may occur, only three were observed during the month: "Incorrect product" with 1817 ppm; "Wrong product and incorrect quantity" with 1514 ppm; and "Defective quality" with 605 ppm.

For a deeper analysis of the indicator's performance, the measurements of the following months are required. Once obtained, it will be possible to determine the types of errors that are repeated more frequently, and in greater quantities, and in turn, it will allow proposing and applying corrective measures to reduce their impact.

Conclusions

The indicators proposed in this article will allow offering and implementing improvements based on the analysis and monitoring of processes, identifying irregularities that hinder the normal development of operations. Also, the systematisation in the data collection process allows having reliable and real-time information, identifying those processes that are not being carried out correctly and implementing actions that contribute to their improvement. Therefore, this case study serves the purpose of showing the substantial potential of KPIs to address Supply Chain Management problems.

The implementation of more sophisticated technologies for data capture is considered as a future line of research, as well as the development of a decision support system that integrates the KPIs in the hierarchical decision process.

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An integrated approach for supply chain risk management

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ABSTRACT
Currently, every company is competing to improve the performance of their supply chain, and the efforts include loss mitigation, which requires risk management. This study aims to identify risks and develop risk mitigation strategies for Indonesia's "PT. SPLP" company. First, this study identifies every risk in the Supply Chain Operation Reference to determine the causes. A mitigation strategy is formulated based on the criteria. According to the study results, each division faced specific risks, and the best mitigation strategy was a briefing at the beginning of each shift. The results indicate that different data processing methods used by companies lead to various risks and mitigation strategy results. Risk management is carried out and evaluated at "PT. SPLP" regularly.

KEY WORDS
supply chain, risk management, house of risk, analytical hierarchy process

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Introduction

Globalisation made supply chains longer and more complex (Behzadi et al., 2018). They consist of every party, directly or indirectly involved in fulfilling a customer's request, including the system of organisations, people, activities, information and resources (Chopra, 2016; Singh & Verma, 2018; Madani & Wajeetongratana, 2019). Therefore, supply chain management can be defined as the integration of all involved business processes (Junior et al., 2018). Sup-

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ply chain management aims to increase the products' value (Militaru, 2019), facilitate the flows of goods, information and money through their design, management and coordination (Zhang et al., 2019; Soheilirad et al., 2017).

Undoubtedly, every supply chain management activity is related to risks, which can be defined as a combination of a hazardous event's likelihood and the severity of its consequences (Toyfur & Pribadi, 2016). Therefore, supply chains require risk management.

Risk management consists of planning, organising, leading, and overseeing risk management programmes (Maralis & Triyono, 2019). Supply chain risk management is an activity seeking to eliminate, reduce and control risks in supply chain activity (Raghunath & Devi, 2018). Supply chain risk management aims to identify, assess, mitigate and monitor the risks which might cause a loss in any part of a supply chain (Baryannis et al., 2019).

The heightened risks in increasingly complex supply chain networks have brought risk management to the forefront of research and managerial efforts. Supply Chain Risk Management (SCRM) refers to the management of supply chain risks through approaches coordinated among supply chain partners (Tummala & Schoenherr, 2011; Toyfur & Pribadi, 2016; Chakraborty, 2015; Komza, 2017).

Several recent articles have discussed the idea of collaborative or integrated risk management along supply chains to enhance performance. Tummala and Schoenherr (2011) performed risk management using the Supply Chain Risk Management Process (SCRMP) approach. This study found that the suggested tool could effectively help managers make strategic decisions. The SCRMP can be divided into several phases: risk identification, risk assessment, risk evaluation, preparation of mitigation plans, risk control and monitoring.

Li and Chen (2014) conducted a risk analysis in supplier selection using the Failure Modes and Effect Analysis method. This study was developed by generating two technical deliverables to support risk analysis. First, a framework was prepared to be filled with risks and an assessment of the criteria. Then, calculations were carried out based on the previous framework, and results were sorted to evaluate each supplier. The study results showed that Company H was the best supplier to meet methanol needs.

Sun et al. (2015) conducted a supply chain risk evaluation by studying risk causes based on the operating mechanism, essential characteristics, and results of previous research. Furthermore, the Fuzzy TOPSIS method with four criteria was proposed to evaluate the supply chain risks. As a result of this study, a Chinese manufacturer can choose the best scheme for its supply chain management with the lowest risk.

Hamid et al. (2017) prepared a risk management framework in the Oil Field Development Project. This study was conducted using the Fishbone Analysis method for finding possible risk causes. The study results indicate that potential risks in the Oil Field Development Project can be found and identified to formulate a mitigation strategy.

Pujawan and Geraldin (2009) proposed a supply chain risk management method by developing a House of Quality (HOQ) model with the calculation of Failure Mode Effect Analysis. It aims to rank the mitigation strategies based on the calculation results so that certain mitigation strategies can be prioritised based only on the effectiveness-to-difficulty ratio. The research demonstrated that conducting strategic negotiations with gas suppliers is the best mitigation strategy.

Some previous studies (Tummala & Schoenherr, 2011; Li & Chen, 2014; Sun et al., 2015; Hamid et al., 2017) found that supply chain risk management requires a process sequence, a tool for managers to make strategic decisions. Furthermore, any risk events and risk causes must be identified and assessed first. Several criteria are required to determine the best mitigation strategy that is also more accurate. Therefore, this study combines the House of Risk (HOR) method that assesses each risk event and risk cause and uses the Analytical Hierarchy Process to determine the best mitigation strategy based on several criteria.

This study also adopts the framework proposed by Ghadge et al. (2013) that includes risk identification, risk assessment, and risk mitigation. Risk identification is the first stage of risk management, which ensures risk management effectiveness. Risk managers need to identify possible losses that challenge the organisation to make the risk manageable (Kiprop, 2017). The risk assessment identifies and analyses the associated hazard and prioritises the risk by considering the available data (Ramesh et al., 2017; Accomaso et al., 2018). Risk mitigation is a stage of decision-making based on risk assessment (Bruinen et al., 2007).

Several more recent contributions are addressing risk management from the logistics perspective, such as managing risk with Supply Chain Risk Management Process (Tummala & Schoenherr, 2011), risk

analysis for the supplier using FMEA (Li & Chen, 2014), supply chain risk evaluation based on FUZZY TOPSIS (Sun et al., 2015), risk management in oil field development project using Fishbone Analysis (Hamid et al., 2017), and risk management using House of Risk (Pujawan & Geraldin, 2009).

However, a research gap still exists for investigating risk management with a systemic supply chain perspective, assessing important SCRM issues for severity, occurrence, and correlation between risk and its causes and prioritising the mitigation strategy based on several criteria. Hence, this paper aims to fill the gap by understanding the holistic risk assessment for SCRM by combining the House of Risk's Phase 1 (HOR 1) with the Analytical Hierarchy Process. This study aims to generate identified risks and determine the priority order of risk management strategies.

1. Research methods

This study focuses on the supply chain of the "PT. SPLP" company as a case study. The company specialises in Polyvinyl Chloride (PVC) compounds for cable insulation. The production requires around 3 to 15 tons of material for each customer. "PT. SPLP" runs the production non-stop, in three shifts per day. It has hundreds of customers scattered throughout Indonesia.

"PT. SPLP" has a complex supply chain to meet the needs of its customers. Unfortunately, it does not yet have risk management. Therefore, company divisions encounter risk-related losses, e.g., in 2019, the production met the target in only two months out of ten due to engine failure in the production line. Waste production also exceeded the limit for ten consecutive months due to machine errors and inaccuracy of workers. Risk management is necessary to reduce losses.

This study applied the House of Risk approach proposed by Pujawan and Geraldin (2009). First, the risk is identified and assessed; then, the risk mitigation strategy is formulated. The difference is in the part of the formulated mitigation strategy using various criteria to determine the best alternative.

The first data collection aimed to identify risks and their causes in each business process. The objective was achieved by interviews and questionnaires with each division's manager. The respondents were chosen for their knowledge of internal division business processes.

Once risks and causes were identified, an assessment was performed using the FMEA method, where each risk was measured for its severity, frequency and the level of correlation between the risk and its causes. This assessment process was also carried out using a questionnaire filled out by managers of each division.

Then, calculations were made using the House of Quality method for sorting the Aggregate Risk Potential (ARP) of each risk cause from the largest to the smallest. The risk cause with the largest ARP must be prioritised. Using the 80–20 concept, a Pareto Diagram was drawn to show risk causes with the greatest impact.

Once the risk causes were sorted, a mitigation strategy was drawn up based on interviews with division managers. However, several criteria are required to find mitigation strategies to be prioritised as the best. Therefore, the Analytical Hierarchy Process method was used at this stage to compute the importance of each criterion. Criteria weights were selected by division managers. Then, the managers also selected criteria weights for each mitigation strategy.

This series of methodologies was used to obtain the risks and their causes in each company's division to be prioritised for mitigation, the respective mitigation strategies, and the best mitigation strategies based on several criteria.

2. Results and discussion

In the risk management process, risk identification is required first. Risks existed in each company's division and could occur in every process. Therefore, the first data collection focused on the flow of activities within divisions, referred to as business processes. The benefit of knowing business processes in each division is the ability to explore each sub-process for possible risks. The data collection was organised through interviews with each division manager. Table 1 shows the summary of each division's sub-processes.

As already mentioned, these sub-processes were explored for risks that were assessed for severity and occurrence levels. This data was obtained during interviews with division managers to obtain risks and their causes. Questionnaires were used for division managers to assess severity and occurrence levels using the scale set by Geramian (2019). Table 2 lists the risks in each division, risk causes and severity and occurrence levels. The table provides 17 risk events

Tab. 1. Summary of sub-processes

SCOR process	Sub-process
Plan	Receive order
	Input the order to the ERP system
	Schedule the production
Source	Make sales order
	Receive sales order
	Check the inventory
	Purchase the material
	Receive the material
	Inspect the material
	Store the material
Make	Ask for material
	Prepare and deliver the material
	Process the material
	Test the finished goods
	Store the finished goods
Deliver	Store the finished goods
	Inform the delivery schedule
	Deliver the product
Return	Receive a defect claim
	Receive defect goods
	Create the TGA
	Inspect the goods
	Take the decision
	Retype/Reprocess
	Receive the Retyped/Reprocessed goods
	Deliver back the goods

Source: elaborated by the authors based on interview data.

and 25 risk causes. Severity levels range from one to ten, and occurrence levels range from one to six.

The correlation level between risk events and risk causes is required as it shows the influence of a risk cause in producing a risk event. The scale set by Pujawan and Geraldin (2009) was used to determine the magnitude. This data was also collected through the questionnaire filled out by division managers. Table 3 provides the correlation level between risk events and their risk causes.

The obtained severity, occurrence and correlation levels were processed using HOR 1. The purpose of using the method is to determine the number of ARPs for each risk cause. The risk cause with the largest ARP also indicates the largest calculation result for severity, occurrence and correlation. Thus the mitigation needs to be prioritised. Fig. 1 shows the calculation results for HOR 1, and Table 4 provides the sequence of risk causes with the largest ARP in cumulative percentage to apply the 80–20 concept. According to Fig. 1, RA19, "Low demand supplier", has the largest ARP. Tables 5 and 6 show 10 out of 25 risk causes prioritised to be mitigated based on the 80–20 concept.

Once 10 out of 25 risk causes were prioritised, the strategy for handling these risk causes needed to be planned. Mitigation strategies were also obtained through interviews with division managers. Table 5 shows risk causes and their mitigation strategies.

Several criteria are required to determine the best mitigation strategy. These criteria were obtained dur-

Risk Events	Risk Agents																								Severity
	RA1	RA2	RA3	RA4	RA5	RA6	RA7	RA8	RA9	RA10	RA11	RA12	RA13	RA14	RA15	RA16	RA17	RA18	RA19	RA20	RA21	RA22	RA23	RA24	RA25	
E1	9	3	9	3																						8
E2					9	9																				6
E3							9																			6
E4								9	1																	3
E5										3																5
E6	9		9	3							3															2
E7		1																								9
E8												1	3													10
E9														9												1
E10															9	3										1
E11														9												1
E12																	3	9								1
E13																			9	9						10
E14																					9	3				7
E15																							3			5
E16																								3		8
E17																									3	7
Occurrence	3	2	1	3	3	2	5	3	3	1	1	1	1	2	4	1	4	2	6	2	1	1	5	3	3	
ARP	270	66	90	90	162	108	270	81	9	15	6	10	30	36	36	3	12	18	540	180	63	21	75	72	63	
P	2	12	7	8	5	6	3	9	23	20	24	22	17	15	16	25	21	19	1	4	13	18	10	11	14	

Fig. 1. House of risk calculation
Source: elaborated by the authors based on Pujawan & Geraldin (2009).

Tab. 2. Risk activity and causes with severity and occurrence levels

	Risk activity	Severity	Risk causes	Occurrence
Plan	Production is not on schedule	8	Problem in processing machine	3
			Shortage of operator (absent)	2
			Natural disaster	1
			Power outage	3
Make	The finished goods do not match the spec	10	Formula incompatibility	3
			Human error	2
	Imprecise measurement	7	Dirty scales	5
	Damaged products	9	Production process does not match the SOP	3
			Humid environment	3
	Available inventory cannot be utilized	10	Damaged due to time (expired)	1
	Delay in production execution	1	Lack of raw material	1
			Problem in processing machine	3
			Natural disaster	1
			Power outage	3
	An error occurred the number of products produced	1	Shortage of operator (absent)	2
	High scrap rate	1	Change type of product	1
			Engine disassembly required	1
	Leakage of package items	1	Exposed to rain	2
Deliver	Delay in delivery to customers	5	Delivery request is too early	4
			Quality check requires long time	1
	The goods arrived at the customer in poor condition	8	Exposed to rain	2
Source	Delay in delivery raw materials from supplier	6	Material is still in production	4
			Stuck in port	2
	Price fluctuates	5	Low demand on supplier	6
			Exchange rate fluctuation	2
	Damaged raw materials from supplier	2	Bad packaging	1
			Moist in material	1
	Lack of raw material quantity from supplier	6	Material out of stock	5
	Difficulty in looking for items with appropriate spec	3	Not sold by all places	3
Return	Delay in return product to customer	7	Lot of production schedule	3

Source: elaborated by the authors based on questionnaire data and Geramian (2019).

ing interviews through the questionnaire on criteria weights. The Superdecision software and the Pairwise Comparison method were used for calculations. Fig. 2 shows the weight for each criterion. The most important criterion based on the Pairwise Comparison computation was "The result can be seen quickly".

Once criteria weights were found, mitigation strategies could be compared. The weighting was also done through questionnaires filled out by division managers. Weights of each mitigation strategy were also computed using the Superdecision software and the Pairwise Comparison method. Figs. 3–5 show the results of the mitigation strategy comparison.

According to Fig. 3, "Hold a briefing at the beginning of every shift" was the best mitigation strategy based on "easy to apply" criteria. It was also the best mitigation strategy based on "higher benefit-cost" criteria (Fig. 4). Based on criteria "The result can be

Tab. 3. Risk activity and agents correlation level

Risk event-code	Risk activity	Risk agent codes	Risk agents	Correlation
E1	Production is not on schedule	RA1	Problem in processing machine	9
		RA2	Shortage of operator (absent)	3
		RA3	Natural disaster	9
		RA4	Power outage	3
E2	The finished goods do not match the spec	RAS	Formula incompatibility	9
		RAS	Human error	9
E3	Imprecise measurement	RA7	Dirty scales	9
E4	Damaged products	RAS	Production process does not match the SOP	9
		RA9	Humid environment	1
E5	Available inventory cannot be utilized	RA10	Damaged due to time (expired)	3
E6	Delay in production execution	RA11	Lack of raw material	3
		RA1	Problem in processing machine	9
		RA3	Natural disaster	9
		RA4	Power outage	3
E7	An error occurred the number of products produced	RA2	Shortage of operator (absent)	1
E8	High scrap rate	RA12	Change type of product in the machine	1
		RA13	Engine disassembly required	3
E9	Leakage of package items	RA14	Exposed to rain	9
E10	Delay in delivery to customer	RA15	Delivery request is to early	9
		RA16	Quality check requires long time	3
E11	The goods arrived at the customer in poor condition	RA14	Exposed to rain	9
E12	Delay in delivery raw materials from supplier	RA17	Material is still in production	3
		RA18	Stuck in port	9
E13	Price fluctuates	RA19	Low demand on supplier	9
		RA20	Exchange rate fluctuation	9
E14	Damaged raw materials From supplier	RA21	Bad packaging	9
		RA22	Moist in material	3
E15	Lack of raw material quantity from suppliers	RA23	Material out of stock	3
E16	Difficulty in looking for items with appropriate spec	RA24	Not sold by all plates	3
E17	Delay in return product to customer	RA25	Lot of production schedule	3

Source: elaborated by the authors based on questionnaire data and Pujawan and Geraldin (2009).

seen quickly", "Apply the PLC programme" was the best mitigation strategy (Fig. 5).

Figs. 3–5 show the best mitigation strategy for each criterion. Fig. 6 is the computation result that determined the best strategy based on all the previously weighted criteria. It shows that "Hold a briefing at the beginning of every shift" is the best mitigation strategy based on all the criteria combined.

Supply chain management is an important concept at the "PT. SPLP" company. It aims to eliminate losses from risks in supply chain activities. Therefore, the company requires supply chain risk management to reduce the possibility of risks.

The first step in risk management is to identify risks in each company's division. Based on data in Table 2, 17 risk events were found in all supply chain

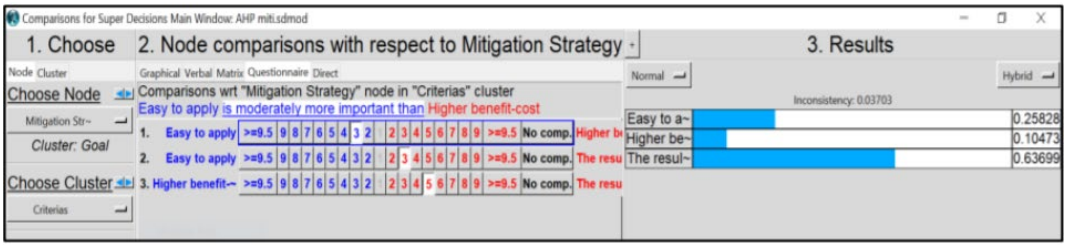

Fig. 2. Mitigation strategy criteria weight
Source: elaborated by the authors using the Superdecision software.

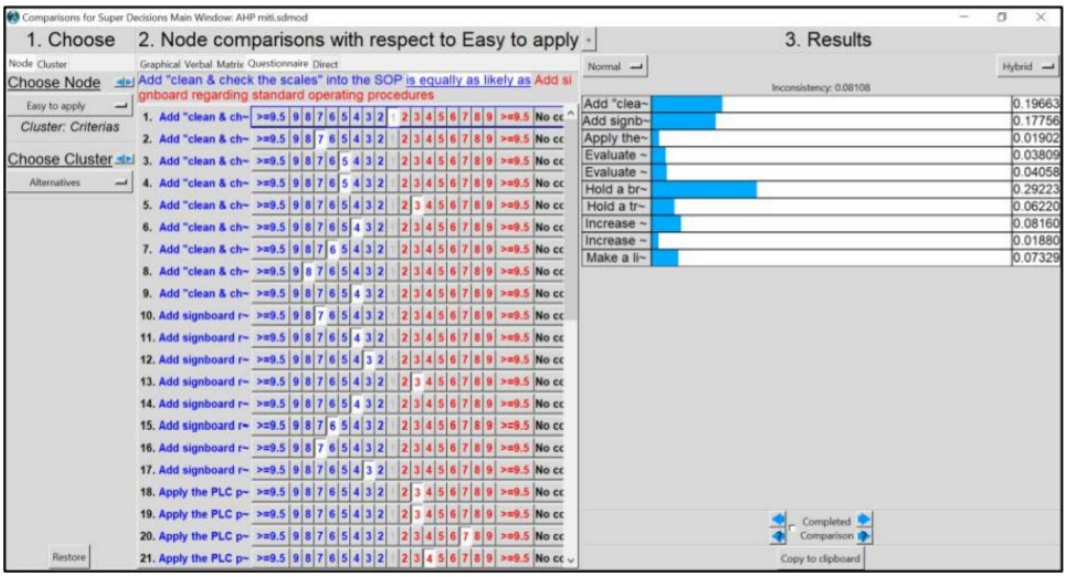

Fig. 3. Mitigation strategy comparison using first criteria
Source: elaborated by the authors using the Superdecision software.

Fig. 4. Mitigation strategy comparison using second criteria
Source: elaborated by the authors using the Superdecision software.

Fig. 5. Mitigation strategy comparison using third criteria
Source: elaborated by the authors using the Superdecision software.

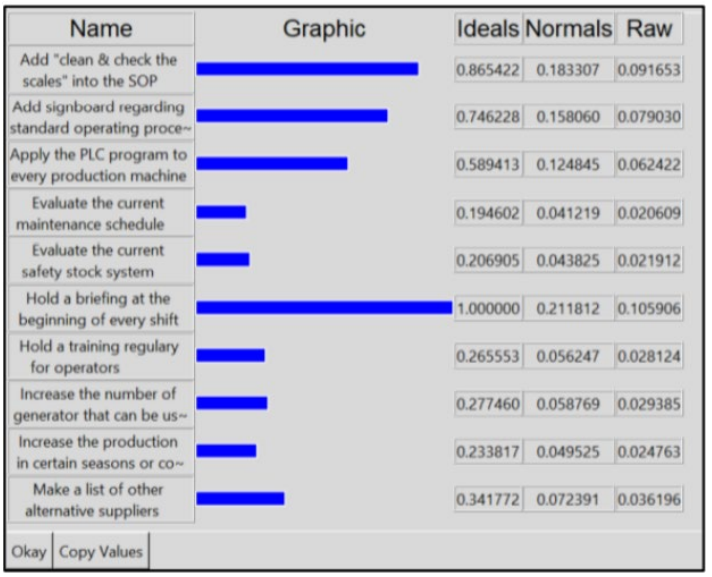

Fig. 6. Mitigation strategy computation result
Source: elaborated by the author using the Superdecision software.

activities. Most risk events were in the production process, which is not fully automated and works non-stop. All risk causes were assessed for their severity, and those with the highest level were related to the inability to use the inventory and finished goods not matching the specification. Such risks cause financial losses due to wasted production material.

Once risk events were identified, their causes had to be determined. Based on Table 2, 25 risk causes were found for 17 risk events, and some risk causes produced several risk events simultaneously. The risk causes with the highest occurrence level were related to low demand on suppliers resulting in fluctuating material prices. The correlation between risk causes and risk events was assessed and confirmed.

This study prioritised some risks by using the House of Risk method calculating severity, occurrence, and correlation levels. Then, using the 80–20

Tab. 4. Risk agent rank with cumulative percentage

P	Risk agent codes	Risk agents	ARP	%	%Cum
1	RA19	Low demand on supplier	540	23.22	23,22
2	RA1	Problem in processing machine	270	11.61	34,82
3	RA7	Dirty scales	270	11.61	46,43
4	RA20	Exchange rate fluctuation	180	7.74	54,17
5	RA5	Formula incompatibility	162	6.96	61,13
6	RA6	Human error	108	4.64	65,78
7	RA3	Natural disaster	90	3.87	69,65
8	RA4	Power outage	90	3.87	73,52
9	RA8	Production process does not match the SOP	81	3.48	77,00
10	RA23	Material out of stock	75	3.22	80,22
11	RA24	Not sold by all places	72	3.10	83,32
12	RA2	Shortage of operator (absent)	66	2.84	86,16
13	RA21	Bad packaging	63	2.71	88,87
14	RA25	Lot of production schedule	63	2.71	91,57
15	RA15	Delivery request is to early	36	1.55	93,12
16	RA14	Exposed to rain	36	1.55	94,67
17	RA13	Engine disassembly required	30	1.29	95,96
18	RA22	Moist in material	21	0.90	96,86
19	RA18	Stuck in port	18	0.77	97,64
20	RA10	Damaged due to time (expired)	15	0.64	98,28
21	RA17	Material still in production	12	0.52	98,80
22	RA12	Change type of product in the machine	10	0.43	99,23
23	RA9	Humid environment	9	0.39	99,61
24	RA11	Lack of raw material	6	0.26	99,87
25	RA16	Quality check requires long time	3	0.13	100,00
Total			2326	100.00	

Source: elaborated by the authors based on Pujawan and Geraldin (2009).

Tab. 5. Risk mitigation strategies

No	Risk codes	Risk agents	Mitigation strategy
1	RA19	Low demand on supplier	Make a list of other alternative suppliers
			Evaluate the current safety stock system
2	RA1	Problem in processing machine	Evaluate the current maintenance schedules
3	RA7	Dirty scales	Add “clean & check the scales” into the SOP
4	RA20	Exchange rate fluctuation	Evaluate the current safety stock system
5	RA5	Formula incompatibility	Apply the PLC program to every production machine
6	RA6	Human error	Hold a briefing at the beginning of every shift
			Hold a training regularly for operators
7	RA3	Natural disaster	Increase production in certain seasons or conditions
8	RA4	Power outage	Increase the number of generators that can be used
9	RA8	Production process does not match the SOP	Hold a briefing at the beginning of every shift
			Add signboard regarding standard operating procedures
10	RA23	Material out of stock	Make a list of other alternative suppliers

Source: elaborated by the authors based on interview data.

concept, ten risk causes were prioritised out of 25. The next step in risk management is to develop a mitigation strategy for each risk cause and obtain ten mitigation strategies in total. Several risk causes could be handled with several mitigation strategies, but one mitigation strategy can also handle several risk causes.

In determining the best mitigation strategy, several considerations are required in the form of criteria that are considered important. Three criteria were determined, and the Superdecision software was used to find that "the result can be seen quickly" was the best option. Furthermore, each mitigation strategy was compared with others based on criteria showing the best mitigation strategy for each criterion. "Hold a briefing at the beginning of every shift" was deemed the best mitigation strategy.

This study demonstrated that risk events and causes must be prioritised to be addressed by the best mitigation strategy based on several predetermined criteria. Therefore, it demonstrated the significance of supply chain risk management at the "PT. SPLP" company, which needs to be implemented, maintained and evaluated regularly.

In the supply chain literature, the risk management process has been proposed as a highly relevant theoretical lens to inspect SCRM issues, therefore, deserving more research. This study contributes to the SCRM literature by investigating risk management with a systemic supply chain perspective and assessing important SCRM issues from the standpoint of their severity, occurrence, and correlation between risks and their causes, also prioritising the best mitigation strategy based on several criteria. Moreover, this study contributes to the literature by empirically identifying risks and developing risk mitigation strategies at "PT. SPLP".

To the best knowledge of the authors, there are very few studies in SCRM literature that focus on the empirical investigation of the holistic method's role in mitigating supply chain risks and prioritising mitigation strategies. By doing so, this study seeks to address the call in the literature to test the integrated method on the SCRM effectiveness and, consequently, on performance outcomes (Tummala & Schoenherr, 2011; Li & Chen, 2014; Sun et al., 2015; Hamid et al., 2017; Chaudhuri et al., 2018).

The study findings suggest that integration of HOR 1 and AHP is important for assessing the supply chain risk and developing appropriate mitigation strategies. This finding extends the existing literature, which mainly focuses on the importance of an integrative method for a risk mitigation strategy. Furthermore, the results reveal that the proposed model builds for effective risk management and enhanced performance.

Conclusions

This study ranks identified risk causes based on severity, occurrence and correlation levels calculated using the House of Risk (HOR) method. Mitigation strategies for each risk cause were identified and sorted based on the criteria that are considered most important using the Analytical Hierarchy Process (AHP) method with the Superdecision software.

Based on data processing results collected in the studied company using a risk confirmation questionnaire, 17 possible risk events were identified in SCOR processes. One risk event was identified in "Plan" process, five — in the "Source" process, seven — in the "Make" process, two — in the "Deliver" process, and one — the "Return" process.

Questionnaire results indicated 25 risk causes, and ten of them were prioritised using HOR calculations. Ten mitigation strategies were identified based on ten risk causes that were prioritised previously.

Based on the results of the Analytical Hierarchy Process (AHP) using the Superdecision software, the best mitigation strategy is to hold a briefing at the beginning of every shift. This measure met all mitigation strategy criteria the most, followed by "Add 'clean & check the scales' into the SOP", "Add signboard regarding standard operating procedures", "Apply the PLC program to every production machine", "Make a list of other alternative suppliers", "Increase the number of generators that can be used", "Hold a training regularly for operators", "Increase production in certain seasons or conditions", "Evaluate the current safety stock system", and "Evaluate the current maintenance schedule".

Further research requires focusing on the relationship between risk causes as they may trigger other risk causes. Then, a programme can also simplify the calculation of supply chain risk management.

There are also some suggestions for the "PT. SPLP" company is to follow the practical implication contained in this study and establish supply chain risk management as a regular exercise.

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Understanding the adoption of autonomous vehicles in Thailand: an extended TAM approach

Sarawut Ramjan Purimprach Sangkaew

ABSTRACT

Autonomous vehicles (AVs) are receiving attention in many countries, including Thailand. However, implementing an intelligent transport system has many challenges, such as safety and reliability and the lack of policy supporting such technology use, leading to hazards for passengers and pedestrians. Hence, factors affecting the adoption of autonomous vehicles require better understanding. This research proposes and employs an extended Technology Acceptance Model (TAM) by integrating ethical standards, legal concerns, and trust to predict the intended use of autonomous vehicles by Thai citizens. A total of 318 questionnaires were collected from online panel respondents. Research hypotheses were tested using a structural equation modelling approach. The study results suggest that ethical standards have a significant positive effect on the intention to use the technology. Meanwhile, the intention was negatively affected by perceived usefulness, perceived ease of use and legal concerns. On the other hand, the results indicate that perceived ease of use directly affected trust, leading to AV adoption. However, other factors influenced trust insignificantly. This study demonstrates the vital role of trust in AV adoption. The study also suggests ideas for further study and discusses the implications for the government and autonomous vehicle companies. The article aims to forecast a success factor that the Thai government should use to consider the policy for autonomous vehicle adoption in Thailand. This paper relies on the technology acceptance model to assess and forecast autonomous vehicle adoption. The theoretical model also includes ethical issues, legal concerns and trust in technology. The model was analysed using the structure equation modelling technique to confirm the factor affecting Thailand's successful autonomous vehicle adoption. This research confirmed that ethical standards, legal concerns, and trust in technology are the factors significantly affecting the intention to use an autonomous vehicle in Thailand. On the other hand, the perceived ease of use significantly affects the trust in autonomous vehicle technology. This research found that such social factors as ethical standards, legal concerns, and trust in technology affect technology adoption significantly, especially technology related to AI operation. Therefore, the technology acceptance model could be modified to confirm technology adoption in terms of social factors. The government could use the research results to develop a public policy for the regulation and standard supporting autonomous vehicle adoption in Thailand.

KEY WORDS

Technology Acceptance Model, autonomous vehicles, trust, ethical, legal concerns, Thailand

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Introduction

Artificial intelligence advances are revolutionising and disrupting our society (Schwab, 2017). The effects of this technology can be observed in breakthroughs in various sectors, such as finance, healthcare and transportation (Bezai et al., 2021). Conversely, the ageing population, environmental and international security issues are the main chal-

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lenges for future urban development (Ejdys & Halicka, 2018; Manfreda et al., 2021). Thus, adopting the right technologies while protecting the environment could help address such challenges (Shao, 2020).

Among all emerging technologies, autonomous vehicles (AVs) are seen as having a vital role in addressing these issues. Introducing such technology to support the ageing society and reduce energy consumption offers unprecedented opportunities (Nelson, 2020). However, AV adoption still faces challenges. For example, the young generation is more likely to use AV than other generations (Manfreda et al., 2021). Consequently, it may not be worth investing in such technology to serve only one particular group of people. Also, AV adoption is associated with various risks. For example, the use of AV would negatively affect workers and service providers, such as truck and bus drivers.

Safety and privacy problems resulting from AV adoption are among the issues discussed globally (Ljungholm, 2020), as many unpredictable situations can occur when AVs share roads with other vehicles (Tho et al., 2019). This aspect has been noted in previous studies on AV adoption, suggesting that safety issues are likely to affect AV adoption strongly (Bezai et al., 2021; Manfreda et al., 2021). There are safety issues for AV passengers, pedestrians and other road users who could be harmed by AVs (Gill, 2020), which means that AV systems should be in good condition and robust. Another AV hazard is associated with the driving mode (full automation and no automation), which can lead to complications and miscommunication (Kangwansil & Leelasantitham, 2020; Roth, 2019; Straub & Schaefer, 2019). Hazards are not limited to a system failure; other potential risks are associated with cyberattacks (Kim, 2018) and ethical standards, such as accident liability caused by the technology (Roth, 2019). This is particularly important in developing countries where rules and regulations may not keep up with the advancement of technology.

Thailand aims to implement an intelligent transport system. According to the Thai National Strategy Report issued by the Royal Thai Government, by 2037, Thai citizens will have access to autonomous vehicle services in the major cities of Thailand (Chailungka et al., 2021). However, the adoption of such a transportation system in Thailand is uncertain as citizens remain unaware of its safety and do not know how such technology could enhance their quality of life. Therefore, if the Thai government aims to encourage the adoption of Avs, it is necessary to look into the factors that influence this process. Hence, this study aims to investigate the factors that affect AV adoption in Thailand, as the findings could assist in the planning of a suitable AV system to improve the quality of life of Thai citizens while also reducing cost and environmental damage.

This study addresses the above-mentioned aims by employing the Technology Acceptance Model (TAM), which is extensively employed in studies on system user behaviour in various contexts, such as Internet Banking (Rathnaweera & Karunasena, 2020), the Internet of Things (Park et al., 2017; Patil, 2016), e-learning (Thongkoo et al., 2020), wearable devices (Chang et al., 2016), event technology (Sangkaew et al., 2019), healthcare (Alhashmi, Salloum & Mhamdi, 2019; Sıcakyüz & Yüregir, 2020), websites (Noor et al., 2005) and online communities (Chung et al., 2010). Although TAM has been applied in various contexts, the application of this model for AVs is limited.

This study is divided into four main parts. The theoretical background is presented first, followed by the development of the conceptual framework and the hypotheses of this study. An explanation of the relationship between constructs is provided. The second part focuses on the research methodology and data analysis. Next, the results of this study are discussed, including the implications and limitations. The final part is dedicated to conclusions.

1. Theoretical background, hypotheses, and research framework

1.1. Autonomous vehicle

Autonomous vehicles are self-driving and have six levels of driving control (Williams, 2021). No automation is level 0, at which a human fully controls the car. Driver assistance is level 1, providing a human driver with steering and acceleration or deceleration support. Partial automation is level 2, operating many automatic car systems to support a human driver with steering and acceleration or deceleration. Conditional automation is level 3, at which a car uses the self-driving mode, and a human driver may intervene in the case of a possible incident. High automation is level 4, adopting the self-driving mode without human interference and managing unexpected incidents with the guideline system. The last level is full

automation and the full self-driving mode with a human becoming a passenger.

Thailand has many vendors importing autonomous vehicles (Chailungka et al., 2021). However, the Thai environment and, in part, the public infrastructure, streets and telecommunications do not support the full self-driving mode. Sensor technology would not communicate well under the current Thai infrastructure. Therefore, autonomous vehicles of level 3 could be sold in Thailand as they still support a human driver with some steering and acceleration or deceleration.

The Thai government experimented with an autonomous vehicle at a pilot area with installed sensor technology to support the full automation mode (Chailungka et al., 2021). Then, they expanded the experiment to a village, factory and hospital. An autonomous vehicle can transfer a product and passenger within a controlled area. However, an acceptance evaluation among Thai citizens is required before developing a digital public policy on autonomous vehicle implementation in Thailand (Chailungka et al., 2021).

Technology adoption studies are extensive. The Technology Acceptance Model (TAM), developed by Davis (1989), is one of the most popular frameworks in the study of technology adoption (Sangkaew et al., 2019). The TAM model is derived from the Theory of Reasoned Action (TRA) by Ajzen and Fishbein (Luarn & Juo, 2010; Sangkaew et al., 2019; Venkatesh et al., 2003), and explains the reasons affecting the success of adopting a technological solution and policy in many organisations and countries (Chao, 2019; Sıcakyüz & Hacire, 2020). This model is developed based on the assumption that the technology adoption not only depends on solid innovation but also individual user motivations (Liu & Chou, 2020) and that such motivations influence attitudes towards new technology, which leads to behavioural intention to use such technology (Sangkaew et al., 2019). These motivations are perceived usefulness (PU) and perceived ease of use (EOU) (Davis, 1989). Perceived usefulness is the degree to which technology users believe that adopting a given technology will enhance their job performance (Diop et al., 2020), whereas perceived ease of use refers to the expected level of difficulty involved in using such technology. These two determinants help technology developers to understand user behaviour and solve technology adoption issues (Mousa et al., 2021).

Although the traditional TAM framework was successful in investigating technology adoption in various contexts, this model does not integrate psychological factors, such as trust (Akbari et al., 2020; Chong et al., 2003) and facilitating conditions, such as ethical issues and policies (Hutchins et al., 2017; Manfreda et al., 2021), which seem to be essential drivers in the adoption of autonomous vehicles. Consequently, this study extended TAM (Davis, 1989) to investigate the adoption of autonomous vehicles in Thailand by integrating AI ethical standards, legal concerns and perceived trust. To be precise, this study argues that four core factors determine the adoption of autonomous vehicles in Thailand with trust as the mediator.

1.2. Perceived usefulness

TAM indicates that the perceived usefulness of technology has a direct impact on the individual's intention to use it (Raut et al., 2018; Yin et al., 2019; Zhao et al., 2018; Alzamel, 2021; Alraja, 2016) as it determines related benefits (Luarn & Juo, 2010). In this study, perceived usefulness refers to the expectation for autonomous vehicles to help Thai citizens travel for work or leisure. Previous research confirmed the influence of perceived usefulness on the behavioural intention to use a particular technology. Park et al. (2017) investigated the positive relationship between perceived usefulness and intention to use the Internet of Things. Similarly, Alhashmi, Salloum and Abdallah (2019) proved that perceived usefulness strongly impacted the intention to use artificial intelligence in healthcare. This study proposes the following hypothesis:

Hypothesis 1: Perceived usefulness positively affects the intention to use autonomous vehicles.

1.3. Perceived ease of use

Perceived ease of use indicates the degree of difficulty in using particular technology (Jamšek & Culiberg, 2020). In the current study, perceived ease of use refers to the convenience and ease that an individual will feel when using an autonomous vehicle. To be precise, this variable reflects the ease of autonomous vehicle operation and the resolution of possible problems. Many studies have shown that perceived ease of use also impacts the user's intention to use the technology (Patil, 2016; Thongkoo et al., 2020), which is supported by the findings on the wireless Internet (Lu et al., 2003), Internet Banking systems (Nasri & Charfeddine, 2012), social media (Lee et al., 2012), the Internet of Things (Patil, 2016),

Near Field Communication (NFC) (Luarn & Juo, 2010) and artificial intelligence (AI) (Alhashmi, Salloum & Abdallah, 2019). Thus, this study proposes the following hypothesis:

Hypothesis 2: Perceived ease of use positive affects the intention to use autonomous vehicles.

1.4. Ethical issues

Ethics refers to the rightness or wrongness of an action (Lee & Charles, 2021). As artificial intelligence (AI) can produce automated decision-making machines, some complex ethical issues need to be addressed (Wright, 2020; Zhou et al., 2020). In the context of autonomous vehicles, it means that technology should not harm people, and safety should be a priority (Yijia et al., 2019). In contrast to human-driven vehicles, it may be difficult to determine the proximate cause of accidents and other events that may cause damage to people and property. Additionally, there are also ethical issues regarding AI use (Hutchins et al., 2017). For example, citizens expect AVs to follow traffic laws like other vehicles (Prakken, 2017). Thus, manufacturers and governments face challenges in resolving such issues (Showalter, 2005). In this study, the ethical issues related to the production, development and regulation of autonomous vehicles, ensuring they do not threaten human life and property.

The impact of ethical standards on behavioural intention has been investigated in various contexts (Hadi et al., 2021; Lee & Charles, 2021; Nadeem & Al-Imamy, 2020). For instance, Lee and Charles (2021) showed that ethical standards affect repurchase intention in online retailers. Likewise, Nadeem and Al-Imamy (2020) suggested that ethics could drive the intention to create value in digital sharing economy platforms. Wang et al. (2020) found that consumer perceptions of AI significantly affected the intention of customers to use its service. The fear of privacy issues, security, reliability and service recovery, may prevent individuals from using autonomous vehicles. Thus, this study proposes the following hypothesis:

Hypothesis 3: Ethical standards positively affect the intention to use autonomous vehicles.

1.5. Legal concerns

AV-related privacy and security issues may restrict technology adoption (Carr, 2019; Manfreda et al., 2021) as it may impact people inside and outside the vehicle (Księżak & Wojtczak, 2020; Manfreda et al., 2021). In this research context, legal concerns refer to legal conditions covering the liability related to passengers, pedestrians and other drivers, which may affect the intention to use autonomous vehicles. The study by Manfreda et al. (2021) revealed that legal concerns led to defensive behaviour in AV adoption. The potential for AV malfunction and damages raises legal concerns among prospective adopters. Therefore, this study proposes the following hypothesis:

Hypothesis 4: Legal concerns negatively affect the intention to use autonomous vehicles.

1.6. Trust in technology

In technology studies, trust is a user's confidence in purchasing and using technology (Wang, 2011). More specifically, it refers to an individual's belief that a given technology's functionality and reliability will help them accomplish tasks despite the risks in the working environment (Akbari et al., 2020; McKnight et al., 2020). It is unquestionably an important factor influencing the intention to use new technology (Gempton et al., 2013; Hernandez-Ortega, 2011; Manfreda et al., 2021), as trust can help potential users overcome their scepticism or fear about using new technology (Akbari et al., 2020). This study refers to trust as the extent to which Thai citizens believe that using autonomous vehicles is reliable and safe.

Trust affects the intention to use autonomous vehicles despite possible convenience, saved time and reduced energy consumption (Nelson, 2020). Perceived usefulness, perceived ease of use, ethical standards and legal concerns have been included among trust-related factors in many information systems' studies investigating their influence on trust regarding the intention to use new technology (Amin et al., 2014; Coeckelbergh et al., 2016; Felzmann et al., 2019; Lui & Jamieson, 2003; Revels et al., 2010). For example, Amin et al. (2014) proved that perceived usefulness and perceived ease of use directly influenced trust in mobile phones. Likewise, Revels et al. (2010) stated that although mobile users enjoyed the flexibility of access and the use of many applications, trust was still considered the main antecedent to intention when compared to perceived usefulness and perceived ease of use. Furthermore, Lee and Wan (2010), who predicted the level of success of e-Ticket implementation in China by TAM, found that ease of use of technology had a significant effect on trust in technology usage. In terms of ethical standards,

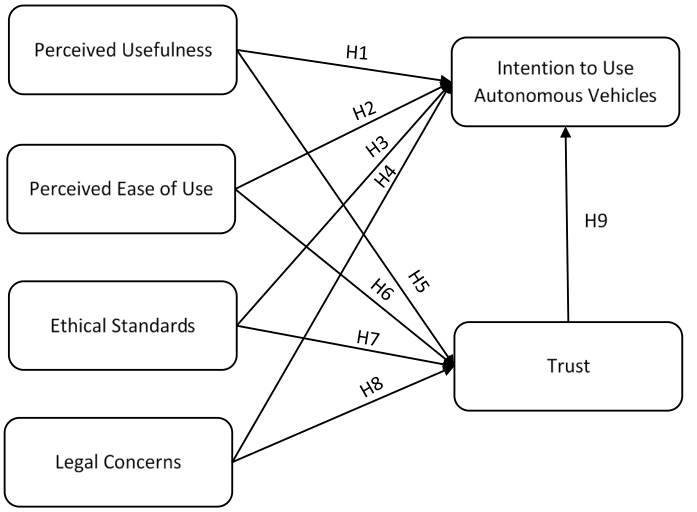


Fig. 1. Proposed model of technology acceptance for autonomous vehicles in Thailand

Coeckelbergh et al. (2016) found a strong relationship between ethics and trust. Their studies confirmed that individuals tended to trust robot assistance with children with an autism spectrum disorder. Furthermore, Felzmann et al. (2019) stated that the transparency of legal policy on artificial intelligence directly influenced trust in such technology. Although legal concerns may be a significant antecedent to the intention to use, transparency of legal issues in the specific context could strengthen the trust of technology users.

Hypothesis 5: Perceived usefulness positively affects trust.

Hypothesis 6: Perceived ease of use positively affects trust.

Hypothesis 7: Ethical standards positively affect trust.

Hypothesis 8: Legal concerns positively affect trust.

Numerous studies confirmed the significance of trust on the intention to adopt technology (Akbari et al., 2020; Gempton et al., 2013; Kaushik et al., 2015; Zolotov et al., 2018; Ejdys, 2020). For example, Luarn and Juo (2010) proved that trust directly affected e-wallet payments. Likewise, consumers with high levels of trust tend to have a greater intention to use online services (Al-Sharafi et al., 2017). In the case of highly reliable emerging technology, trust in 5G technology affects consumer expectations related to usage (Akbari et al., 2020). This seems significant when trust is based on benefits obtained from the technology (Liao et al., 2011; Ejdys, 2018). Lack of trust was one of the most common issues for those not wishing to use artificial intelligence (Gempton et al., 2013; Kaushik et al., 2015). Kaushik et al. (2015) observed defensive behaviour in using self-service machines in hotels, which reflected the lack of trust among consumers. Similarly, Gempton et al. (2013) revealed that the lack of trust was one of the reasons for not using autonomous vehicles by passengers. Different people have different opinions towards a given technology as they may expect different outcomes when using it. Consequently, trust plays a vital role in regard to perceived usefulness, perceived ease of use, ethical standards, legal concerns and, ultimately, the intention to use AVs. The positive effect of these four core factors increases the level of trust, which results in a greater intention to use autonomous vehicles. Therefore, this study proposes the following hypothesis:

Hypothesis 9: Trust positively affects the intention to use autonomous vehicles.

The constructs and their hypothesised relationships are presented in Fig. 1. The following sections present the research methodology and the results of this study, respectively.

2. Research methodology

2.1. Measurement development

The questionnaire consists of two parts. The first part presents the demographic profiles of the respondents, including age, gender and education. The second part involves the measurements of this

Tab. 1. Measurement items from the proposed model with references

Latent Variables	Observed Variables	Content	Reference
Perceived usefulness (PU)	PU1	Autonomous vehicles are a type of transportation that supports me when I am physically unable, such as drunk or sick	Alhashmi, Salloum & Abdallah (2019); Kangwansil and Leelasantitham (2020)
	PU2	When I am a passenger in an autonomous vehicle, I can do other activities	
	PU3	Overall, autonomous vehicles have improved my quality of life	
Perceived ease of use (PE)	PE1	I think it is easy to learn how to operate an autonomous vehicle	Alhashmi, Salloum & Abdallah (2019); Kangwansil and Leelasantitham (2020)
	PE2	I think I can understand the controls on autonomous vehicles	
	PE3	Overall, I think autonomous vehicles are easy to use	
Ethical standards (ES)	ES1	The autonomous vehicles company is liable for any damage caused by autonomous vehicles	Hadi et al. (2021); Lee & Charles (2021)
	ES2	When an autonomous vehicle is in unexpected situations, it ensures safe travelling	
	ES3	Overall, the determination of liability is an ethical issue for AVs	
	ES4	Overall, I think information regarding autonomous vehicles' ethics is clearly presented	
Legal concerns (LC)	LC1	The current law in Thailand is not yet capable of dealing with AVs due to their complexity	Manfreda et al. (2021)
	LC2	I worry about legal-related issues	
	LC3	I worry about cybersecurity-related issues	
Trust (T)	T1	I trust in the safety of autonomous vehicles	Akbari et al. (2020); Luarn & Juo (2010)
	T2	I trust that autonomous vehicles can protect me from accidents	
	T3	Overall, I trust autonomous vehicles	
	T4	Overall, autonomous vehicles are trustable	
Intention to use an autonomous vehicle (IU)	IU1	I definitely intend to use autonomous vehicles	Man et al. (2020)
	IU2	I expect that in the future, I will desire to use autonomous vehicles	
	IU3	Overall, I plan to use autonomous vehicles	

study, which adopted a deductive approach to operationalising the proposed conceptual model by obtaining the measurement items from previous studies (Hinkin, 2005). Scales measuring the latent variables, including perceived usefulness, perceived ease of use, ethical standards, legal concerns and trust, were derived from the literature on technology acceptance in general and artificial intelligence (AI) acceptance in particular. In addition, the items measuring intention were gathered from the literature on technology acceptance in various contexts. All measurement items used in this study are presented in Table 1. All items were measured using a Likert scale from strongly agree (5) to strongly disagree (1).

The survey was pretested using 50 industry professionals and academic researchers in the digital transformation field to check the research instruments' clarity, reliability and validity (Creswell & Creswell, 2017). Based on the pretest, the intercorrelation and validity of dimensionality were examined by employing Exploratory Factor Analysis (Hair, 2010). No items were eliminated. Therefore, six factors were tested: perceived usefulness (3 items), perceived ease of use (3 items), ethical standards

(4 items), legal concerns (3 items), trust (4 items) and intention to use (3 items).

2.2. Data collection and sample characteristics

This study employed a quota sampling method. Official census data from the Thailand National Statistical Office (2021) was obtained to calculate the adequate number of Thai respondents in the gender category. The online questionnaire was distributed between January and June 2021. A total of 320 questionnaires were returned; however, some were defective and eliminated, leaving 318 fully completed questionnaires. The demographic characteristics of respondents are shown in Table 2.

In summary, there were slightly more female (59.4 %) than male (40.3 %) respondents. The majority of the respondents were aged between 36 and 45, which accounted for 34 % of all valid questionnaires, and the group aged 25–35 accounted for 31.1 % of all valid questionnaires. Interestingly, the group aged 46–55 had the smallest sample size (22 %) in this study. The number of respondents with a bachelor's degree and middle and high school education were 250 and 52, respectively, which accounted for 78.6 % and 16.4 %, respectively. The proportion of those with a post-graduate degree was 5 %.

Tab. 2. Demographic characteristics of respondents (N = 318)

	Characteristics	Frequency	%
Gender	Male	128	40.3
	Female	189	59.4
Age	18 – 25	41	12.9
	26 – 35	99	31.1
	36 – 45	108	34
	46 – 55	70	22
Education	Middle and high school	52	16.4
	University (4-year college degree)	250	78.6
	Graduate School	16	5
Total		318	100

3. Analysis and results

3.1. Measurement model

This study employed Structural Equation Modelling (SEM) for data analysis to assess the causality between model parameters. Conducting SEM for data analysis, the model research should have: 1) an assessment of the measurement model's adequacy with Confirmatory Factor Analysis (CFA), and 2) tests of the adequacy of the structural model for hypothesis testing (Gerbing & Anderson, 1992; Bharadwaj & Deka, 2021). Therefore, CFA was performed to test the measurement model using AMOS 21.0. Several goodness-of-fit assessments were adopted to assess how measurement items were associated with the constructs. These include a value of 3.0 or lower for the ratio of Chi-square (X2) to degrees-of-freedom (d.f.), a value of 0.90 or higher for goodness-of-fit index (GFI), a normalised fit index (NFI), a comparative fit index (CFI) and the Tucker-Lewis index (TLI), a value of up to 0.80 for root mean square error of approximation (RMSEA) and a value up to 0.60 for standardised root mean square residual (RMSR) to determine acceptable model fit (Bagozzi & Yi, 1988; Hu & Bentler, 1999). In addition, three criteria for construct reliability and validity were employed: factor loading (0.70 or higher), average variance extracted (AVE) value to measure convergence validity (0.50 or higher) and composite reliability indicating internal consistency reliability (0.60 or higher) (Fornell & Larcker, 1981).

As shown in Table 3, one item with low factor loadings of below 0.50 was dropped from further analyses. Composite reliability (CR) scores of all constructs were above 0.6 (Fornell & Larcker, 1981); average variance extracted (AVE) scores exceeded the cut-off point of 0.50, indicating convergent validity (Fornell & Larcker, 1981). The X2 fit was 236.103 with 137 degrees of freedom ($p<0.000$). The goodness-of-fit index (GFI) presented a good model fit (i.e., GFI= 0.900; NFI = 0.946; SRMR = 0.20 CFI = 0.976; TLI = 0.971; RMSEA =0.048). Table 4 presents the discriminant validity of the construct in this study. The square root of the AVE between each pair of constructs exceeds the estimated correlation between constructs, thus indicating adequate discriminant validity (Bagozzi & Yi, 1988; Hair, 2010).

Tab. 3. Measurement model from confirmatory factor analysis

Constructs and variables	Standardised factor loading	CR	AVE
Usefulness		0.835	0.629
PU1. Autonomous vehicles are a type of transportation that supports me once I am physically unable, such as drunk or sick	0.798		
PU2. When I am a passenger in an autonomous vehicle, I can do other activities	0.778		
PU3. Overall, autonomous vehicles have improved my quality of life	0.804		
Ease of Use		0.808	0.587
PE1. I think it is easy to learn how to operate an autonomous vehicle	0.774		
PE2. I think I can understand the controls on autonomous vehicles	0.774		
PE3. Overall, I think autonomous vehicles are easy to use	0.744		
Ethical Standard		0.876	0.876
ES1. The autonomous vehicles company is liable for any damage caused by autonomous vehicles	0.802		
ES2. When an autonomous vehicle is in unexpected situations, it ensures safe travelling	0.800		
ES3. Overall, the determination of liability is an ethical issue for AVs	0.799		
ES4. Overall, I think information regarding autonomous vehicles' ethics is clearly presented	0.797		
Legal Concerns			
LC1. The current legal-related technology in Thailand is not yet capable of dealing with AV due to their complexity [c]		0.752	0.752
LC2. Worried about legal-related issues	0.830		
LC3. Worried about cyber security-related issues	0.720		
Trust		0.874	0.633
T1. I trust in the safety of autonomous vehicles	0.798		
T2. I trust that autonomous vehicles can protect me from accidents	0.782		
T3. Overall, I trust autonomous vehicles	0.789		
T4. Overall, autonomous vehicles are trustable	0.814		
Intention to use Autonomous Vehicles		0.902	0.754
IU1. I definitely intend to use autonomous vehicles	0.890		
IU2. I expect that in the future, I will desire to use autonomous vehicles	0.866		
IU3. Overall, I plan to use autonomous vehicles	0.848		

a. Model Fit Indices: X^2 = 236.103, df= 137; *sig* = 0.000; GFI= 0.900; NFI = 0.946; SRMR = 0.20 CFI = 0.976; TLI = 0.971; RMSEA =0.048.

b. CR = composite construct reliability; AVE = average variance extracted. c. Items were deleted after CFA analysis.

Tab. 4. Discriminant validity of the constructs in this study

	1	2	3	4	5	6	Mean	SD
1. Perceived Usefulness	*0.793*						4.005	0.69521
2. Perceived Ease of Use	0.586	*0.766*					3.883	0.66629
3. Ethical Standards	0.600	0.610	*0.935*				3.874	0.64307
4. Legal Concerns	0.485	0.491	0.533	*0.867*			3.872	0.68695
5. Trust	0.582	0.685	0.586	0.491	*0.795*		3.786	0.68980
6. Intention to Use	0.613	0.615	0.644	0.596	0.645	*0.868*	3.745	0.74590

Diagonal: correlation estimated between the factors; diagonal: square root of AVE.

3.2. Structural model

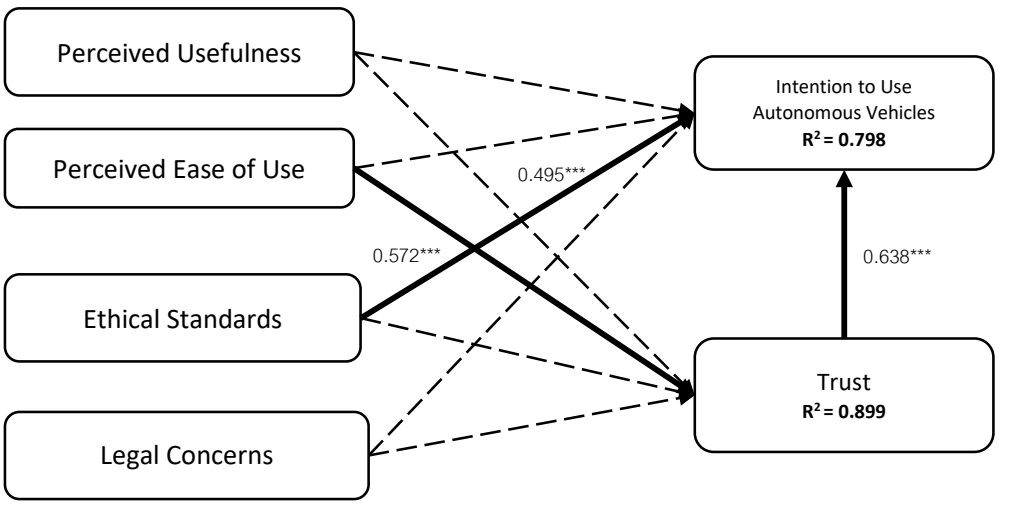
For the structural model, the X2 fit was 206.81 with 136 degrees of freedom (p<0.000). The GFI was 0.936, the NFI was 0.953, the RMSR was 0.16, the TLI was 0.979, the RMSEA was 0.041, and the CFI was 0.983. All fit indices in this study are confirmed, indicating that the estimated structural equation model is statistically suitable and valid for hypothesis testing. The squared multiple correlation (R2) for the structural equations for trust and intention to use AV were 0.899 and 0.798, respectively. Over 70 % of the variance (R2 = 0.798) in the intention to use AV was determined by the effects of trust, perceived usefulness, perceived ease of use, ethical standards and legal concerns. For trust (R2 = 0.899), most of the variance was explained by the effects of perceived usefulness, perceived ease of use, ethical standards and legal concerns.

The testing of hypotheses H1, H2, H3, and H4 determined whether perceived usefulness, perceived ease of use, ethical standard, legal standard affect the intention to use AV. Only one determinant of intention to use was identified; ethical standards positively affected the intention to use (β = 0.495, p = 0.01). On the other hand, three negative effects of intention to use were identified: perceived usefulness (β = 0.022, n.s.); perceived ease of use (β = -0.021, n.s.); and legal

Tab. 5. Standardised structural estimates and tests of hypotheses

Path (hypotheses)	Standardised coefficient	P-value	Results
H1 Perceived Usefulness → Intention to use	0.022	-	Rejected
H2 Perceived Ease of Use → Intention to use	-0.021	-	Rejected
H3 Ethical Standards → Intention to use	0.495	0.01	Supported
H4 Legal Concerns → Intention to use	-0.018	-	Supported
H5 Perceived Usefulness → Trust	0.161	-	Rejected
H6 Perceived Ease of Use → Trust	0.572	0.01	Supported
H7 Ethical Standards → Trust	0.188	-	Rejected
H8 Legal Concerns → Trust	0.080	-	Rejected
H9 Trust → Intention to use	0.638	0.01	Supported

a. Model Fit Indices: X^2 = 206.81, df= 136; *sig* = 0.000; GFI= 0.936; NFI = 0.953; SRMR = 0.16 CFI = 0.983; TLI = 0.979; RMSEA =0.041.



Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$;
Bold Line: Supported, Dash Line: Rejected

Fig. 2. Results of the structural model

concerns (β = -0.018, n.s.). Hence, the results provide support for hypotheses H3 and 4. However, H1 and H2 were not supported.

The set of hypotheses H5, H6, H7 and H8 examined whether perceived usefulness, perceived ease of use, ethical standards and legal concerns influenced trust. Perceived ease of use had a positive effect (β = 0.572, p = 0.01). However, three negative effects of trust were identified: perceived usefulness (β = 0.161, n.s.); ethical standards (β = 0.188, n.s.); and legal concerns (β = 0.80, n.s.). Thus, the results provide support for hypothesis H2 but do not support hypotheses H1, H3 and H4. Finally, the results confirm that trust positively affected the intention to use AV (β = 0.638, p = 0.01). Thus, H9 was supported. The results of the hypothesis testing are shown in Table 5. The results of the structural model are presented in Fig. 2.

4. Conclusions and implications

4.1. Conclusions

Autonomous vehicles are receiving attention in many countries, including Thailand. However, implementing an intelligent transport system has many challenges, such as safety and reliability and the lack of policy supporting the technology use, leading to hazards for passengers and pedestrians. Therefore, factors affecting the adoption of autonomous vehicles require better understanding. Few studies on autonomous vehicle adoption have investigated the effect of trust. Therefore, this study aimed to develop a theoretical framework that extends the TAM model by integrating ethical standards, legal concerns and trust and to test the effect of these factors on the intention to use autonomous vehicles. The study results suggest that Thai citizens are likely to use autonomous vehicles if this technology is perceived as trustworthy.

Previous studies in different contexts (Alhashmi, Salloum & Abdallah, 2019; Kangwansil & Leelasantitham, 2020; Park et al., 2017) demonstrated that perceived usefulness positively affected intention in the case of adopting the Internet of Things and artificial intelligence. However, perceived usefulness does not affect AV adoption (H1), implying that perceived usefulness is not an issue for potential adopters as the vehicles are assumed to be implemented as a form of basic transport in the near future. Thai residents expect to use intelligent transport systems regardless of the travel purpose. Similarly, the hypothesis regarding the perceived ease of use (H2) was not confirmed either. Patil (2016) and Alhashmi, Salloum and Mhamdi (2019) studied individual intention to use emerging technologies, such as artificial intelligence and the Internet of Things, and their results confirmed that the perceived ease of use is a factor in using these technologies. Less effort in using technology tends to encourage individuals to use it. However, in the case of autonomous vehicles, navigating may be fully controlled by a transport centre. Therefore, the complexity in using this technology may not be an issue for passengers unless there is an incident requiring the passenger's intervention.

Ethical standards (H3) and legal concerns (H4) were influential factors for AV adoption, but the former had a positive influence while the latter had a negative influence. The literature suggests that individuals perceiving artificial intelligence as reliable are more open to this technology (Lee & Charles, 2021; Nadeem & Al-Imamy, 2020; Wang et al., 2020). Furthermore, this study also found that the liability needs to be covered no matter the incident caused by an autonomous vehicle. Thus, before implementing this policy, the Thai government should investigate AI ethical issues, such as the production process, the import procedure, traffic laws, and the liability law. The findings are consistent with the study of Manfreda et al. (2021), who established that legal concerns negatively affected the intention to use autonomous vehicles. Legal concerns are among the factors that cannot be ignored when exploring the intention to adopt AV due to potential incidents using AV. For instance, the Thai government should have the policy to support passengers and pedestrians in the case of accidents. Once the vehicle is on the road, it affects more than just the passenger's safety.

Noticeably, the effects of perceived usefulness (H5), ethical standards (H7) and legal concerns (H8) on trust differ from the results of previous studies (Amin et al., 2014; Coeckelbergh et al., 2016; Felzmann et al., 2019; Lui & Jamieson, 2003; Revels et al., 2010). The negative effect of these factors implies that Thai citizens who may trust autonomous vehicles do not consider their usefulness, ethical standards or legal concerns. Although these factors do not seem to be an issue in this study, the government should not ignore them as they could strengthen the level of trust in the technology. Interestingly, Thai user perceptions about the ease of use of autonomous vehicles (H6) positively affect trust in the use of autonomous vehicles. This is in line with studies by Lee and Wan (2010) and Revels et al. (2010), which revealed the effect of

ease of use on trust in the context of emerging technology. This means the convenience of autonomous vehicles is crucial in enhancing trust among Thai citizens. Hence, the Thai government should prepare measures related to imported autonomous vehicles that start at automation level 3 (conditional automation) (Poisson et al., 2016). This level is a form of autonomous driving that allows a human driver to intervene in certain situations. Automation modes support the ease of use of autonomous vehicles.

Finally, trust has a significantly positive effect on Thai citizens' intention to use AVs (H9), which is consistent with previous studies (Akbari et al., 2020; Gempton et al., 2013; Kaushik et al., 2015; Zolotov et al., 2018). Additionally, trust also plays a mediating role between perceived usefulness, perceived ease of use, ethical standards, legal concerns and the intention to use AVs. This could mean that trust strengthens the level of confidence among Thai citizens, increasing the level of autonomous vehicle adoption.

4.2. Implications and limitations

Few studies have investigated the adoption of autonomous vehicles. Thus, this study aims to examine factors influencing autonomous vehicle adoption. The results of this study have both theoretical and practical implications. First, it extends TAM by integrating other factors, such as ethical standards, legal concerns and trust, which had positive and negative impacts on the intention to use autonomous vehicles.

For the practical implications, this study provides insight that may assist the government in preparing strategic plans and implementing infrastructure development to support the use of autonomous vehicles in Thailand. For example, the findings show that ethical standards affect autonomous vehicle adoption. The Thai government should initiate a policy related to autonomous vehicles ethics and industry standards, including public transportation, which will use autonomous vehicles in the near future. Another important implication for the government is related to the role of trust. The study found a highly significant and positive relationship with the intention to use. Thus, to enhance citizens' trust in autonomous vehicles, the government should encourage trust. For instance, developing Internet of Things technologies could support autonomous vehicle communication with other vehicles and satellites. Furthermore, the improvement of road surfaces would help the government reduce hazards related to autonomous vehicle use. The study also suggests that the intention to use is related to perceived usefulness, perceived ease of use, ethical standards and legal concerns as mediators of trust.

Some limitations of this study should be noted. First, it examined the opinion of citizens in a single country. The technology is relatively new and not yet widely analysed; thus, the results may not be generalisable. Future research should investigate these issues in different countries and under different legal conditions that could affect the intention to use autonomous vehicles. Another important limitation of this study is related to the mode of autonomous vehicles (e.g., full automation and no automation). This study did not address such distinctions. Hence, indicating the mode of autonomous vehicles may provide more insightful findings that may assist in decision making. Autonomous vehicle companies may be interested in identifying the differences for each mode since it could help them identify their target market more effectively. Different AV modes may result in different levels of trust. Lastly, this study also shows that AV adoption factors are required since perceived usefulness, perceived ease of use and legal concerns were found to have negative effects on the intention to use. Consequently, future studies in this area need to be conducted to obtain more detail.

To sum up, rapid technology development will transform passenger transportation in many countries. The use of autonomous vehicles will change transportation businesses and impact the citizens' quality of life. To keep up with this paradigm shift, governments have to provide standards, policy and a supportive environment that facilitates business efficiency and competitiveness.

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Digital twin technology — awareness, implementation problems and benefits

Małgorzata Gulewicz

ABSTRACT
Aiming to ensure current market needs, manufacturing companies search for tools and methodologies that would help them deliver their products efficiently and cost-effectively and enable them to become a part of Industry 4.0. Digital twins are a technology created based on the idea of the Fourth Industrial Revolution. The solution helps recreate physical devices in virtual space based on gathered data. It supports performance tests, configuration changes, and predictive maintenance without engaging existing machines. The paper aims to gain knowledge about the awareness level of the digital twin technology among industry representatives and identify the most important problems that stand in the way of implementing the technology in enterprises. The research focused on market awareness of the described technology. It also examined how companies use employee suggestions to improve their organisations and the factors that influence process efficiency. The methods used for the research were a literature review and cross-sectional survey conducted with 50 employees of manufacturing and IT companies. The research showed the need to implement digital twins in enterprises. Half of the survey respondents replied that the technology would help improve the efficiency of the company's processes. The main benefit of the conducted research is identified awareness of the technology among industry representatives. In the future, the research will be extended to include the analysis of specific cases affecting the implementation of digital twins in enterprises.

KEY WORDS
Industry 4.0, digital twin, cyber-physical system, Internet of Things

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Introduction

In 2010, the German government introduced the concept of Industry 4.0. (German: Industrie 4.0.), which was very quickly adopted by foreign economies. "The concept of 'Industry 4.0' is, in general, to use the automation and digitisation processes of the industry that have been taking place in German industry for years to transform existing factories into self-steering and self-adaptive socio-technical systems (Smart Factories), allowing for the creation of intelligent value

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chains (...)" (Bendkowski, 2017). The Fourth Industrial Revolution is built based on the widespread Internet access and the collection of large amounts of data that "must be processed and managed" (Gajdzik, 2018). This concept integrates people, machines, and processes. The collected information allows the effective management of production processes and the adaptation of these processes to the current market needs. "Determinants of the development of industry at the 4.0 level are shorter product lifecycle, shorter manufacturing cycle, short production series, increased product range, personalisation of products, integration of information technology (IT) with operational technology (OT), increase in the development of devices such as automats, robots, chatbots, change of manufacturing processes to processes with parameters of high productivity and precision of product execution" (Gajdzik, 2018). The challenges faced by the economy are overcome by implementing new ICT (information and communication technologies) solutions and methodologies, which allow adapting enterprise processes to the Industry 4.0 requirements (Szum & Magruk, 2019; Bialobrodzki et al., 2020; Siderska, 2021).

The digital twin technology is a solution related to Industry 4.0 that has been gaining popularity in the manufacturing sector.

The first definition was created in 2002 by Michael Grieves in reference to product management issues. "A digital twin in its original form is described as a digital-information construct about a physical system, created as an entity in its own right and connected to a given physical system. The digital representation should optimally contain all the information about the system's resources that could be obtained by analysis in the real world." (Kritzinger et al., 2018). Another definition indicates that "A digital twin is a mathematical representation (mathematical model) of physical objects in a virtual layer within cyber-physical systems.

The mathematical model of the object processes data from sensors installed on a specific object and data associated with the object, with both physical and virtual sensors present at the sensor level (Maintenance, 2016)" (Gajdzik, 2018). This solution allows a digital reproduction of any physical object and entire groups of objects and processes. The resulting virtual copies can support a range of activities, such as configuration changes, performance tests, and simulations, saving time and resources as this is done without stopping production lines or involving physical devices.

The digital twin technology is also useful for changes in management methodologies of manufacturing companies. Companies are looking for new ways to adapt their organisation's operations to changing market conditions, increasing their competitiveness while reducing waste of resources and reducing costs. These changes concern processes within the organisation and the entire supply chain.

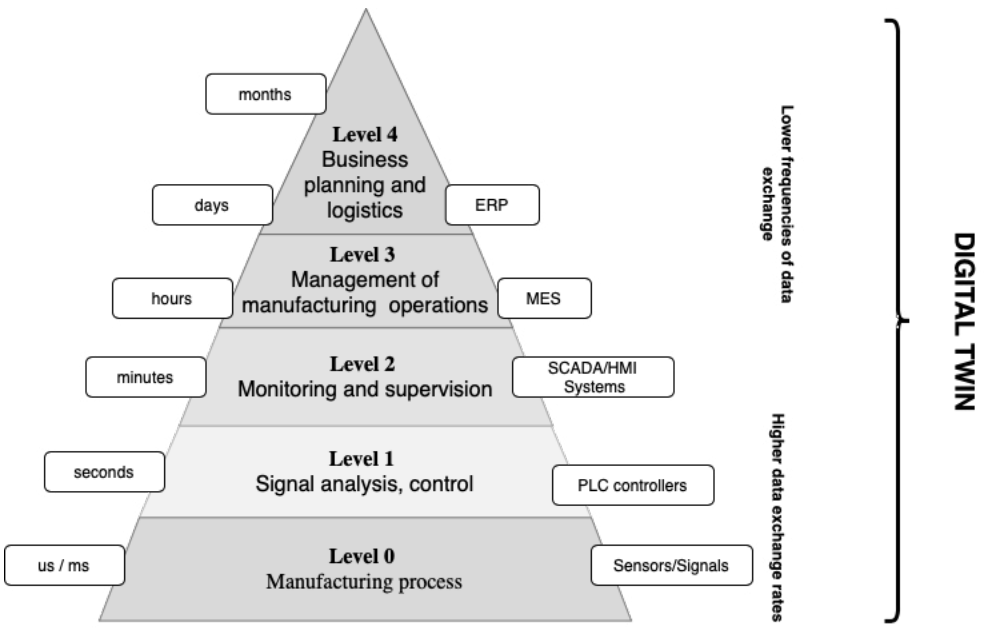

Fig. 1. Levels of management and automation of processes in a company
Source: Elaborated by the author based on (Akerman, 2018, p. 2).

Fig. 1 presents the individual levels of management and automation of processes in an enterprise, indicating the systems currently supporting their implementation and the frequency of data exchange. In the author's opinion, the digital twin technology occurs at all levels of automation and allows to monitor the work of individual devices horizontally and vertically to maintain and optimise them predictively. It enables a synergic combination of MES (Manufacturing Execution System) features and SCADA (Supervisory Control and Data Acquisition) class solutions. From a micro perspective, it consists of descending to the level of data collected from individual sensors, their observation, and analysis for further use and optimisation. It allows for internal detection of deviations from the norm, bottlenecks, performance problems, and their improvement through monitoring of parameters and work indicators. On a macro scale, it enables the management of specific sub-processes and processes involving more than one machine and, thus, impacts the entire company's operation and, consequently, the possibility of its self-improvement (Barni et al., 2020).

This article is divided into four parts. The following part of the article describes the literature review related to the topic of "Digital Twins" over the past years. The next part addresses the research method. Then, the article presents the results of a survey conducted by the author and a discussion of the conducted analyses and findings. The last part presents conclusions, limitations and defines further research directions.

The paper aims to gain knowledge about the awareness level of the digital twin technology among industry representatives and identify the most important benefits and problems that stand in the way of implementing the technology in enterprises.

1. Literature review

Initially, a review of literature trends in the SCOPUS and Web of Science databases was performed, which showed that the term "digital twins" is becoming more popular every year. Based on the analysed literature, the author identified the research gap as a lack of information on the awareness level of the digital twin technology and the identification of problems that may prevent the implementation of the technology in Polish enterprises.

A query was performed in the SCOPUS database using the phrase "digital twin" (Fig. 2). Before 2016, the number of new publications did not exceed ten per year. Since 2016, the interest has shown noticeable growth with 24 new publications. In the following years, the number of articles was as follows: 114 in

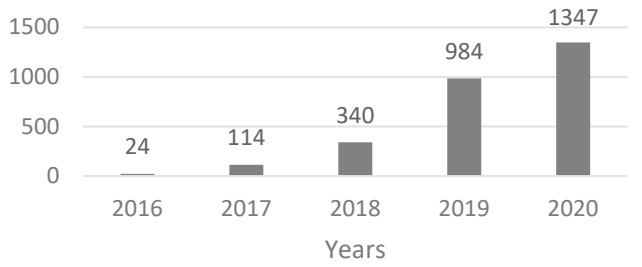

Fig. 2. Number of publications in the Scopus database per year

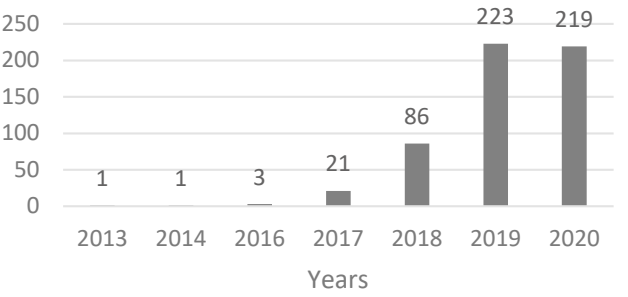

Fig. 3. Number of publications in Web of Science per year

2017, 340 in 2018, 984 in 2019, and 1 347 in 2020. After 2020, the total number of all articles in the database relating to digital twins was 2 920.

An analysis of the Web of Science database revealed 540 entries containing the phrase "digital twin". The first publication dates back to 2013 and concerns the development of an ICME-based digital twin model of a single-composite aircraft fuselage (McWilliams et al., 2013). A significant increase only occurred in 2017. Fig. 3 shows the number of publications in the Web of Science database by year.

The author verified the relationship between the analysed technology and other disciplines based on network building methods and cluster creation used in the paper by Gudanowska (2017). The overall analysis showed that the concept of digital twins mainly occurs in two areas: "Engineering" and "Computer Science". The other areas are: "Mathematics", "Decision Sciences", "Energy, Material Science", "Physics and Astronomy", "Business", "Management and Accounting", "Earth and Planetary Sciences", and "Social Sciences".

Fig. 4 and 5 show the scheme created based on a graph generated in VOSviewer (Halicka, 2017; Winkowska et al., 2019; Siderska & Jadaan, 2018; Szpilko, 2017; Szum, 2021) regarding the co-occurrence of the term "digital twin" with other terms. After optimisation, six clusters were obtained.

Cluster 1, "Data management", created in VOSviewer, contains concepts related to learning, forecasting, decision-making, and prediction. It includes issues related to artificial intelligence and predictive maintenance, the operation of which is largely based on the previously mentioned concepts. Cluster 2, "Modeling and design", is a group of concepts related to data visualisation and modelling, product, and lifecycle management. The strongest cluster group is the term "lifecycle management" mentioned 166 times, and its strength of connection with the term "digital twin" is 580, which is the second strongest connection. Terms in Cluster 3, "Industry", relate to manufacturing and industry. In this group, it is worth noting the term "manufacturing", mentioned 195 times, whose strength of connection with the

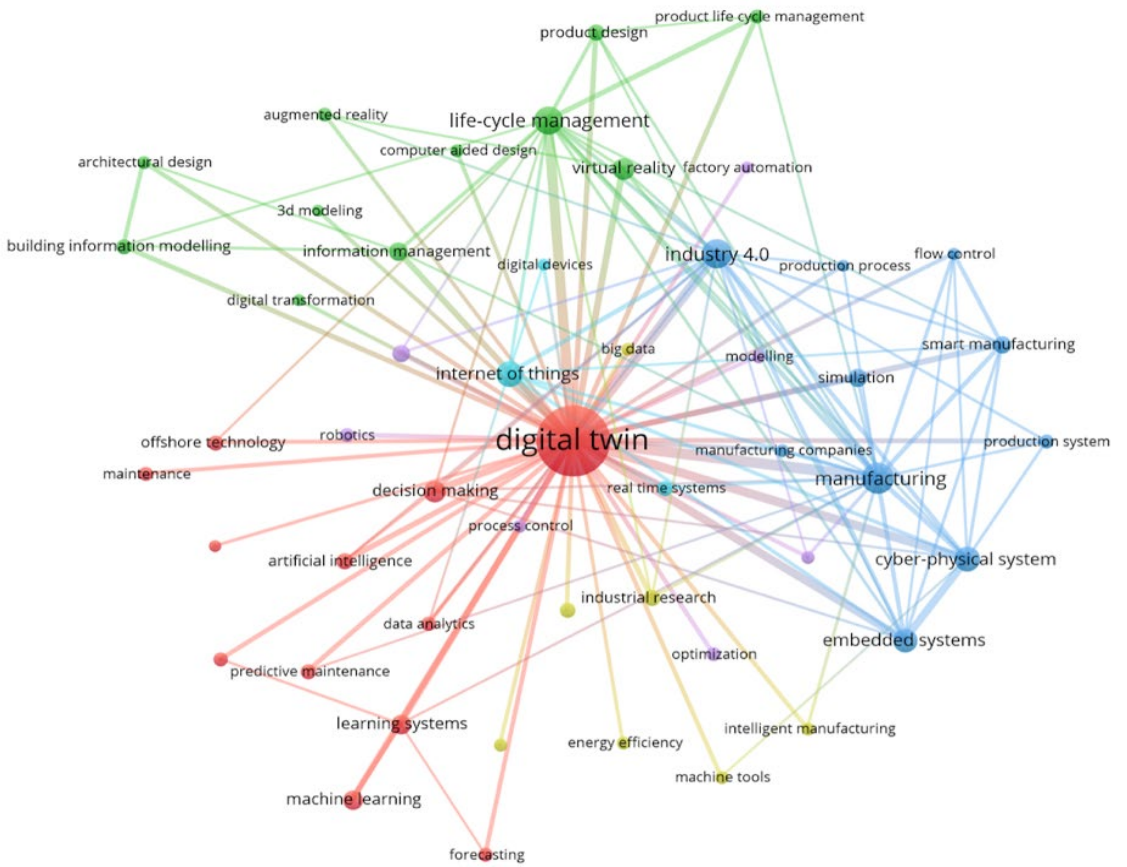

Fig. 4. Association graph obtained in VOSviewer

Fig. 5. Clusters obtained in VOSviewer

term "digital twin" is 683. Cluster 4, "Architecture and data storage", contains concepts related to the management and storage of data and industrial research. Cluster 5, "Processes and automation", brings together concepts relating to the modelling, control, and management of processes and their optimisation. Cluster 6, "Systems and devices", has three concepts: "digital devices", "Internet of Things", and "real-time systems".

The study showed a strong correlation of terms "digital twins" and "manufacturing", "Industry 4.0",

"Internet of Things", "lifecycle management", "embedded systems", and "cyber-physical system". A noteworthy aspect is the increasing occurrence of phrases "information management" and "decision making" concerning the digital twin technology, which suggests that this technology is considered not only in the context of technical aspects and benefits but also as a tool for managing processes and products in companies.

Articles on digital twins tend to address specific use scenarios, specific cases. This indicates a lack of generic technology applications to cover broader areas.

The literature survey showed a frequent occurrence of the digital twins' topic with the terms "industry 4.0", "predictive maintenance", "manufacture", and "lifecycle management". This correlation may indicate areas where the digital twin technology is currently developing the strongest and most frequently find its applications. Based on the review presented above, to confirm the thesis on the use of the described technology in the manufacturing sector, an analysis of representative examples of the use of digital twins in manufacturing sector companies was performed, and the nature of benefits was determined in individual cases.

Europe is the largest supplier of production equipment. Nevertheless, in recent years, more and more suppliers from Asian countries have appeared in the market (Armendia et al., 2019). Increasing competitiveness of suppliers from Europe is closely related to the implementation of Industry 4.0 postulates in enterprises. The development of ICT, such as CPS (Cyber-Physical Systems), IoT (Internet of Things), or cloud systems and the increase of process knowledge through data monitoring has a significant impact on the perception of machine design and use processes in companies.

They enable significant improvements to be made at the design stage and throughout the product lifecycle, as well as increasing Overall Equipment Effectiveness (OEE). OEE is an indicator used to determine the performance of machine fleets and is a combination of availability, productivity, and quality (Shanghua et al., 2020).

Additionally, to reduce maintenance costs and ensure a high level of equipment operability, companies tend to move away from reactive to predictive maintenance (Sasiadek & Basil, 2018). Predictive maintenance is "a strategy assuming optimal use of machinery and equipment by eliminating the occurrence of failures and optimal planning of maintenance works based on technical condition survey" (Gunia, 2019). The main objective of predictive maintenance in the manufacturing sector is to avoid downtime of production lines and to determine when equipment service will be necessary. The basis of predictive maintenance is to have prior information about possible failures that may happen in a specific period (Wisniewski, 2010). Such knowledge allows to order earlier inspections, service parts of the line and thus prevent downtime in the factory (Plinta & Banach, 2015). As an example of the implementation of predictive maintenance with the help of a digital twin, it is possible to point to making calculations of the Remaining Useful Life (RUL) of equipment (Aivaliotis et al., 2019).

Manufacturing companies frequently face problems with physical equipment tests due to downtime and high repair costs. Obtaining failure data from the physical device seems to be the best solution, but it is not a common practice. A digital twin allows determining the parameters of equipment operation during a failure to generate specific data to learn algorithms (e.g., predictive ones). Repair of specialised equipment is expensive, so many companies use the predictive model as a way to reduce potential costs. The implementation of this maintenance model is enabled by pre-collected data from sensed equipment that can be used to create algorithms to predict failure (Tomkowiak & Kolinski, 2010).

Table 3 presents the most important areas for the use of digital twins and possible benefits to the enterprise. This study showed groups of organisational and technological benefits, analogous to Kaizen methodology areas implemented in enterprises (Mauer, 2017; Piotrowska, 2011; Piasecka-Gluszak, 2011).

The organisational benefits relate mainly to human resources, financial, and management processes in the company, while the technological benefits cover the area of production process management and production efficiency, with a particular emphasis on infrastructural and technological aspects (Yuik et al., 2020).

Both cases concern the organisational sphere supporting financial and employee processes and processes related to knowledge collection and sharing, and the technological sphere covering infrastructure, production processes and their optimisation (Philbin & Kennedy, 2020; Lyp-Wronska, 2016).

Based on the literature study and the analysis of the benefits from implementing digital twin technologies in a company, a survey was conducted to assess the familiarity of industry representatives with digital

Tab. 1. Examples of the use of the digital twin technology

Example of use	Method of use	Benefits
Predictive maintenance	Gathering information about possible failures that may occur within a specific period	Reduce maintenance costs and downtime [O]; Ensure a high level of operability of the equipment [T]; Carry out simulations to determine when failure may occur (e.g., in the case of an increase in the temperature of the equipment), including performance tests of the infrastructure [O]; Possibility to check different failure scenarios [O]; Generating sensor data to learn predictive algorithms [T]; Determination of specific characteristics understandable for algorithms; characteristics are determined based on collected data, often not feasible to process in an automated way; a digital twin is an aggregation of data, a reflection of operation of a specific device [T]; As a result, a possibility to order earlier maintenance, servicing of line components and thus preventing work downtimes in the factory [O]
Identification of bottlenecks	Perform tests and configuration changes on virtual copies of devices and processes	Ensure the adequate performance of production lines [T]; Implementation of innovations, configuration changes [T]; Improve the performance of production lines [O]
Tracking of equipment wear to increase OEE	Simulating the wear and tear of equipment under specific conditions	Optimising the equipment design process — reducing the number of prototypes and test iterations produced (Armendia et al., 2019) [O]; Reduction of equipment manufacturing costs [O]; Reduction of device delivery time by 20 % (Armendia et al., 2019) [O]; Carrying out identical actions on a physical device and a virtual model; the former provides data for a faithful representation of the device in virtual space, the latter allows to carry out the same actions to detect anomalies — check for differences in data [O]

O — organisational, T — technical

twin technology. The survey and its results are described below.

2. Research method

These studies used literature review and questionnaire survey as research methods. The survey was conducted at the end of 2020 on a sample of 50 employees of the industrial and supporting sectors (including IT). Some survey questions used a 5-point Likert scale. The part related to technology assessment used a modified 7-degree scale. This was done to diversify the respondent answers and minimise the phenomenon of extreme answers (Tarka, 2015).

In this article, a diagnostic survey was chosen as the research method; the technique was surveying, while the research tool used was a questionnaire built in the form of an online survey prepared on the Google Forms platform. Data collection was based on the technique of CAWI (Computer Assisted Web Interview). The link to the survey was provided to respondents in emails via social media (mainly Facebook platform).

The prepared questionnaire consisted of three parts:

Part A. Scope of the potential use of technology

Part B. Actions affecting the improvement of process efficiency in the enterprise

Part C. Factors affecting the implementation of digital twins technology in the enterprise

Part D. Evaluation of the Digital Twins technology

Part E. Respondent Profile.

The author examined the level of familiarity with the digital twin technology among representatives of industrial enterprises. The study involved 50 respondents, mainly from Podlaskie Voivodeship (94 %). Among the respondents, 76 % were residents of cities with a population above 250 thousand, and 66 % were male. The age groups were below 25 y/o (10%), 25–35 y/o (40 %) and 36–45 y/o (26 %), 46-55 y/o (10%), 56-65 y/o (2%) and above 66 y/o (2%). The vast majority (88 %) of respondents had higher education.

An analysis of the respondents in terms of their position (Fig. 6) showed that a vast majority (88 %) declared openness to new technological solutions and were convinced that the development of technologies guaranteed the competitiveness of their companies (78 %). In addition, 79 % of the respondents believed that using the digital twin technology would confirm their openness to novelty. Subsequent questions focused on familiarity with the technology and factors favouring and hindering its implementation in enterprises.

3. Results

Half of the respondents declared having heard of the digital twin technology before. A significant percentage (64 %) believed there was a need to develop this technology, 34 % believed it should be developed, 2 % had no opinion. Half of the respondents believed that the technology would help to increase the efficiency of the company's processes, 46 % thought it would allow their optimisation, 4 % had no opinion. On the other hand, 32 % of respondents were willing to use this technology in their enterprise, 46 % would rather use it, and 16 % did not know. This shows awareness among industry representatives of the digital twin technology and related opportunities and benefits.

When asked in what time frame the digital twin technology would be used globally, 30 % believed that it was already in use, 6 % — it would be used within the next year, 50 % — within the next five years, 14 % — within the next ten years. Concerning Poland, 52 % of respondents believed the technology would be widely used within the next five years, 28 % — within the next ten years, 18 % — within the next 20 years, and 2 % believed it would never be implemented. The results indicate that respondents consider the implementation of the digital twin technology in Poland being at an earlier stage compared to the rest of the world. The survey also identified problems related to the uptake of the digital twin technology (Fig. 7).

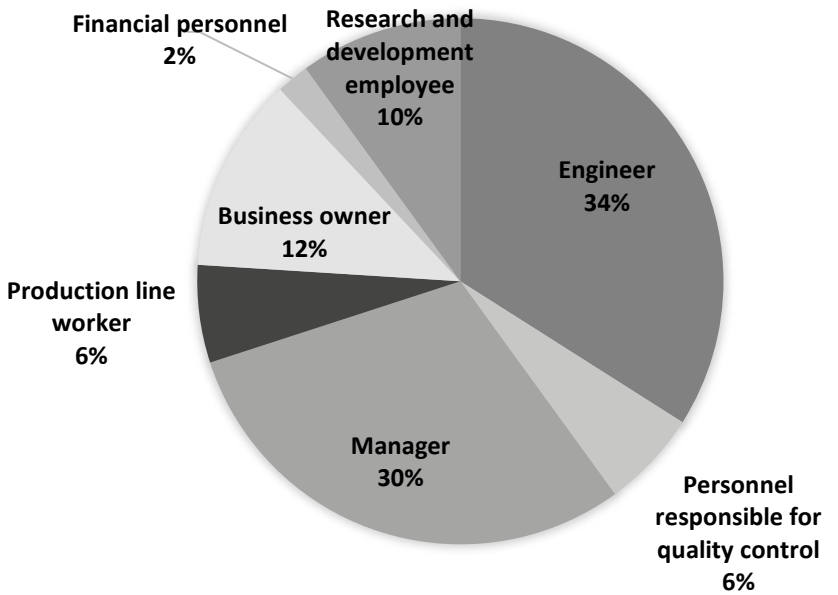

Fig. 6. Distribution of responses regarding positions held by respondents

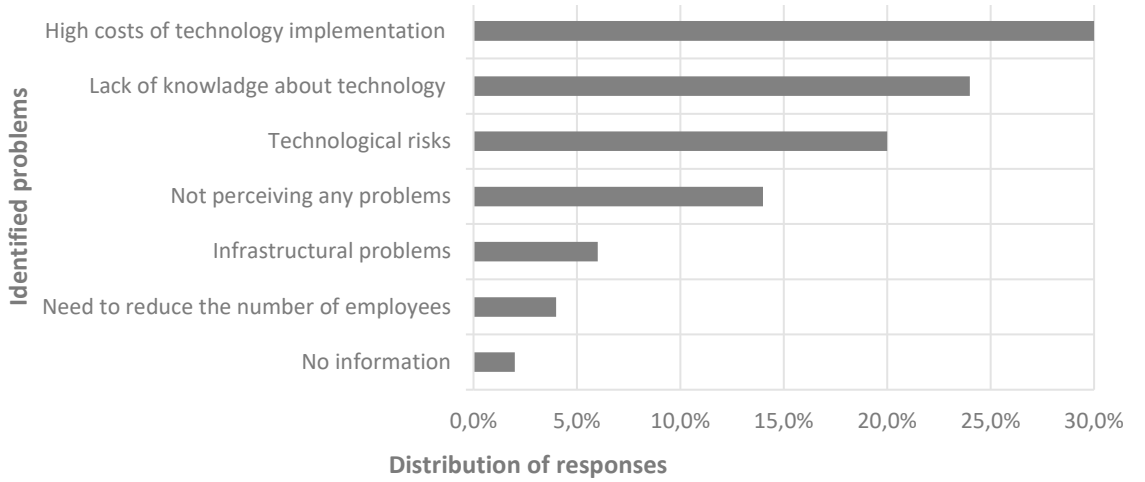

Fig. 7. Distribution of responses regarding problems in the uptake of the digital twin technology

The most common problem (indicated by 30 % of respondents) was high costs of the technology implementation, i.e., the technology itself (adding new devices, preparation of appropriate mathematical models, the complexity of the process of modelling the real object), the adaptation of the infrastructure, personnel costs (hiring new employees), and subsequent costs of repairing errors resulting from the inaccurate operation of the solution.

As the main obstacle, 24 % of respondents indicated a lack of knowledge about the technology and the general awareness of its use. The lack of knowledge was suggested both by business managers and rank-and-file employees.

One-fifth of respondents pointed to technological risks as the main obstacle to implementing the technology. They underlined such problems as creating a universal tool to digitally represent objects, the uncertainty about the reliability of the digital copy, failure to consider all environmental variables, the accuracy of the mathematical model, the emergence of substitutes of lower quality, and data security. The percentage of respondents not perceiving any problems with the introduction of this technology in enterprises amounted to 14 %. Some respondents (6 %) pointed to infrastructural aspects, such as the lack of a standardised platform for creating digital twins, the need to collect large amounts of data, and the lack of infrastructure in the form of sensor devices, while 4 % indicated other obstacles, such as the need to reduce the number of employees in enterprises to implement ICT systems.

In the context of the declared technology implementation obstacles, it was important to verify factors determining the increased effectiveness of processes in enterprises and their possibility to implement the digital twin technology. Among them were:

- investments in machinery and modern tools,
- employee training,
- the implementation of IT systems,
- the implementation of Lean/Kaizen tools.

Fig. 8 provides the distribution of answers to the question "Please indicate which of the listed actions will have a significant impact on increasing the efficiency of processes in your company — from 1 to 7, assuming that 1 — 'has no impact', 7 — 'has a significant impact'".

Respondents (38 %) indicated that employee training would have a significant impact on increasing the effectiveness of processes in an enterprise. This is in line with current trends arising from studies into the development of, primarily, micro, small and medium-sized enterprises, which indicate the accumulation of knowledge and improvement of employee competence having a definite impact on the survival of the organisation and improvement of competitiveness (Pauli, 2012). It also causes greater openness and increased awareness of the need for innovation in an enterprise.

The implementation of IT solutions is also important as 32 % of respondents indicated that their implementation would have a significant impact on improving the work of their organisation. Numerous studies have confirmed the positive influence of IT tools, among others, in the areas of supply chain management and related business processes (e.g., planning, execution, extended cooperation) (Cywka, 2007).

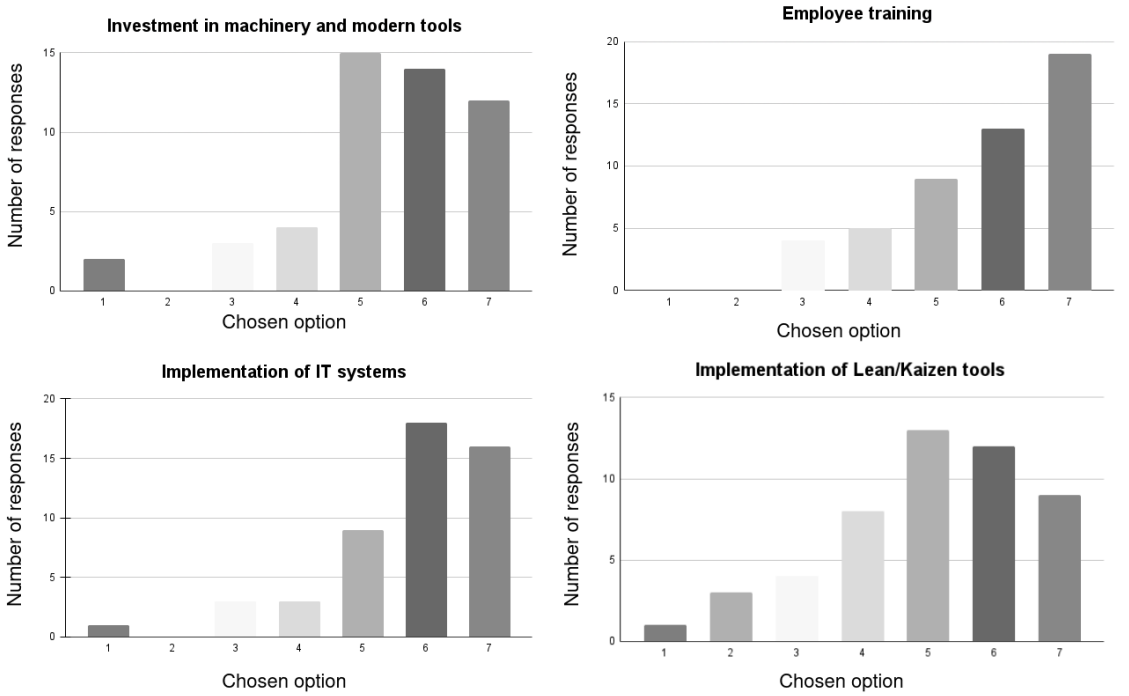

Fig. 8. Distribution of responses to the question on factors having a significant influence on increasing the efficiency of the company's processes

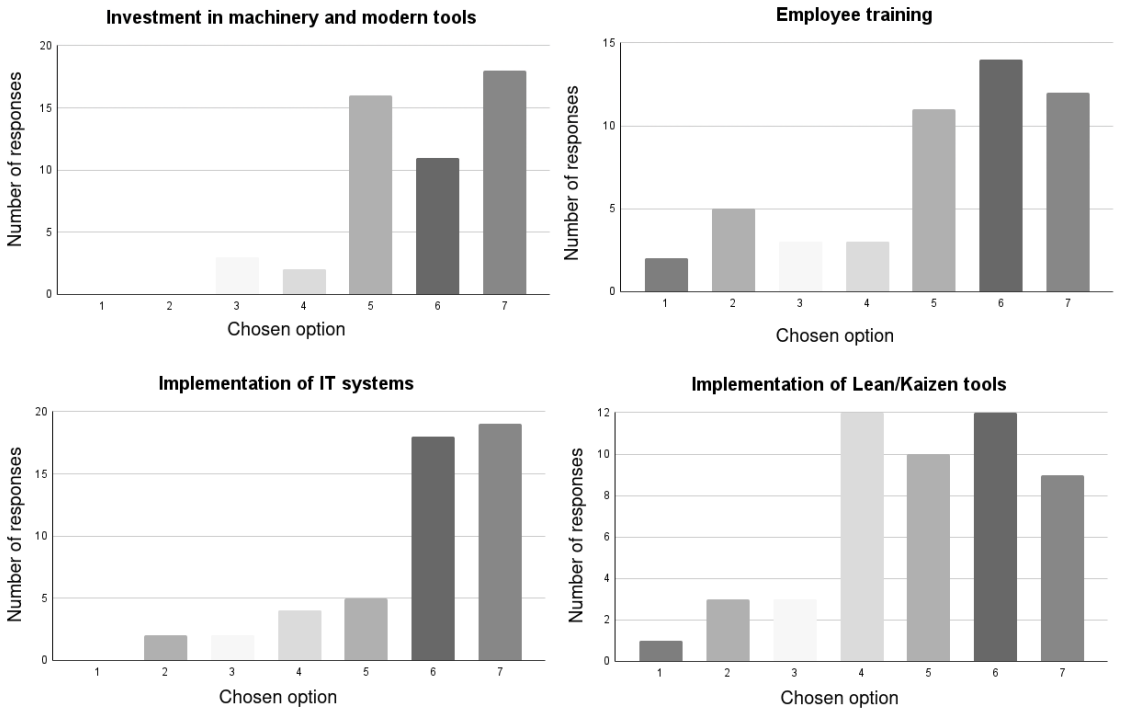

Fig. 9. Distribution of responses to the question on factors having a significant impact on the implementation of the digital twin technology in the company

Fig. 9 presents the distribution of answers to the question "Please indicate which of the listed factors, in your opinion, may determine the implementation of digital twin technologies in the enterprise, assuming that 1 — 'has no impact', 7 — 'has a significant impact'".

In terms of factors that may influence the implementation of the digital twin technology, the

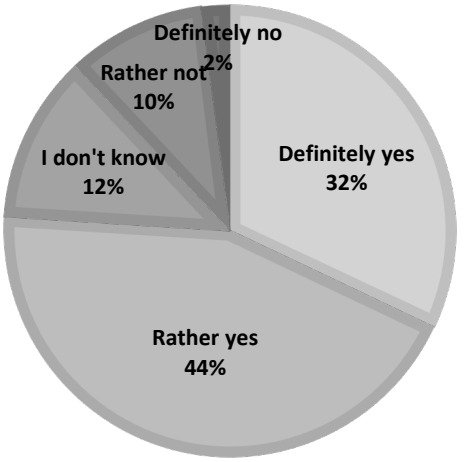

Fig. 10. Distribution of responses to the question regarding the treatment of employee suggestions in their company

respondents indicated investments in machinery and modern tools (15 respondents or 36 %) and the implementation of IT systems (18 respondents or 38 %) as having a significant impact. Respondents believed that modern infrastructure would determine the introduction of the technology in enterprises. Consequently, enterprises should first modernise their infrastructure by either purchasing new equipment or modernising (retrofitting) the existing one to fully benefit from the opportunities offered by the digital twin technology.

Additionally, the research verified whether companies were open to employee suggestions for improving company operations, implementing optimisation, and process improvement (Fig. 10).

Almost half of the respondents (44 %) indicated that their organisations tend to consider employee suggestions for the process performance improvement. 32 % indicated that they rather consider the suggestions. In the author's opinion, this is a good result, not far from the average of Polish enterprises, which is 80.7 % (the average for manufacturing enterprises is 83.9 %) (Dekier & Grycuk, 2014). It is worth pointing out that systems for considering employee suggestions are used by Polish companies often and are usually connected with the introduction of lean management tools (Dekier & Grycuk, 2014). In the author's opinion, building appropriate organisational culture, increasing the involvement of employees and their responsibility for the effects of the company's activity, is an inseparable element of improving its operation, streamlining processes, and, consequently, implementing innovations (Wisniewski & Dobrowolska, 2019; Tomaszuk, 2018).

4. Discussion of the results

The research conducted within the framework of this article has shown an increasing interest in the subject of digital twins over the recent years. This was confirmed by the literature review, indicating an increase in the number of publications in the subject area and interviews conducted with representatives of the industry and supporting sectors. The bibliometric analysis showed that the term "digital twin" mainly occurs in two areas: "Engineering" and "Computer Science". It is a very interesting trend showing sectors where the technology is developing. The literature studies showed a low percentage of publications in Polish. Moreover, existing studies refer to very narrow cases of technology use (case studies), only a few being general. The author's thesis is that the interest in the technology will soon (less than in five years) translate into concrete investments in increasing the level of innovativeness of Polish enterprises and their competitiveness through digital transformation. This is also confirmed by the survey, where more than half of the respondents believed that the implementation of digital twins would take place in Poland within the next five years.

The literature indicates that the concept of digital twins is still very general and inconclusive (Liu et al., 2020). Despite this, both academia and industry are making attempts to define it. For example, such an attempt is the definition coming from CIRP Encyclopaedia of Production Engineering, indicating that, "A digital twin is a digital representation of a unique active product (real device, object, machine, service,

or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions, and behaviours by means of models, information, and data within a single or even across multiple life cycle phases." (Jones et al., 2020). Foreign literature indicates that it is not possible to build a single definition due to the wide implementation of the solution, generalisations or attempts to create extremely highly specialised digital twins dedicated to specific applications. For example, the German literature distinguished five archetypes of digital twins with varying degrees of complexity, considering, e.g., the possibility of autonomous control of a system, data acquisition options, data processing and the possibility of controlling physical assets (Van der Valk et al., 2021).

Furthermore, digital twins can be created for completely different fields of science and technology. Among examples are digital twins (DT) of autonomous robots used in agriculture (Lumer-Klabbers et al., 2021), which allow for parallel motion of DT and an actual robot. Next is DT of autonomous vehicles (Almeaibed et al., 2021) used for research on safety and security. The simulation platform for Unmanned Aerial Vehicles used as a digital twin was described by Yang et al. (2020). In the field of smart factories, examples of digital twins are shown in the paper by Martins et al. (2020).

Even though the technology of digital twins is emerging, industry representatives are aware of its existence and the necessity of its further development (98% of respondents indicated the need for expansion of this technology). According to the conducted research, the implementation of the solution in production companies is still hindered by high costs, insufficient awareness of implemented solution benefits (Maurek, 2015), and technological risks related to inadequate adaptation of mathematical models and algorithms, which may result in an inappropriate representation of physical devices in virtual space. The conclusion from the conducted research is the need to create the product in such a way as to make the managers and decision-makers aware of the benefits of implementation, to show not only technical indicators but, above all, financial indicators and savings resulting from the implementation (Gorustowicz, 2019).

From the point of view of production companies' employees, the most important influence on increasing the process efficiency is employee training and the implementation of IT systems. The greatest influence on the implementation of the digital twin technology will be exerted by investments in machinery and modern tools and the implementation of IT systems (Cywka, 2007).

The limitations of the research were a small sample of respondents, their small geographical diversity (most lived in the Podlaskie region of Poland), and the lack of previous research allowing a comparison of trends and the level of familiarity with technology over time. Considering that the technology is still developing, the author decided to use general questions about the level of familiarity with digital twin technology.

The results may be a prelude to further research, which could include research in enterprises where digital twins are being used, identifying the factors (organisational, financial) that favour the implementation and verifying them in detail (investment in machinery, employee training, IT systems, Lean/Kaizen tools) influencing implementation. In addition, it is possible to verify the use of employee suggestions by Polish enterprises, the correlation of this phenomenon with the level of innovativeness of enterprises, and the possibility of its classification as a factor determining the implementation and development of the digital twin technology.

Conclusions

The implementation of new technologies and innovative solutions determines the competitiveness of enterprises and has a significant impact on their long-term development and the achievement of short-term goals.

This study aimed to gain empirical knowledge about the level of familiarity with the digital twin technology among industry representatives and to identify the most important problems that stand in the way of implementing the technology in enterprises. Within the framework of the study, the author performed a bibliographic analysis and classification of benefits resulting from the implementation of the solution, distinguishing organisational and technological benefits.

The conducted research showed that new technologies such as digital twins are becoming increasingly popular and are an integral part of the development of manufacturing companies, among others. Many of the respondents perceive limitations in the form of insufficient readiness to implement them by enterprises and high costs of their imple-

mentation; however, they see modern IT systems as an inseparable element of the industrial revolution.

As part of further research, the author intends to verify the level of knowledge of the technology and the factors determining its implementation and development (Halicka, 2016). A survey is planned on a larger sample of respondents with increased participation of managers to thoroughly examine the impact of knowledge and the level of technology knowledge on the possibility to introduce it in the company's operations. Additionally, it is planned to verify the influence of the cost factor on the possibility to implement solutions in organisations and on the development of technology itself (Nazarko, 2016; Magruk, 2017).

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Awareness of the prevention through design (PtD) concept among design engineers in the Philippines

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ABSTRACT
The "Prevention through Design" (PtD) concept considers construction safety during the design process. Several countries are currently practising PtD, including the UK, Singapore, Malaysia, Australia, and the USA, which is still not the case in the Philippines. The study presented in this paper aimed to indicate the current level of awareness of the PtD concept among the structural engineers and purposed to generate a basis of initiatives to introduce or improve the understanding and adoption of PtD in the Philippines. A knowledge, attitude, and practice (KAP) questionnaire was distributed to survey respondents selected through a snowball sampling method, consisting of structural engineers currently working in the Philippines. Sixty-one (61) structural engineers responded and were analysed in this study. Results indicated that PtD was relatively a new concept for most structural engineers in the Philippines. Similarly, the designers' knowledge of the concept was still low. However, structural engineers viewed PtD as necessary and its implementation as essential in the construction industry. Despite the known concerns in the PtD implementation, structural engineers favoured the adoption of the concept. The paper also discussed challenges and key drivers for implementing PtD in the Philippines based on the questionnaire results and supporting literature reviews. The findings and methodology presented in this paper could serve as a baseline for a larger sample size covering other design trades, such as architectural, electrical, and mechanical design services leading to the broader adoption of PtD in the Philippines. Furthermore, the framework of this study could also apply to other countries with similar contexts.

KEY WORDS
construction safety, Prevention through Design, Design for Safety, Philippines, KAP, structural design

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Introduction

The construction industry is an occupationally risky environment. Recorded statistics have shown that the number of accidents in the construction industry is higher than in other manufacturing industries (Sousa et al., 2014). The injury and illness rate was approximately five times greater than in all other industries on average (Hallowell, 2012). The Occupational Safety and Health Administration (OSHA) of the United States Department of Labor

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reported that 21.1 % of total fatalities in 2018 occurred in the construction industry. Though the Architecture, Engineering, and Construction (AEC) industry aspired to a "zero accidents/injuries", it is still far from such vision considering the recorded accidents in the construction. Also, the records of accident fatalities in construction still significantly increase despite the construction safety endeavours (Zhou et al., 2015).

Every construction project has inherent health and safety risks, and mitigating these risks can be done proactively or reactively. According to ANSI/AIHA Z10 standard, in the hierarchy of controls for occupational accidents, hazard elimination is the most cost-effective and practical approach to prevent hazards in the construction workplace.

For construction hazard elimination, which is considered a proactive assessment, this should be done before the project's construction phase. The increased recognition of the designer's influence on the construction of a project has led to a safety management innovation called Prevention through Design (PtD).

It is essential to investigate the current awareness of the concept's prospects before establishing a starting point for its adoption or diffusion. Therefore, the present study aimed to indicate the current level of PtD awareness among designers in the Philippines. Also, this study aimed to identify the designer's perceptions and concerns about the implementation of PtD. This study purposed to generate a basis of initiatives to introduce or improve the understanding and adoption of PtD in the Philippines.

As a part of a larger research endeavour about PtD adoption nationally, this study focused only on one specific design trade as the target group, i.e., structural design. The researchers aspired to have a comprehensive study with data from different design trades. Nevertheless, each design trade involved in a construction project faces unique occupational safety challenges and needs a thorough separate study.

The remainder of the paper is structured as follows. Section 2 provides a brief review of relevant literature in PtD and the Construction occupational health and safety in the Philippines. Section 3 explains the data-gathering methodologies, the study framework, and analysis tools.

Section 4 details the analysis results while discussing the study's results and other connotations in Section 5. Finally, the paper provides conclusions and future research recommendations.

1. Literature review

1.1. Prevention through Design (PtD)

Empirical studies have established a link between design features and their construction process as an accident causation factor (Haslam et al., 2005; Hide et al., 2003; Suraji et al., 2001). Researchers used retrospective analysis to analyse recorded construction accidents and found that design correlates with construction site accidents. For example, Behm (2005) reviewed 224 fatality reports from the Fatality Assessment Control and Evaluation (FACE) database of the National Institute for Occupational Safety and Health. The study showed that 42 % of the recorded fatalities in construction could be linked to design. Driscoll et al. (2008) also asserted that design was a significant contributor to work-related fatal injury based on the analysed record from Australia. Henceforth, the viewpoint of construction safety hazard assessment on the project's design phase has gained attention from researchers.

The main concept of Prevention through Design (PtD) is the consideration of construction safety during the design process (Behm, 2005; Gambatese, 1998; Toole & Carpenter, 2013). The idea suggests a higher proactive construction safety assessment accounting for the project's design phase as a possible stage for considering construction safety. In PtD, designers must consider construction workers' safety while performing design tasks. It requires designers to make design decisions based on how the project affects construction workers' inherent risk and include safety considerations during constructability reviews. However, it does not require a designer to take an active role in construction safety during construction, nor holds the designer partially responsible for any construction accidents (Toole & Gambatese, 2017).

PtD has been called Design for Safety (DfS) in Singapore, Construction Design Management (CDM) in the UK, and Safe Design in Australia. The US National Institute for Occupational Safety and Health (NIOSH), in 2007, launched its PtD initiative to make it a standard practice to analyse occupational hazards. In Singapore, the Manpower Ministry enacted the DfS Regulations in July 2015, which was enforced from August 2016. In Malaysia, a PtD-based guideline was introduced by the Occupational Safety and Health in Construction Industry (Management) (OSHCI(M)).

The following terms are how scientific papers referred to the idea of PtD:

- Prevention through Design (PtD) (Ferrante, 2010; Hallowell et al., 2016; Karakhan & Gambatese, 2017; Kasirossafar & Shahbodaghlou, 2013b; Toole & Carpenter, 2013);
- Design for Safety (DfS) (Jin et al., 2019; Lee et al., 2020; Mering et al., 2017);
- Safety in Design (Horberry, 2014; Li et al., 2020; Taiebat et al., 2012);
- Design for Occupational Safety and Health (DfOSH) (Manu et al., 2019; Poghosyan et al., 2020);
- Design Risk Management (Harvey et al., 2019; Mesaros et al., 2019).

1.2. The Philippines construction occupational health and safety

The Philippine construction industry faces many challenges and problems regarding construction health and safety (Demeterio et al., 2019). For instance, in 2018, the Philippine Statistics Authority (PSA) published a report for 2015 – 2016 from a nationwide sample survey covering 12 926 establishments with 20 or more workers. The LABSTAT report stated 2 115 cases of occupational injuries in the construction industry. Three out of every five (66.1 % or 1 399) cases of occupational injuries were cases without workdays lost, while the rest were temporary incapacity cases (32.6 %) and fatal cases (0.6 %) (Philippine Statistics Authority, 2018). The Philippines has several sets of OSH rules and regulations for general occupations. Examples are the Presidential Decree (PD) 442 on Labour Code of the Philippines — Safety and Health Standards and the Republic Act 11058 on Strengthening Compliance with Occupational Safety and Health Standards and Providing Penalties for Violations. However, there was still no institutional effort to introduce the PtD concept in the construction industry in the Philippines. Furthermore, no existing regulations mandate the designers to consider workers' safety in their designs.

2. Methods

2.1. Study design

A nationwide cross-sectional study was performed to evaluate PtD-related awareness using the snowball sampling method through a structured questionnaire. The questionnaire survey technique could help to provide a broad understanding of the phenomenon investigated in this study (Bryman, 2016). Also, the speed, low cost, and scalability of administering questionnaires (Dalati & Gómez, 2018) were considered an advantage of the survey method, especially as the COVID-19 pandemic continued during the time of research. The questionnaire framework was developed based on the study by Goh & Chua (2016) and Che Ibrahim & Belayutham (2020) on Knowledge, Attitude, Practice (KAP) of PtD, complemented by previous research work on PtD. The KAP questionnaire is one of the tools used to determine current knowledge, attitude, and practices in medical and health disciplines in producing an evidence-based intervention (World Health Organization, 2008). Its key components were considered suitable to this study in exploring the awareness of the PtD concept among design engineers in the Philippines. Hence, the KAP questionnaire was framed as follows:

- General information: gathering the demographic information of the respondents.
- Section A. PtD Knowledge: determining the current knowledge and understanding of PtD.
- Section B. PtD Attitude: assessing the respondent's perception of PtD implementation.
- Section C. PtD Practice: considering the possible challenges and problems in applying PtD in the construction industry.

2.2. Study area and sampling

As of 2020, the Philippine Institute of Civil Engineers (PICE) registered 92 316 active professional members working in different civil engineering professions. The specific number of structural engineers was challenging to determine from this list since anyone with a civil engineering license in the Philippines can work as a structural designer. Nevertheless, the Association of Structural Engineers of the Philippines (ASEP) published a record of more than 900 active members as of 2020. The list was used to reach each prospected participant. However, aiming for views from structural designers in general and not limited to a specific institution, a supplementary search for respondents was carried out on an available social media professional network LinkedIn, which is an online professional and career development networking of different disciplines, including structural designers/engineers. Therefore, a search for qualified participants through LinkedIn was done with search

keywords such as "Structural Engineer Philippines", "Senior/Junior Structural Engineers Philippines", and "Proprietor/Owner/Principal Structural Engineers Philippines". In total, three hundred (300) active prospects working as structural designers were identified, contacted, and requested to answer the questionnaire (representing a sampling frame of this research). In total, 145 agreed to participate in the study. In addition, each respondent was requested to share the questionnaire with their colleagues, subordinates or friends working as structural engineers in the Philippines. The survey administration process began with the researchers asking for consent from the prospected respondents to participate before sending the questionnaire. Due to the COVID-19 pandemic, the questionnaire was sent via email instead of regular mail to avoid delays by the postal services. Out of 145 questionnaires sent, 61 completed forms were received, representing a response rate of 42 %.

2.3. Analysis

The study used a descriptive statistical analysis in making conclusions for each question and in general. Most questions of the questionnaire used the Likert scale. Therefore, it was necessary to show the results in plots or graphs to provide simple descriptive visualisations.

At each point in the scaling of the Likert scale, corresponding linear numeric response values were reflected. Thus, the data can be considered parametric and used for statistical description using the mean and standard deviations (Norman, 2010; Sullivan & Artino Jr, 2013). The questionnaire's content was structured to obtain awareness of the respondents on PtD and extract some hints of drivers to adopt the concept successfully.

3. Analysis results

3.1. Respondent demographics

Respondents returned sixty-one (61) filled-out forms. The demographic breakdown of respondents (Table 1) shows the fair distribution of respondents' years of experience and ages. Twenty-eight per cent (28 %) of the respondents had at least three years of experience, 60 % — four to 20 years of experience, and 11 % — more than 20 years of experience. In the Philippines, a graduate of the civil engineering bachelor's degree has to take the Philippine Regulation Commission's (PRC) board examination and be 21 years old. Thus, the average age of respondents was 33, ranging from 22 to 61 years.

3.2. Knowledge and understanding of PtD

To have a better demographic view of the study, the respondents were further grouped into private

Tab. 1. Demographic information of the respondents (n = 61)

Variable	Category	N	%
Age (years)	≤30	35	57
	31 - 50	20	33
	>50	6	10
	< 4	17	28
Experience (years)	4 –20	37	60
	>20	7	12
Work sector	Public	10	16
	Private	51	84
Position	Civil/Junior/Associate/Senior Engineer	41	68
	Firm Manager/Principal/Owner/Proprietor	10	16

and public sectors. The private group was further split into employees and management or firm/company ownership roles. The groups were Civil/Junior/Associate/Senior Structural Engineer (68 %), Manager/Principal/Owner/Proprietor Structural Engineer (16 %), and Public Design/Civil, Structural Engineer (16 %). The variability of work experience and age gave credibility and less biased analysis, covering opinions from novices to more experienced respondents.

KAP questionnaires were sorted, and four questions were analysed to determine how the respondents encountered PtD (Table 2). The first two questions were both direct on when and how respondents learned about PtD. Results show that most respondents (57 %) learned about PtD just after reading the questionnaire. Thirty-four per cent (34 %) said they learned about it from their company, while very few (only 12 %) learned about PtD through education, e.g., tertiary education, published papers, and training courses. Almost no (95 %) respondents attended a PtD training course.

Referring to Table 3, the overall mean level of PtD understanding among the designers was low. Though the majority had indicated they had an average understanding (mode = 3), a considerable number of respondents have indicated they had less than average understanding of PtD, thereby pulling the mean to 2.62. Designers working in the public sector had a higher understanding of the concept compared to the private. Further demographic analysis within the private sector shows a slight difference in the mean level of understanding between owners and employees. The duration of work experience is a factor for the level of understanding among structural engineers, as its mean level rises with increasing years of experience. Also, the table provides the level of familiarity with the PtD concept among structural engineers. The overall level of familiarity was of the average level ("somewhat familiar"), which the majority of the respondents also had pointed out (mode = 3). However, the respondents in the private sector were more familiar with the concept than those working in the public sector. More experienced structural engineers (with work experience longer than 20 years) had more understanding and were evidently more familiar with the concept. The younger practitioners (with less than four years of experience) had little understanding and familiarity with the concept. Results presented in Tables 2 and 3 show that respondents were not aware of the PtD existence in the industry. However, they somehow understood the concept when it was introduced. Also, the PtD concept was more familiar to designers with more experience with structural design.

Furthermore, PtD is just one of the terms used by researchers, but in general, its core idea is the consideration of safety in the design phase. Respondents may have unknowingly implemented the idea though

Tab. 2. Results on how respondents encountered PtD

Questions	Answers	N	%
When did you first learn about PtD?	Just now, after reading this questionnaire	35	57
	After I started my profession	21	34
	Before I started my profession	3	5
	Other	2	3
How did you first learn about PtD?	Just from this questionnaire	35	57
	Through my company	19	31
	Tertiary education	4	7
	Scholarly published papers	1	2
	Seminars or training courses	2	3
Have you attended any PtD courses?	Yes	3	5
	No	58	95
How often have you been asked to address construction worker's safety In the design phase?	(5) Always	0	0
	(4)	6	10
	(3) Sometimes	17	28
	(2)	11	18
	(1) Never	27	44

Tab. 3. Mean level of understanding and familiarity of the designers with PtD

Variable	Category	N	Understanding		Familiarity	
			Mode	Mean	Mode	Mean
Overall		61	3	2.62	3	3.02
Work Sector	Public	10	3	3.3	1	2.4
	Private	51	3	2.49	3	3.13
	Owner/Manager	10	2	2.80	3	3.60
	Employee	41	3	2.41	3	3.02
Work Experience (years)	< 4	17	3	2.47	3	2.65
	4–20	37	2	2.54	3	2.92
	>20	7	3	3.43	5	4.43

Scale Indicator: 1 (Very Poor/Not Familiar at All), 3 (Average/Somewhat Familiar), 5 (Excellent/Very Familiar)

they have not encountered the exact terms used by the researchers, such as PtD or DfS. Thus, the designers were asked whether they were often asked to address construction workers' safety during the project's design phase. Results showed that only 28 % answered they were asked sometimes. However, almost half (44 %) of the respondents were never asked to do so (Table 2). Upon further analysis, those who have been asked to consider construction safety in their designs have a high level of familiarity (20 out of 23 or 87 %) on PtD. In comparison, only 25 out of 38 (68 %) of those who have not been asked to consider construction safety in their design were familiar with PtD (Table 4). Since designers were rarely required or asked to incorporate construction health and safety assessments in their designs, their familiarity with the concept was also low. In addition, these results could imply that the capability of designers to mitigate construction hazards were not recognised or that the other construction stakeholders, contractors, and clients were also unaware of PtD.

A new idea, product, or practice can be adopted as the first step according to the diffusion of innovation model (Rogers et al., 2014; Potoczek, 2021; Bharadwaj & Deka, 2021). In the knowledge stage, the person becomes aware of an innovation and how it functions. The results showed that the majority of the structural engineers in the Philippines still had no idea the PtD concept existed. Further research demonstrated that OSH of the Philippines still had not specifically introduced the PtD or DfS concepts among designers, unlike Singapore and Malaysia in the Southeast Asian region (Che Ibrahim & Belayutham, 2020; Goh & Chua, 2016). The PtD concept is still relatively new for structural designers in the Philippines.

Some respondents indicated having encountered the PtD idea at their company. Thus, companies could be a viable medium for introducing the PtD concept among structural designers. However, its importance should be exhibited by incorporating the PtD idea in educational programmes to make aspiring engineers aware at the earliest stage. The lack of PtD acknowledgement is also the reason for no PtD training offered or organised for designers. Certain companies and governmental institutions have offered and organised a course on Construction Occupational and Health (COSH). However, the course is intended for safety officers/engineers on-site and not for structural or design engineers.

Despite the lack of PtD knowledge, results showed that overall, respondents had a considerable understanding and familiarity with PtD. The structural design aims for structural safety to the end-

Tab. 4. Cross-Tabulation of the effect of being asked to consider safety in design to the familiarity of PtD

Have you been asked to address construction workers' safety in the design phase?	Level of familiarity		Total
	≥ "Somewhat" (≥ 3)	< "Somewhat" (<3)	
≥ "Sometimes"	20	3	23
< "Sometimes"	25	13	38
Total	45	16	61

users. To some extent, the structural design includes the structural stability of the building and the safety of construction workers. In PtD or DfS concepts, the words "safety" and "design" are very close to the structural designer's nature of work. In this study, the likeness of the concept may be one of the reasons many structural engineers were at least somewhat familiar with the concept. However, respondents were given a short PtD definition in the questionnaire, which may have influenced the analysis results.

3.3. Attitude towards PtD

As part of awareness level inquiry among structural designers about PtD, it would also be valuable to determine their perceptions about the concept and its details. Table 5 shows that designers were all optimistic about the importance of PtD implementation. They all believed that PtD would decrease the construction industry's rate of accidents. Furthermore, no disagreement was found among the designers that their duty should involve design for construction safety. No further demographic analysis of the results was made in terms of these aspects since the results showed an overall favourable agreement on the subject.

Table 6 shows the respondents' perceptions of each example of PtD guidelines regarding its effectiveness to improve construction safety and the practicality of each item to be applied in their designs. These examples of PtD guidance for design were taken from suggestions of earlier literature and published design guidelines from other countries. The selected items were in line with the structural design aspects and could be incorporated into their works. Overall results showed that the designers perceived the given items to decrease construction hazards effectively. Moreover, designers saw the practicality of applying each item in their design. It was observable that some items have high mean values. Upon closer observation, the items with high mean values were general design concepts that may apply to PtD, for example, item 1. However, when it comes to detailed design concepts that may apply to PtD (e.g., item 5), some respondents were somehow hesitant about the effectiveness and practicality of such items.

Aside from the designer interest in PtD, there must be some external motivation that should push its implementation (i.e., to drive the designers towards PtD implementation). Referring to Fig. 1, forty-four per cent (44 %) of the structural designers considered the contractors as the top motivator to push them to apply PtD. Designers knew that construction site safety was the responsibility of the contractor. Thus, a push from the direct source of concern is necessary. Furthermore, as the direct builder, a contractor has the knowledge and experience concerning construction site safety that should be shared with designers (Gambatese et al., 2017; Tymvios et al., 2012). Hence, designers would rely on the contrac-

Tab. 5. Designer's Attitude Towards PtD

Attitude towards PtD	Level	%
	5 (Very Important)	62
	4	30
Implementation of PtD	3 (Somewhat Important)	8
	2	0
	1 (Not Important)	0
	5 (Strongly agree)	77
Designer's duty	4	13
Should involve design for	3 (Neutral)	10
Construction safety?	2	0
	1 (Strongly disagree)	0
	5 (Strongly agree)	72
PtD will decrease the rate of injuries and	4	18
Fatalities in the construction	3 (Neutral)	10
Industry	2	0
	1 (Strongly disagree)	0

Tab. 6. Designers' mean level of perception on the effectiveness and practicality of PtD items

No.	Examples of the PtD guidance for design	Effectiveness	Practicality
1	Design the structural members to withstand all anticipated construction loading during fabrication, storage, erection, and final connection	4.62	4.11
2	Design member depths to allow adequate headroom clearance around stairs, platforms, valves, and all areas of egress	4.57	4.31
3	Design members which are consistent in size, light-weight, and easy to handle	4.41	4.28
4	Design columns with holes at 21 and 41 inches above the floor level to provide support locations for lifelines and guardrails	4.03	4.00
5	Locate column splices between 2 and 3 feet above the finished floor level, and two-story intervals	3.95	3.92
6	To allow a sufficient walking surface, use a minimum beam width of 6 inches	3.74	3.59
7	Consider alternative steel framing systems, which reduce the number of elements and where beams are landed on supports rather than suspended between them	3.97	3.72
8	Design welded connections such that weld locations can be safely accessed	4.46	4.23
9	Limit the lift heights of steel erection	4.39	4.07
10	Use a metal deck and concrete fill rather than a slab that requires temporary formwork	4.07	3.79

Scale indicator: 1 (Not at All Effective/Not at all Practical), 3 (Somewhat Effective/Somewhat Practical), 5 (Very Effective/Very Practical)

tors' knowledge and experience to guide them aside from the responsibility concerns.

Based on their understanding of PtD, structural engineers had a very optimistic attitude towards the concept. The majority of the respondents strongly agreed on the necessity of incorporating PtD in their work.

Despite being fresh to the PtD concept, respondents saw that the PtD implementation would help the industry with its construction safety issues. Furthermore, this positive attitude from the structural engineers would set an optimistic tone to encourage the adoption and boost the diffusion of PtD in the Philippines.

3.4. Perspective of the PtD practice

In this part, though PtD was not yet implemented in the Philippines, structural designers were asked in the questionnaire about their perceived challenges and issues of possible PtD adoption in the industry. The items (Table 7) reflected concerns regarding the direct PtD implication to the designers. Designers ranked these items by choosing the rank number in

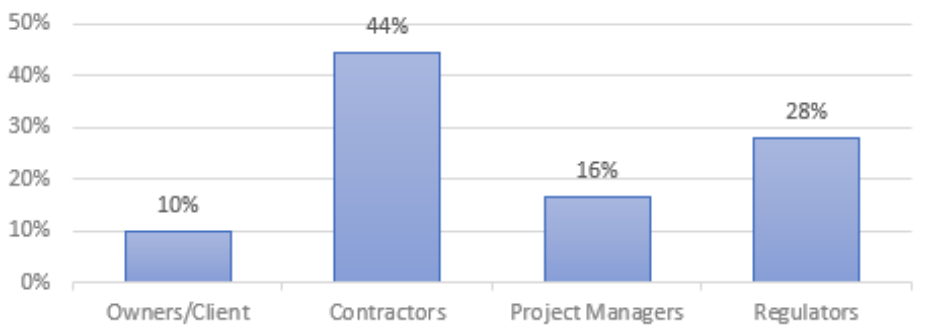

Fig. 1. Who should push designers to apply PtD

the dropdown menu beside each item, marking one (1) as the topmost concern, and a higher value of ranking meant a lower level of concern. Each corresponding mark of ranks was considered a score. The ranking was based on the sorted sum of the scores for each item, where the lowest sum has the top rank. The top concern of the designer was the liability involved when participating in the PtD process. Secondly, designers were concerned about additional incentives for such work and could not afford to do it voluntarily.

Respondents were given an open-ended question on the general problems they would face when practising PtD. They were allowed to point out and add a particular problem or select from the given examples. These items were the perceived barriers of PtD implementations from different works of literature. As shown in Fig. 2, the topmost problem designers perceived in PtD implementation was the cost consideration from the client or company (75 %). Designers also identified the availability of design guides (61 %), design tools or software (54 %), and checking standards for analysis (54 %).

Concerns regarding the assumption of liabilities were the most prominent when considering the PtD aspect of the design. Structural designers were among the many stakeholder groups engaged in risk management throughout the construction life cycle and may be reluctant to assume the risk for all stakeholder groups (Weidman et al., 2015). However, the PtD concept does not attach such liabilities to the designer. Instead, PtD just encourages designers to be safety conscious in their design works (Gambatese et al., 2008; Gambatese, Gibb et al., 2017; Toole & Gambatese, 2008; Votano & Sunindijo, 2014). If implemented, PtD would be an additional task for designers, who were also concerned about doing it voluntarily. Accordingly, designers would naturally seek additional compensation, considering the liabilities involved as viewed by the designers. This top faced or anticipated concern was similar to the study conducted by Che Ibrahim & Belayutham (2020) in Malaysia and Goh & Chua (2016) in Singapore. Moreover, while developing tools and guidance materials, it is essential to improve the PtD knowledge among engineers (Jin et al., 2019; Qi et al., 2014). The results indicate a current lack of PtD guidance material and the need for publicity of existing materials, but this is understandable for a country that has not introduced the PtD concept yet. Nevertheless, there were already efforts to develop PtD guidance material in other countries, e.g., Behm et al. (2012) and Workplace Safety and Health Council (2011).

The items reflected in Fig. 2 were specific concerns that could hinder the PtD implementation from the designer's perspective. Based on the result,

Tab. 7. PtD Implementation concerns

Rank	Concerns in PtD implementation
1	It will give me liabilities for accidents that may occur during the construction
2	I have to do it voluntarily
3	It will result in complications in the procurement process
4	It will compromise my design creativity

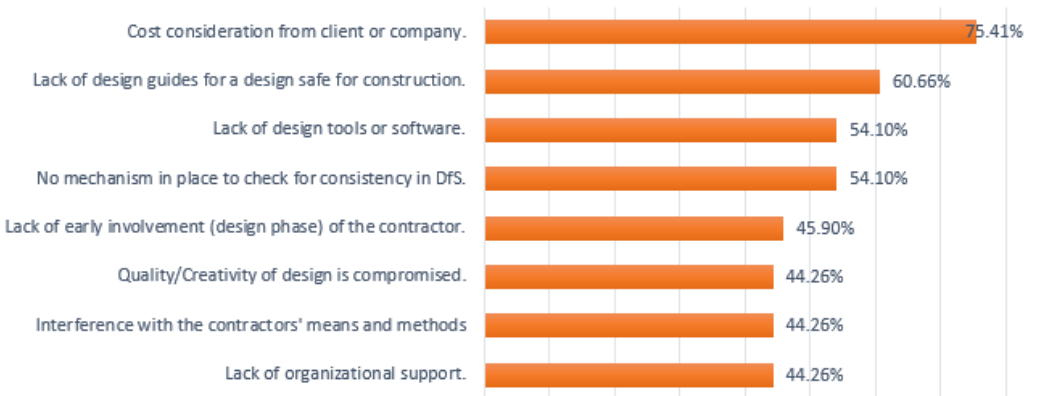

Fig. 2. Problems faced in PtD practice

designers focused more on their basic needs for the PtD adoption, such as incentives and designer tools (design guidelines, software and checking tools), rather than the construction industry's management practices. Hence, considering the listed items as possible barriers to PtD implementation, data suggests that it would be best to head start intervention for PtD adoption among the designers in the Philippines by providing them with tools that would boost their ability to perform in PtD.

4. Discussion

The following synthesis discusses the perceived challenges and key drivers for the PtD adoption among designers in the Philippines as extracted from the respondent answers to the survey questions. The answers provided some insight needed for the successful adoption of PtD in the Philippines, and the items were framed based on the outlined research objectives and scope.

4.1. Perceived key drivers for the PtD adoption in the Philippines

PtD, as a proactive approach, is recognised to be effective as a general concept for the field of occupational safety and health. However, the construction industry's dynamic nature compared to the manufacturing industries made it more challenging to implement. Furthermore, many stakeholders were involved in the construction industry, making it difficult to instil the concept without complicating its system dynamics. Other countries that attempted to adopt PtD encountered such friction in the PtD implementation, and the Philippines will not be exempt from facing such challenges. In particular, the items listed in Table 7 and Fig. 2 signify the apparent concern in the PtD implementation. The concerns and problems mentioned above also hinder PtD adoption. Consequently, PtD adoption can be directly driven by needs, such as the provision of design tools. Nevertheless, from a higher perspective, systematic avenues could be manipulated to inculcate PtD into stakeholders' safety culture.

This study focused on the designer perspective and suggested particular drivers to PtD implementation in the Philippines. PtD acknowledges the capability of designers to influence the health and safety of the construction through their designs. At the same time, it explicitly considers giving high value to safety in construction from the designers (Tymvios & Gambatese, 2019). To succeed in the PtD application, researchers believed that it must start from the designer's mindset to have safety consciousness in their design work, to which respondents agreed. The PtD application among designers in the Philippines is viable but needs some practical intervention for its successful implementation.

4.2. Equipping designers with knowledge and tools

Education is known to be the best way to introduce a concept. Accordingly, as cited by most of the studies on PtD implementation, PtD education could be a valuable information driver on PtD, especially for younger engineers (Behm et al., 2014; López-Arquillos et al., 2015; Olivencia et al., 2017). Mann III (2008) viewed education as the main driver to ensure the success of PtD implementation. The findings in this study indicated that to develop an awareness of construction safety among designers, construction OSH must be included in the education curriculum. An education intervention for PtD adoption would increase students' awareness and knowledge of construction OSH (Behm et al., 2014). PtD curriculum will equip the student with knowledge and develop skills to prepare for a safety-conscious designer. Rubio-Romero et al. (2014) insisted that it would be difficult for designers to implement a new concept that they have not studied. An educational drive is, therefore, necessary to improve PtD awareness and application.

Likewise, to educate and enhance designer awareness is by providing PtD training. The majority of the respondents have not attended any PtD training. The numbers were understandable because PtD was still not implemented. However, designer training needs to be considered in the PtD adoption intervention because designers should possess sufficient knowledge of construction process issues and familiarity with construction safety hazards and their mitigations. PtD training will help designers to be efficient in PtD application (Goh & Chua, 2016). Thus, with appropriate guidance materials and information, PtD training will surely equip the practising designers for PtD.

Several technological tools were available for construction safety management, especially software. The availability of analysis software tools is another avenue considered to help designers know and apply PtD. It is inevitable now that design software could

enhance the awareness of its users in terms of the aspects it is capable of. Particularly, the emergence of the Building Information Modelling (BIM) technologies has revolutionised the safety culture and management of the construction industry (Olugboyega & Windapo, 2019). BIM technology is a suitable tool to integrate safety management with its dynamic visualisation, especially on the design stage. BIM-based tools in construction safety can be considered a basis to enhance workers' safety by employing these new technologies (Bhagwat et al., 2021; Fargnoli & Lombardi, 2020). Its digital nature allows it to be customised with multiple interdisciplinary applications. For OSH, examples of BIM applications are knowledge-based tools (Bloch & Sacks, 2020; Fargnoli & Lombardi, 2020; Zhang et al., 2013), fall preventions (Jin et al., 2019; Zhang et al., 2013), risk identification and quantification (Jin et al., 2019; Kasirossafar & Shahbodaghlou, 2013a; Kim et al., 2020), and virtual realities (Bhagwat et al., 2021; Yan et al., 2020). Studies have shown that BIM in construction applications can improve workers' safety performance (Fargnoli & Lombardi, 2020; Ganah & John, 2015). With its digital 3D nature along with its capability to hold information, BIM technologies were very suitable for PtD. First, designers can check directly or collaboratively with other stakeholders on the project on a 3D model and have a visual or virtual safety assessment of PtD concerns of the project's design model. Secondly, BIM's ability to be customised for a specific trade or task is an open opportunity for PtD aspects to be incorporated in the software tools or in the project model itself. Examples were automation of safety checking (Melzner et al., 2013; Mering et al., 2017), identification of safety risks (Malekitabar et al., 2016), and automation of additional PtD aspects in design detailing (Rodrigues et al., 2020; Zhang et al., 2015). Thus, Practical BIM applications can be an essential tool for PtD educational training and, most importantly, an efficient tool for designers.

4.3. External push to designers

As is true for most significant innovations in design and construction, PtD carries considerable risks for early adopters and specific groups within the industry (Toole & Erger, 2019). Based on the study results, designers acknowledge the risks and barriers to the PtD implementation in the Philippines. Though designers were seen as the main actor of PtD, it is important to provide a motivational force to promote and support PtD applications.

Main construction stakeholders can influence safety performance in the construction (Tymvios et al., 2012; Wu et al., 2016). Thus, motivation from each of the stakeholders would be relevant to push the PtD practice. These external motivations may come from other construction industry's main stakeholders: contractors and clients. Some of the respondents indicated learning about PtD through their company. However, few respondents were asked by their contractor or client to consider construction safety in their design. Results implied there was still a lack of acknowledgement from other construction stakeholders for the capability of designers to mitigate construction safety and health. This outcome suggests a need for an information drive to reach out to the direct stakeholders involved in the construction industry on the PtD awareness.

The traditional practice places the responsibility for the construction H&S implementation with the contractor. Consequently, in terms of a push to apply PtD, most structural engineers believed that the contractors should drive them to consider the H&S of the construction and apply PtD. With the most common type of project delivery method, the Design-Bid-Build, the coordination between designers and contractors was not prevalent. However, improving the collaboration between designers and contractors is one of the motivations of the PtD concept. Thus, other project delivery methods or contract standards should be explored or applied to improve the designer's participation in health and safety in the construction. Also, the project owner or the client plays a vital role in the overall project and definitely can influence project safety (Huang & Hinze, 2006). The owner controls the project and provides the financial resources needed for the design, and is in the position to influence the collaboration of construction stakeholders to consider safety (Gambatese et al., 2017). Thus, PtD implementation can be pushed through with the persuasive influence of the owner. As seen in the result of the questionnaire, the designers were concerned about the cost considerations from the client. Designers were afraid of implementing PtD voluntarily. Unless the designer is convinced that PtD analysis provides added value, an incentive for the additional task should be given to the designer, which is in the client's capacity.

Furthermore, regulatory bodies play important roles in reinforcing the legislation of PtD for the construction industry to comply. PtD was initially introduced as a voluntary scheme in some countries like Singapore and the USA. Later, it became a man-

date in Singapore through their Ministry of Manpower (Goh & Chua, 2016). Respondents indicated that aside from the contractor, regulators and engineering institutions could push designers to apply PtD. The current results implied the need for industry associations and regulatory agencies to reach out to engineers. Institutional organisations in the Philippines served as a respected, authoritative, and proactive voice in developing codes and standards of professional practice. For example, the ASEP produced the National Structural Codes of the Philippines (NSCP) for structural engineering practice aside from the general National Building Code of the Philippines of the national government. Therefore, professional engineering institutions in the Philippines could also push or mandate the PtD concept to their subordinates.

Conclusions

The study explored and aimed to determine the current awareness of structural designers of the PtD concept in the Philippines. It purposed to generate bases of initiatives to introduce or improve the PtD understanding and adoption. Results indicated that PtD was relatively a new concept for most structural engineers in the Philippines. Despite the lack of PtD awareness, based on their understanding, structural engineers viewed PtD as necessary and its implementation as essential in the construction industry. Despite the known concerns in PtD implementations, structural engineers favoured the adoption of the concept. Respondents perceived the liabilities involved, cost considerations, and availability of design tools and guidelines to be the challenges of PtD implementation. The study also had synthesised the results and shed some light on the perceived challenges and key drivers for implementing PtD in the Philippines based on the questionnaire results and supporting literature reviews. The methods and findings of this study could provide a baseline for a future study with a larger sample size covering other design trades, such as architectural design, electrical design, and mechanical design leading to the adoption of PtD in the Philippines. Furthermore, the framework of this study could also apply to other countries with similar contexts.

The researchers aimed for a careful and comprehensive study. Nevertheless, multiple design trades of the construction industry would be challenging in one comprehensive questionnaire. Thus, further studies on the context of other design trades were highly recommended for a comprehensive view from the designers. Similarly, the views of the contractors and clients are also considered vital for the PtD adoption and are then recommendable for further studies. Future work is prepared on framework development for the diffusion intervention or improvement of the PtD concept in the Philippines.

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Investigation of factors responsible for delays in the execution of adequately funded construction projects

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ABSTRACT
Many research efforts have identified funding as a critical factor responsible for the delays in the execution of construction projects. These funding challenges affect the client and contractors alike. However, there is limited information on why delays occur in sponsored projects with evidently adequate funding. Therefore, the study focuses on exploring the factors that impact the cash flow during the execution of sponsored construction projects. The multiple-site case-study method of qualitative research was adopted, involving five universities benefiting from the infrastructure funding provided by a government agency in Nigeria. The Delphi technique was used for data collection and analysis, complemented with interviews. The findings identified six factors causing the delays. They were divided into internal and external factors. The internal factors are faulty contractor selection processes resulting in delays by contractors and the failure to complete appropriate phases of a project. The external factors include the delays in the project management system of the funding agency in terms of inspection, monitoring, evaluation and progress certification. The research identified that the combined effect of internal and external factors negatively impacts the project cash flow, which in turn influences project delivery delays. Therefore, this study recommends improvements in the in-house contractor selection processes and the decentralisation of the project inspection, monitoring and evaluation operations of the funding agency. This will facilitate timely inspection, audit, and progress certification, enabling the early release of the second tranche of the project fund. This will ameliorate the negative effects arising due to low cash flow and associated delays in project delivery.

KEY WORDS
adequate funding, construction projects, delays, Delphi technique, funding agency, internal and external factors

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Introduction

Research efforts aimed at exploring the factors responsible for the delays in the execution of construction projects have continued to attract the attention of academics and practitioners of the engineering, construction, and built environment professions. The delays are experienced in developed and developing economies, and the size of construction projects does not limit the delays. The effects and severity of delays are influenced by the factors responsible for the delay

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(Durdyev & Hosseini, 2020). Most research efforts have identified funding as one of the critical factors responsible for project delays. These financial concerns include the client's inability to pay for work completed by the project execution team (PET), low cash flow to the contractor, its negative effects in meeting site obligations, and the inability of contractors to access credit facilities (Yalini & Alan, 2015; Turkar & Apte, 2016). Assumingly, if the funding problem is addressed, the construction project could run smoothly. Unfortunately, even the sponsored construction projects with evidently adequate funding experience delays. Therefore, it is important to explore the factors that impact the cash flow during the project execution, and which are responsible for the associated delays when the funding issue has been addressed.

This paper reports on a pilot study that explored the factors responsible for the delays in executing construction projects funded by the tertiary education trust fund (TETFUND) in Nigeria. The study involved five universities. Six factors were identified as responsible for the delays. These factors were classified as internal or involving the in-house operations of the benefiting universities and external, which emerged from the deficiencies in project-management systems of the funding agency. To ameliorate the negative effects of the cash flow during construction projects and improve infrastructure delivery, recommendations were made to address the observed deficiencies in the in-house operations of the benefiting universities and the funding agency.

1. Literature review

The literature review provides an opportunity for new research to be based on previous efforts by harnessing existing information, models, and methodologies to support new endeavours. The reviewed literature explores the general delay causes, the influence of procurement systems, funding administration, project inspection, monitoring and evaluation of construction projects and how each sub-section impacts the cash flow during the construction project execution.

Delays in construction projects simply mean project slip-over, time overrun, the inability of the PET to achieve definite milestones or complete a part of or deliver the whole project on schedule (Yalini & Alan, 2015; Turkar & Apte, 2016). This happens in small and large construction projects in developed and developing economies. Nevertheless, the level, the causes, and the severity of delays vary from project to project and between project types (Durdyev & Hosseini, 2020;). Delays have varied effects on different project stakeholders, i.e., the client, end-user, and contractor. To the client, it means the delayed realisation of project objectives; immense capital is tied down, resulting in the loss of revenue, cost overrun and failure to receive value for money (Yalini & Alan, 2015). In the case of the end-users, any delay in completing a planned construction project has multi-dimensional effects on their operations. It means stunted growth, the inability to implement planned expansions, new products or programmes, low productivity and downsizing in extreme cases (Turkar & Apte, 2016). Yalini and Alan (2015, p. 3221) discussed the effects of contractor delays and suggested that "delay means higher overhead costs because of [a] longer work period, higher material costs through inflation, and increase in labour cost". Summarised below are other factors that cause delays resulting from the negative impacts of a low cash flow identified by different research teams:

- Delay in honouring certificates; underestimation of the project costs; difficulty in accessing bank credit; poor supervision; underestimation of time for completion of projects by contractors (Fugar & Agyakwah-Baah, 2010, p. 113).
- Delay in payment from the head office; frequent staff turnover; poor site management; improper management of the engineers; delay in supply of materials and the lack of workforce (Indhu & Ajai, 2014, p. 112).
- Poor quality of construction materials; low motivation and morale of labour; labour shortage; labour injuries on-site; and shortage of construction materials resulting in low productivity (Yalini & Alan, 2015, p. 3223),
- With respect to the research efforts, Turkar and Apte (2016, p. 864) identified the following delay factors caused by clients, contractors, or consultants:
- Owner (client) related: delay in approving shop drawings; slow decision-making; suspension of work; changed orders.
- Contractor related: rework due to errors during construction; poor site management; poor communication and coordination; improper implemented construction methods; delay in site mobilisation.
- Consultant related: delay in producing design documents; the complexity of project design;

insufficient data collection and survey before design; misunderstood owner requirements by design consultants.

In addition, the role of the human factor (client's specialisation and competence of the project team leader) should not be brushed over when discussing the factors responsible for the delays in the execution of construction projects and their impacts on cash flow (Durdyev & Hosseini, 2020).

Notwithstanding the volume of available information on the causes of delays and proposed solutions, the construction industry is still experiencing project delays. However, the construction procurement system, the mode of execution and the method of selecting PET members for a construction project may help ameliorate the possible causes of delays.

The level of success achieved during the execution of any construction project is influenced by a combination of factors, including the project procurement method (Pourrashidi et al., 2017). In many developing economies, two common project procurement methods used in public and private sectors are the traditional procurement system and, in some selected situations, the relationship-based procurement system (Babatunde et al., 2010; Jefferies et al., 2014). Whichever procurement system is adopted, the selection of the PET members and especially contractors is critical. In practice, the contractor selection follows a two-stage process known as the pre-qualification and post-qualification stages (Jafari, 2013).

The pre-qualification process involves inviting many contractors to submit the information required by the procurer. The information required during the pre-qualification stage should be comprehensive. The study should include the examination of the submitted documents and physical verifications. The categories of contractors to be invited for pre-qualification should be specified to ensure that the shortlisted contractors possess adequate capacity, capability, equipment, personnel and experience suitable for the infrastructure project. Sifting through the provided information helps identify an array of eligible contractors possessing approximately identical capacities (Jafari, 2013). After the pre-qualification evaluation, a shortlist of suitable contractors is produced. In the second stage — the post-qualification — the shortlisted contractors are invited to tender for the construction project. Their bids are examined and evaluated. This process helps establish their technical competency, balanced pricing and workable schedule or the project timeline (Jafari, 2013; Deep et al., 2017). The outcome of the bid analysis leads to selecting the contractor with the most "responsible bid" and not necessarily the lowest bidder (Deep et al., 2017). A suitable procurement system and a thorough selection of suitable PET members are expected to facilitate effective project execution. However, the fund administration policies and practices significantly impact the cash flow during the project execution, which may determine the timely or delayed project delivery.

The construction project funds can be administered by the client or a funding agency. Their policies dictate how the allocated funds can be accessed and utilised, specifying the required deliverables and reports. Implementing these policies significantly influences the cash flow during the project execution, the project completion time, and the cause of delays in most cases (Olatunji, 2019; Omopariola et al., 2020). Finance-related factors have been identified as a major cause of delays in construction projects because available funds dictate the robustness of the project cash flow (Fugar & Agyakwah-Baah, 2010).

The cash flow issue is the combined effect of the contractor progress, the release of interim certificates for payment by the consultant and the time lag for honouring the payment by the client (Olatunji, 2019). Furthermore, the ability of the client or beneficiary (when the project is funded through an agency) to meet the payment obligations for executed work on time depends on the operational policies of the funding agencies. Some of these policies include the progress payment duration, progress payment condition, and the release of retention (Zayed & Liu, 2014).

Omopariola et al. (2020) identified the payment delays for completed work as the major source of cash flow problems for contractors, responsible for "project delays, reduced profit margins and in the worst scenarios, abandoned projects" (Omopariola et al., 2020, p. 308). Contractor satisfaction has an overarching influence on the successful execution of construction projects and is influenced by the payment regularity for the executed work (Olatunji, 2019; Steinerowska-Streb & Głód, 2020; Zamojska & Próchniak, 2017). To ameliorate the cash flow burden, it is important to manage project inspection, monitoring and evaluation (IM&E), valuation intervals for executed work and the actual time payments made to the contractor (Olatunji, 2019). In practice, delays in any of the payment process steps culminate and cause a strain in the contractor's cash flow and delays in the execution of the construction project

(Al-Joburi et al., 2012; Omopariola et al., 2020). Therefore, it is important to adopt a pragmatic approach to project IM&E.

Effective project IM&E provides suitable project performance reports, which educate all stakeholders on the current project scope, schedule, cost, resources, quality, and risk. IM&E includes status reporting, progress measurement, and the forecast of the expected project progresses (Kamau & Mohammed, 2015). Furthermore, the authors identified three components of effective IM&E: the strength of the IM&E team, approaches to IM&E and stages for IM&E in the project life cycle. These three components must be effectively integrated for IM&E operations to be successful. Therefore, when setting up an IM&E department, the organisation should ensure adequate finances, human capacity in terms of the number and skill for the effective operation of the unit (Magondu, 2013). Without relevant skills, it is hard to master the rules of any game. Therefore, adequate finance and equipped human capacity are essential for effective IM&E performance and success. If IM&E depends on the initiative of the client or the funding agency, their role should be clearly defined as it affects the valuation certificates and funds released for paying for the completed work. It is the seamless operation of the IM&E and the cooperation of relevant consultants that will guarantee adequate cash flow during the project execution. Deficiencies in the relationship and operations of IM&E, the consultants and contractors, have negative impacts on the release of project funds and cash flow during the project execution (Al-Joburi et al., 2012; Magondu, 2013; Olatunji, 2019).

The literature reviewed showed how generally different factors impact the cash flow during the execution of construction projects. Therefore, this study explores the factors impacting the low cash flow that causes a delay during the execution of sponsored construction projects with evidently adequate funding.

2. Research method

The multi-site case study was adopted as a qualitative research approach, involving five federal universities chosen at random. A small sample of Nigerian universities was chosen for a pilot study. The case-study approach allows the detailed and in-depth investigation of situations or phenomena in their context (Yin, 2014). It also enables the contextual relationship with the officials directly involved in the investigated subject matter. The Delphi technique was used as a data-collection instrument, complemented by interviews.

The Delphi technique is a hybrid method that combines the qualitative and quantitative approaches in a single exercise (Sekayi & Keeney, 2017). As a tool for consensus building, the technique hinges on the concept that "several people are less likely to arrive at a wrong decision than a single individual" (Hasson et al., 2000, p. 1013). The participants in a Delphi exercise are experts or knowledgeable persons in the research field. They are chosen purposively after measuring them against clearly defined pre-qualification selection criteria. Depending on the research objective, they can be few or as many as possible (Förster & Gracht, 2014).

In this research, the participants were Directors of Physical Planning (DPP) and the Directors of Work (DOW). They coordinate the execution of construction projects and are knowledgeable about the delays experienced in the execution of sponsored construction projects. To qualify, a participant had to be a registered engineering or built environment professional and had been employed as DPP or DOW for not less the three years.

Ten officers from five universities participated in Round 1. However, before Round 2, one of the DPPs died, and another declined to continue participating. Similarly, two DOW members declined to continue with the study for personal reasons. Table 1 provides

Tab 1. Participants in the Delphi exercise

S/No	Participants	Round 1		Round 2		Round 3	
		Yes	No	Yes	No	Yes	No
1	DPP	5	-	3	2	3	-
2	DOW	5	-	3	2	3	-
3	Total	10	0	6	4	6	0

the summary of participants in the three rounds of the research.

2.1. Data collection

The classical Delphi technique variant was used for data collection. In this variant, the first round is open-ended questions, which allow participants to provide qualitative responses to research questions (Franklin & Hart, 2007). Ten participants offered 29 suggestions for possible causes of delays. In the second round, 29 suggestions were circulated to the participants.

They were requested to score the factors according to the level of importance using the Likert scale of 1–5, where 1 was the lowest rating, and 5 was the highest. It was agreed that after the analysis, only those items that scored 3.0 and above were to be escalated to the next rounds. The exercise had two more rounds of data collection and iteration before achieving equilibrium (Day & Bobeva, 2005).

2.2. Data analysis

Considering data size, the arithmetic mean was used for the analysis of consensus. Twenty-nine items from Round 1 were sent to participants in Round 2. After analysis, only eight items satisfied the benchmark of 3.0 and above. Items that failed to meet the benchmark were marked in red.

The list with 29 items and red highlights was recirculated to participants together with the list of eight items that had met the threshold. This step served as Round 3. The participants were requested to examine the items marked red in the list from Round 1 and see if there were any items they felt should be reconsidered. When the document returned in the third round, only eight items from Round 2 were scored.

After the analysis, two more items (25 %) did not meet the benchmark, and they were discarded. The literature suggests that consensus can be achieved if participants no longer change their opinion or attain between 51 % and 80 % agreement on the suggested solutions to the research question (Hasson et al., 2000).

Therefore, having attained a 75 % consensus, the exercise was discontinued. The six resulting factors were discussed with the participants through telephone conversations, which enabled participants to provide additional information. The details of the results are shown in the findings and the discussion.

3. Research results

This section provides the background information on the funding agency used for this research, the results from the analysed data, interviews, and the contextual discussions on the causes of delays in the execution of sponsored construction projects.

3.1. Background to the research

The funding agency used for this research is known as the TETFUND, an agency of the government of Nigeria. The agency's mandate is to support infrastructure development and upgrades, the provision of equipment and human capacity development in all public higher education (HE) institutions in Nigeria. In any given intervention year, each institution is allocated a fixed amount, divided into appropriate sub-headings, with a template specifying the areas where the allocated amount should be spent. No institution can transfer funds from one sub-heading to another or introduce projects outside the template provided for that year. However, an institution may be allowed to accumulate its allocation for any subheading for a maximum of four years to enable the institution to execute a major project. The agency does not accept the idea of co-funding projects. Instead, institutions are encouraged to adopt the concept of phased development.

When the allocation for each intervention year is communicated to the institution, each institution develops appropriate projects within the given template, submits and defends them before the funding agency. Once approved, the agency communicates with each institution through a memo known as "Approval in Principle" (AIP). Upon receipt of the AIP, the institution commences the procurement process and applies for the release of the first tranche of fifty per cent (50 %) of the approved cost estimate for each specific project. The selected contractors from the procurement process are commissioned and paid fifty per cent (50 %) as a mobilisation fee. Once this amount is exhausted, the agency demands that a comprehensive report should be prepared and submitted to the project inspection, monitoring and evaluation (IM&E) unit of the funding agency, and the IM&E department is officially invited to inspect the projects. If the IM&E unit is satisfied, the second tranche of thirty-five per cent (35 %) is released. The final fifteen per cent (15 %) of the approved project cost is released when all the projects bundled together

in an intervention year are completed. Theoretically, all approved projects should be executed within twelve months, within the approved cost estimate, and no variation is allowed.

3.2. Analysis of results

The first round of data collection (using the Delphi technique) was a qualitative response to this open-ended question: "What are the factors responsible for delays in the execution of TETFUND projects?" Each participant was requested to identify between three and five factors. Table 2 represents the collation of responses from all ten respondents, showing 29 factors. This list was circulated to all participants for rating on the Linkert scale of 1 – 5 in Round 2.

After the analysis (the arithmetic mean), tthe items marked in bold black highlight did not meet the benchmark. Eight factors remained. Table 3 shows the eight items that satisfied the benchmark of 3.0 and above. However, Tables 2 and 3 were circulated to all participants, with the request that the participants could review the items marked red. If

Tab. 2. Analysis of round 2

S/No	Suggested reasons	Mean	To round 3
1	Delay in receiving a letter of allocation	2.5	
2	Delay in receiving AIP	3.25	3.25
3	Delay in mandatory monitoring, evaluation and project inspection	3.0	3.0
4	Delay in receiving first tranches	4.75	4.75
5	Delay in receiving the second tranche	3.5	3.5
6	The economic factor of the contractor	2.25	
7	Ill-conceived project	1.5	
8	Delay in the harmony of payment certificates	2.0	
9	The contract awarded to an incompetent contractor	4.0	4.0
10	Inability to meet conditions of release of funds by beneficiaries on time	2.75	
11	Frequent changes in design	1.5	
12	The hostility of the host community	1.25	
13	Late honouring of certificate by the client	2.0	
14	Force majeure	1.25	
15	Incomplete architect's instruction	1.75	
16	Contractors not receiving instruction/drawing/other details on time	3.25	3.25
17	Requesting gratification from contractors	1.5	
18	Incompetent technical in-house staff	2.0	
19	Using inferior materials	1.75	
20	Bad workmanship requiring reworks	2.25	
21	Non-completion of tranches before the release of another by the institution	1.0	
22	Non-submission of observation by the institution when requested by TETFUND	1.5	
23	Delay in calling TETFUND for inspection to access next tranche	2.25	
24	Delay may be caused by the contractor	4.25	4.25
25	Wrong contractor selection method	1.75	
26	Lack of flexibility of fund utilisation (market realities)	2.25	
27	Non-completion of the project affects accessing future funds	3.25	3.25
28	The contractor always holds the client ransom	1.5	
29	Time taken to obtain approvals always attract fluctuation of price	2.25	

Tab. 3. Analysis of Round 3

S/No	Factors	Mean	Accepted results
1	Delay in receiving AIP	2.75	
2	Delay in mandatory monitoring, evaluation and project inspection	3.0	3.0
3	Delay in receiving the first tranche	3.0	3.0
4	Delay in receiving the second tranche	3.5	3.5
5	The contract awarded to an incompetent contractor	3.0	3.0
6	Contractors not receiving instruction/drawing/other details on time	2.5	
7	Delay may be caused by the contractor	4.0	4.0
8	Non-completion of the project affects accessing future funds	3.75	3.75

Tab. 4. Classification of the causes of delay

S/No	Internal factors	External factors
1	The contract awarded to an incompetent contractor	Delay in receiving the first tranche
2	Delay may be caused by the contractor	Delay in receiving the second tranche
3	Non-completion of the project affects accessing future funds	Delay in mandatory monitoring, evaluation, and project inspection

they felt strongly that any should be reconsidered, they could escalate and score them accordingly. When returning the document for Round 3, only the eight items were scored.

After the analysis, two more items scored below the benchmark and were discarded. Only six items satisfied the research objectives as key factors responsible for the delays in the execution of the sponsored construction projects. The resulting six factors were classified as internal and external, as shown in Table 4. During the interview sessions, participants provided additional information, which further explained the other attributes of these factors.

3.3. Synthesis of interview data

The result of the Delphi exercise was circulated to the participants, with this question: "What are the procedural or administrative processes that culminate in the internal and external factors responsible for the delays in the execution of these sponsored projects?"

4. Discussion of results

The findings from the Delphi exercise and the synthesis of the interview response led to the devel-

Tab. 5. Synthesis of interview data

S/No	The factors	Participants' response	Suitable theme
1	Internal factors	• Compromised contractor selection during pre-qualification due to overt stakeholder interests, • Some of the contractors are not competent, • Slow pace of work, frequent reworks, low quality of products and not keeping to the construction schedule	Quality contractor
2	External factors	• The project completion time commences with the receipt of the first tranche, • The delay is mostly in receiving the second tranche, • Precipitated by the structured and over-centralised operation of the project inspection, monitoring and evaluation department	Fund administration; Project inspection, monitoring and evaluation

opment of suitable themes, which are discussed below.

4.1. Quality contractor

The internal factors responsible for the delays in the execution of TETFUND projects revolve around the contractor selection process. However, if the wrong contractor is selected, the process snowballs into construction projects awarded to incompetent contractors, resulting in the slow pace and poor quality of work, leading to delays and non-completion of work within the schedule. The literature suggests that the successful execution of any construction project depends on the selection and use of good-quality contractors (Doloi, 2009). If the two-stage process of contractor selection (pre-qualification and post-qualification) is judiciously followed, it is possible to select good-quality contractors who can deliver infrastructure projects on schedule (Jafari, 2013). As observed by the participants, in many cases, this process is compromised due to the "undue interference of some of the key stakeholders", initially through the promotion of poorly resourced contractors during the pre-qualification selection. This group of contractors usually produces deficient bid documents, who naturally should fail the critical bid evaluation processes (Jafari, 2013; Deep et al., 2017). Again, due to the interest of key stakeholders, this group of contractors is patronised. During project execution, these low-skilled contractors fail to keep to the construction schedule, produce poor quality work requiring frequent reworks, and hinder effective supervision and quality control by PET members. Their performance negatively impacts project supervision, the issuing of appropriate payment certificates and the IM&E certification. This, in turn, significantly impacts the release of funds for the second tranche, low cash flow and causes delays in effective project delivery.

4.2. Fund administration

Fund administration involves the release of funds for project execution. This process influences the contractor cash flow, their ability to honour construction time schedules or delays (Al-Joburi et al., 2012). During the interview session, the participants agreed that although the funding agency has an attractive schedule for releasing funds, there is a significant "time lag in the release of the second tranche/instalment of 35 %". The operational policy of the funding agency is that the first instalment of 50 % (of the approved project estimate) must be exhausted and have produced acceptable progress reports to the funding agency. When the agency is satisfied with the progress report, the benefiting institution can apply for the release of the second instalment of 35 %. In the words of the participants, "the bureaucracies and the structured implementation of the requirements for IM&E, contribute significantly to the delays in the release of the second instalment". There is no gainsaying that implementing any funding policy that impairs the cash flow is a recipe for delays in the construction project execution (Olatunji, 2019; Omopariola et al., 2020).

4.3. Project inspection, monitoring and evaluation

Project IM&E is a standard management practice for every successful project. The IM&E process includes tracking and reviewing the work progress, relating the progress to planned schedules, comparing financial disbursement with the actual progress, and regulating the progress to meet the performance objectives (Kamau & Mohammed, 2015). However, the IM&E execution mode influences the cash flow rate for the relevant project implementation team and the ability to meet the construction project's timeline (Kamau & Mohammed, 2015). The IM&E department of the funding agency, TETFUND, is domiciled at the agency's headquarters in Abuja. The department claims that it has scheduled periods for project inspection. However, this schedule is not known to any of the benefiting institutions. The implications are that the submission of reports and requests for project inspections from any institution may be received early; however, they had no control over when the next inspection would occur. One of the participants observed that "the waiting time may be as short as one month and sometimes longer than four months". Another drawback in the IM&E process is the auditing and certification of progress reports. If discrepancies are observed (which happens often), the reports are returned and amended multiple times. Until the IM&E department is satisfied with the project execution report and is corroborated by physical inspections, the second instalment of 35 % is not released. During these periods, "if the contractor does not have access to alternative sources of funds, the project will be on hold", as observed by the participants. This confirms the postulation of many researchers that the inability of the contractors to

access additional funding sources is a major factor responsible for limiting the cash flow, which results in construction project delays (Al-Joburi et al., 2012; Omopariola et al., 2020).

Therefore, the external factors manifest in the implementation of the operational policies of the funding agency. The fund administration and IM&E have over-arching impacts on the low cash flow for project execution, causing delays and denying the benefiting institutions the privilege of having value for money for the projects being executed (Yalini & Alan, 2015; Turkar & Apte, 2016). Although the funding agency's policies aim to develop good-quality infrastructure, ensure accountability and reduce the risk of abandoned projects, the policies require a pragmatic implementation of IM&E processes to facilitate the timely release of project funds.

Conclusions

Delays of different degrees seem to be synonymous with many construction projects. They have negative effects on different stakeholders involved in a construction project. Major causes of delays were identified by several studies in the form of insufficient funding, client failure to meet the financial obligations for services rendered, low cash flow or contractors having difficulties in accessing credit. Since the issue of adequate funding has been addressed in sponsored construction projects, it was important to explore the factors responsible for delays during project execution, which impacted an effective cash flow.

The case-study method of qualitative research was adopted in this study; the Delphi technique and interviews were used as data-collection instruments. The main stakeholders involved in the coordination of construction projects in HE institutions in Nigeria — the DPPs and the DOWs — were the participants in this research. Initially, 29 reasons for project delays were collated from the participants. After two additional data collection and analysis rounds, the initial 29 factors were reduced to six (6) and classified as internal and external factors. The internal factors amplified the need to improve on the contractor selection process as it significantly influences the quality of contractors engaged in the execution of construction projects. This is against the backdrop that the performance of contractors has overarching effects on the cash flow and the successful execution of construction projects. The external factors showed some deficiencies in the project management system of the funding agency, which includes the fund administration and IM&E policies and procedures. The structured and over-centralised procedure of the IM&E department negatively affects the timely release of the second instalment of the project fund. This, in turn, affects the low cash flow, especially for the contractors. When the contractors do not have access to alternative sources of funds, and the waiting period results in the delayed implementation of construction processes.

Therefore, this study concludes that the causes of delays in the execution of sponsored construction projects with evidently adequate funding are the combined effects of the internal and external factors, which negatively impact the project cash flow. This suggests that the operatives in both the in-house structure of the respective HE institutions and the funding agency have their fair share of responsibilities. This research recommends the decentralisation of IM&E department operations to operational offices in the six geopolitical zones of the Nigerian Federation. This practice will improve responses to project inspections and the auditing of reports, which in turn will fast track the release of the second tranche and therefore improve the project cash flow. Furthermore, extended investigations involving more HE institutions should be conducted to validate the findings of this study and to identify more possible reasons for delays to enable the development of holistic solutions.

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Blockchain technology applicability in New Zealand's prefabricated construction industry

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ABSTRACT
Different industries are modernising their systems and introducing innovations to their management practices. However, the construction industry is recognised for its lack of technological systems on which the success of this sector is deemed to be heavily dependent. Previous studies have focused on enhancing the off-site construction supply chain. However, studies on the importance and utilisation of technology in this sub-sector are scarce, predominantly where the efficiency of off-site supply chain management is stalled as a consequence of the slow implementation of technology. Thus, this article employs an exploratory approach by providing insight into the applicability of blockchain technology in New Zealand's off-site construction and demonstrates the benefits associated with the adoption of this technology. A literature review was used to identify stakeholders' interrelationships in different stages of prefabrication projects. Then, a pilot interview from industry experts followed by a questionnaire survey was used to determine the involvement of stakeholders in different phases and the benefits that blockchain technology can bring to this industry. The results indicate that using blockchain as a secure information management system could improve the integration of prefabrication supply systems by producing a collaborative atmosphere amongst the organisations involved.

KEY WORDS
prefabrication, supply chain, blockchain, information integration, New Zealand

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Introduction

The construction industry in New Zealand is overtaking other industries and has become one of the major contributors to the national GDP (Huang & Wilson, 2020). Supply chain management in this industry is considered a significant pivotal point of success for organisations performing roles in the highly competitive construction market (Samarasinghe, Tookey & Rotimi, 2013). However, fragmentation is an inherent attribute adhered to the

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construction sector, and it can deteriorate in off-site (prefabrication) construction where the concentration of work is scattered across "off" and "on" construction sites (Zhai, Zhong, Li & Huang, 2016). In New Zealand, prefabrication demands specific consideration around the barriers to its efficiency; supply chain integration is perceived as one of the main core subjects requiring enhancement (Darlow, Rotimi & Shahzad, 2021). Studies have shown that information exchanged across the entire supply system in a prefabricated project can substantially impact the outcome of the supply chain (Briscoe, Dainty & Millett, 2001). Numerous documents: design/construction drawings, RFIs, quality assurance documents, and statutory approvals are regarded as the types of information being exchanged daily within the supply system of prefabrication projects and managing the integration of this information results in a positive future collaboration amongst the supply chain partners (Bakhtiarizadeh, Shahzad & Rotimi, 2019).

Prefabrication is acknowledged as a solution to deficiencies in traditional construction methods. Reduced time and costs, enhanced quality of finished products, and increased sustainability factors are some examples of benefits associated with prefabrication (Shahzad, Mbachu, & Domingo, 2015). However, several impediments to the uptake of prefabrication disturb efficiency in its supply chain systems. Little transparency around the distribution of works at different sites, lack of the adoption of new advanced technologies, and ineffective information sharing systems are considered some of them (Jaillon & Poon, 2010). The root cause of the mentioned issues can be linked to inappropriate information integration techniques.

Integrated information ensures an integrated supply chain, and an integrated supply chain ensures the swift processes of preparation, design, manufacture, construction, and assembly (Čuš-Babič et al., 2014). It also provides trust amongst various stakeholders involved in a prefabricated construction project (Bankvall et al., 2010). Hence, using an effective information integration platform, such as blockchain, leads to improved trust and integration amongst participants involved in the supply chain of prefabrication projects (Casino, Dasaklis & Patsakis, 2018). The predominant benefit of blockchain technology compared to other technologies is the decentralisation and anonymity of the data stored in it (Li, Greemwood & Kassem, 2019). Contrary to other recent technologies, blockchain helps information to be processed and saved on multiple remote computers, providing organisations with an opportunity to store their information systematically in different locations (Li, Greemwood & Kassem, 2018; Hofbauer & Sangl, 2019; Florek-Paszkowska et al., 2021; Barczak et al., 2021).

This technology offers integration in the prefabrication and provides a secure decentralised database, helping prefabrication supply chain organisations to exchange and store their information effectively (Wang et al., 2017). Therefore, blockchain provides a transparent and secure information-sharing platform for the prefabrication supply chain (PrefabNZ, 2018).

Different studies have shown various process maps of the prefabrication supply chain. For instance, a study by Bakhtiarizadeh, Shahzad, and Rotimi (2019) explored prefabrication project phases and stakeholders involved in the supply chain. Also, other studies have demonstrated the value of information sharing across supply chain allies in the construction and design of projects (Samarasinghe et al., 2013; Čuš-Babič et al., 2014). However, little research has been conducted on New Zealand's prefabricated construction, and there is inadequate knowledge of the advantages of blockchain technology in this industry.

This study undertook a pilot interview with six prefabricated construction professionals to ascertain the interaction of stakeholders in different phases of prefabrication projects. Also, a questionnaire survey was used to identify the core impediment to the integration of prefabrication and to ascertain the applicability of blockchain technology with its related potential advantages. The following section of this article presents a review of previous studies. The second section discusses the research methodology and data collection and analysis tools. The third part describes the analysis and discussion around the results. The article is concluded with remarks.

1. Literature review

Prefabrication is considered an innovative method of construction that facilitates the construction of a portion of a building remotely or far from the final location (Shahzad, 2016). The major benefit of prefabrication over the traditional construction methods is the low level of inefficiencies in the productivity measures like time, cost, and quality (Darlow et al., 2021). In New Zealand, prefabrication is increasingly contributing to the delivery of construc-

tion projects (Darlow et al., 2021; PrefabNZ, 2018). The rising demand for new-built houses and the shortage of affordable dwellings is growing the need for a more effective and innovative project delivery system (Shahzad & Mbachu, 2013).

Despite the benefits of prefabrication, the industry struggles with several issues, such as a low level of integration and coordination amongst its supply chain organisations (PrefabNZ, 2015). Integration in supply systems refers to the consistency of delivery systems and uniformity of information sharing amongst stakeholders (Dainty, Millett & Briscoe, 2001). The complexity of integration in supply chains depends on the project size. Typically, the number of actors exchanging information in large projects can exceed hundreds, giving rise to the need to adopt innovative technologies in the supply chain integration techniques (Briscoe, Dainty & Millett, 2001).

Adopting technology in the construction supply chain has become critical for enhancing supply chain integration (Wang et al., 2020). Some examples of technological systems being used in supply chains are Enterprise Resource Planning (ERP), Electronic Data Interchange (EDI), Customer Relationship Management (CRM), Drones, Internet of Things (IoT), RFID, and GPS receivers (Wang et al., 2017). These systems have helped the uniformity and integration of information and, consequently, the integration of supply chains. Using these technologies, supply chain partners can exchange real-time information efficiently and effectively. Also, with the help of these technologies, unsafe human interference in information repositories can be minimised (Ngai, Cheng & Ho, 2004).

Information integration is considered collaborative, uniform, and controlled information sharing, and lack of information sharing results in decreased traceability, transparency, and trust (Prajogo & Olhager, 2012; Mentzer et al., 2001). Integration and efficient exchange of information in supply systems require coordination and trust (Cai, Jun & Yang, 2010). The low level of trust results in a low level of collaboration and reluctance to adopt technologies (Shahzad, 2016). Therefore, providing a secure technological source/storage for storing organisational information can lead to a more collaborative and efficient supply system with a higher level of trust (Korpela, Hallikas & Dahlberg, 2017).

One advanced technological system recently introduced globally is Distributed Ledger Technology (DLT) or blockchain technology. Blockchain is a secure consensus-based ledger that simplifies connections amongst its operators (Penzes, 2018). Blockchain was originally developed for crypto-currency transactions and designed based on a network of public and private decentralised nodes (Saberi et al., 2018). This technology enables immutable peer-to-peer (P2P) communication through a secure transaction database (Turk & Klinc, 2017).

New Zealand is showing resilience in adopting innovations and technologies (PrefabNZ, 2013), and blockchain can positively impact the enhancement of supply chains, especially in the prefabrication industry. Blockchain's traceability function is important for supply chain partners since prefabricated construction struggles with multiple stakeholders and suppliers from local or international companies (Bell, 2009). This function also helps clients/customers with the ability to track the provenance of the materials used in their final products, improving their trust and perspective on the genuineness of resources (Casino et al., 2018).

Similarly, blockchain technology helps facilitate interactions and information exchange amongst supply chain organisations in an organised manner (Prajogo & Olhager, 2012). This, in turn, results in the transparency of information and improved accountability of each partner regarding their contribution to the project delivery in New Zealand (Chowdhury et al., 2018). Providing transparency in the stakeholders' interactions can reduce the quality problems and improve organisational trust and confidence (Yang et al., 2020).

Moreover, as opposed to other pre-mentioned technological systems, blockchain provides more data/information security to its users, helping supply chain organisations benefit from a safe information repository that its stored information can be withdrawn and used for future projects (Li et al., 2019). Security in the information exchange is understood as legitimate or trusted information transmission across the communicators and safekeeping the data-generating processes (Tse et al., 2017). Security and trust are interlinked in the prefabrication supply chain. As prefabrication processes encompass a variety of information and sources, information security guarantees trustworthy digital commination and reliability of shared information (Lemieux, 2016).

In summary, blockchain can be the potential remedy for the shortcomings in the prefabrication supply chain integration in New Zealand. This technology can be used for information integration and, consequently, supply chain integration (Wang et al., 2020). Blockchain has the potential to resolve the

problems stemming from the traceability of the origin of the products, transparency of exchanged information and security of systems used for prefabrication stakeholders' information sharing.

Previous studies have investigated the integration of prefabrication supply chain stakeholders and the potential benefits of using information technology. However, few studies have been conducted in New Zealand, and there is little knowledge about the applicability and benefits of using blockchain technology in the prefabrication supply chain. This study addresses the investigation gap in this area and provides insights into utilising blockchain technology in the prefabrication industry of New Zealand.

2. Research methodology

This study adopts mixed research to data collection and analysis as a complementary approach (Johnson, Onwuegbuzie & Turner, 2007). A literature review was carried out to identify and categorise stakeholders' interconnectivity in different stages of prefabrication projects. Then, a pilot study was conducted to ascertain the validity of identified stakeholders and the complexity of their relationships in certain project phases in New Zealand. Then, a questionnaire survey was developed. Firstly, it aimed to measure the significance of information integration amongst different organisations. Secondly, it sought to find the attributes of information essential for the success of the prefabrication supply chain, and finally, to ascertain the advantages of using blockchain technology in this industry.

2.1. Identification of stakeholders and phases of prefabrication

In order to identify the project development phases and stakeholders involved in prefabrication projects in New Zealand, two methods were used: literature review and interview. A total of 12 different phases of projects and a list of nine groups of stakeholders were primarily identified through a literature review. To ascertain the reliability and validity of the identified phases and stakeholders, a pilot study was undertaken. A participation invite was sent to 12 prefabrication construction experts, and six of them showed their inclination to participate. All experts had more than ten years of experience in New Zealand's construction industry. A process map of the 12 project phases and nine stakeholders was shown to them in separate interviews, and they were asked to check the correctness of the identified phases and stakeholders concerning their interrelationships in New Zealand.

2.2. Data collection

A questionnaire survey was developed for exploring the significance of information integration and the attributes of information contributing to the growth and success of the prefabrication construction supply chain (CSC) in New Zealand. Numerous current studies have employed the questionnaire survey as an efficient tool for collecting stakeholders' viewpoints and opinions pertinent to the CSC (Black, Akintoye & Fitzgerald, 2000). In this study, the questionnaire contained three relatively similar sections. A short overview of definitions was provided at the opening of the questionnaire, followed by a segment for collecting the basic information of participants. The respondents were from a broad spectrum of organisations, including, but not limited to, clients, contractors, designers, consultants, and suppliers. They were asked to answer the questions from clients' or contractors' perspectives. In the final section, respondents were required to answer multiple questions about utilising technology in their organisations, the disadvantages of non-integrated information exchange, necessary quality of information for the success of prefabrication, and advantages linked to the use of blockchain technology.

The questionnaire survey was sent to the PrefabNZ, an umbrella organisation for prefabrication in New Zealand, with around 350 members (including individuals and prefabrication firms). The minimum sample size calculated was 132 (at 95 % confidence interval; $p<0.05$). The study participants were initial randomly sampled from PrefabNZ members, and thereafter a snowball technique was used, so the study could develop an in-depth exploration of the applicability of blockchain in prefabrication (Creswell, 2005) and increase the diversity of the sample through a range of viewpoints (Kirchherr & Charles, 2018). To meet the snowball sampling technique requirements, the participants were encouraged to share the online questionnaire with their co-workers and other people they perceived to be qualified in the prefabrication industry of New Zealand. At the end of the data collection, 27 valid responses were collated, forming the basis for the data analysis. This represents a response rate of 20.4 %. Normally, studies related to construction have a rate of 20 to 30 % (Hwang, Shan & Looi,

2018). With direct reference to the questionnaire survey, nine respondents had over 15 years of related experience, seven between 10 and 15 years, eight between 5 and 10 years, and three less than 5 years. Also, 12 participants answered from clients' and 15 from contractors' standpoint.

3. Results and discussion

Prefabricated construction is better for geographically dispersed construction sites (PrefabNZ, 2018). However, this approach involves a more complex supply chain than traditional construction methods (Shahzad et al., 2013). Keeping an effective way of information exchange throughout prefabricated projects can considerably decrease this complexity (Wang et al., 2020). Integration of information among stakeholders in the prefabrication supply chain is complex, giving rise to myriad challenges on obtaining effective supply chain integration (Jaillon & Poon, 2010). Adopting information technology is necessary to streamline the complex information exchange processes and facilitate the prefabricated construction supply chain. In this study, the analysis of the questionnaire survey has been carried out in three steps: 1) utilisation of technology, 2) drawbacks associated with lack of information integration, and 3) advantages of blockchain technology in the prefabrication supply chain.

3.1. Prefabrication phases and stakeholders

A literature review and pilot interviews were used to identify the connection of prefabrication stakeholders with the phases of prefabrication projects in New Zealand. The nine groups of stakeholders comprise statutory bodies, clients, consultants or designers, developers, subcontractors, manufacturers, indirect and direct suppliers, and distributors or logistics enterprises with reference to (Gan, Chang & Wen, 2018) and (Bakhtiarizadeh et al., 2019). This study did not examine other stakeholders previously identified by other researchers. For example, Zhai, Reed, and Mills (2013) categorised the stakeholders into six groups, excluding the government in China. However, in New Zealand, the role of government or statutory bodies is also relevant to the prefabrication projects.

Moreover, according to the Royal Institute of British Architects (RIBA) plan of work 2013, the lifecycle of a construction project undergoes eight different phases from the initiation to the delivery. Also, Gibb (1999) classifies a modular construction project into 12 phases and compares them to the traditional construction approach. Using the mentioned research and with reference to the previous study by Bakhtiarizadeh et al. (2019), twelve prefabrication phases were tailored and tested for this study. The phases are Strategic Definition or Initialisation, Preparation and Briefing, Concept Design, Developed Design, Production Planning, Technical or Detailed Design, Construction (on-site preparation, off-site manufacturing, and transportation for assembly), Handover, Maintenance, Demolition (according to the sustainability criteria for future project use).

Interviewees also acknowledged that three phases: Detailed Design, Construction, and Handover are the main phases, intricately engaging most of the stakeholders. Also, they highlighted the essential roles of clients and contractors who are consistently involved from the inception until the end of projects and whose responsibilities are not limited to certain project phases.

3.2. Utilisation of technology

Adopting information technology in the supply chain has brought many benefits to different industries. Firstly, it has helped reduce products' development timeframes by enabling easier collaboration amongst the production crew. Secondly, it has reduced production costs. And lastly, it has enhanced the quality of products to match customers' requirements (Chou, 2004). Advanced systems, e.g. Electronic Data Interchange (EDI), Customer Relationship Management (CRM), and Enterprise Resource Planning (ERP), are some examples of information technology systems being used for Supply Chain Management (SCM).

However, these are being superseded by web-/cloud-based technologies such as the Internet of Things (IoT) and drones, enabling the swift and effective flow of real-time information across supply chain stakeholders (Ngai et al., 2004; Xing, Qian & Zaman, 2016).

Despite the added value of cloud-based technologies to SCM, there are still a few problems related to them. For instance, information security can be deemed an issue since there is always a risk of malicious attacks by hackers (Finch, 2004). Also, accessibility to information repositories for every supply chain member can be considered another issue

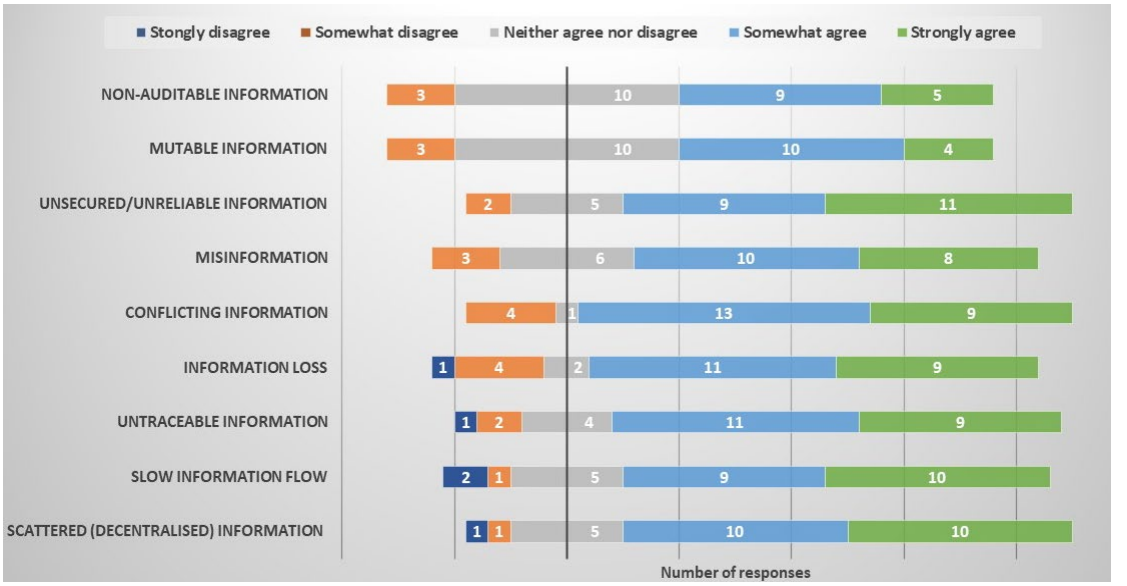

Fig. 1. Importance of information integration

(Chou, 2004). In the construction industry, the issues mentioned above can jeopardise organisations' critical information and trust amongst supply chain partners since all information is prone to change by any user either randomly or deliberately (Tse et al., 2017). With reference to the questionnaire in this study, 19 (out of 27) respondents demonstrated that information technology (in general) is used in their organisations, and 17 of them agreed that technology would be useful as a facilitator for information integration.

3.3. Significance of information integration

Information integration in the supply chain contributes to collaboration, trust and logistics integration (Gielingh & Tolman, 1991). However, uncertainties in supply chains appear when information exchange is not quite streamlined. Literature has proved numerous drawbacks associated with lack of information integration, e.g. scepticism, distrust, and fragmentation amongst the partner organisations.

In this study, an excerpt of previously studied drawbacks associated with lack of information integration was collected and incorporated in the survey. The respondents were asked to use a 5-point Likert scale and confirm the effect of those drawbacks on the outcome of their projects (Fig. 1).

Consequently, they also provided the attributes of information critical for the success of their supply chain (Fig. 2). The identified drawbacks associated with lack of information integration revolve around three main categories: transparency, traceability, and security. Information transparency is regarded as a decline in the uncertainty amongst the information exchangers (Angeletos & Pavan, 2004). Transparent information in the prefabrication supply chain improves trust and collaboration amongst stakeholders (Wang et al., 2020).

Traceability is the second critical attribute of information that helps the development of an efficient prefabrication supply chain. In the prefabricated supply chain, various types of materials are used, and the ability to trace the origin of these materials is highly crucial for prefabrication supply chain organisations and end-users (Saberi et al., 2018).

Information security is interpreted as the integrity of records and legitimacy of data (Lemieux, 2016). Information exchanged within an organisation varies from drawings and reports to legal documents (Sahin & Robinson, 2002). These types of information require an information-exchange platform that is capable of storing the information securely for future use. Therefore, a suitable information security engine is needed to warrant the secure transition of knowledge and learnings of a given project to the next. This attribute is critical for the integration of prefabrication supply chains.

3.4. Benefit of using blockchain technology in the prefabrication CSC

There is a close-knit relationship between information integration and blockchain technology as an enabler of a secure information sharing database. To

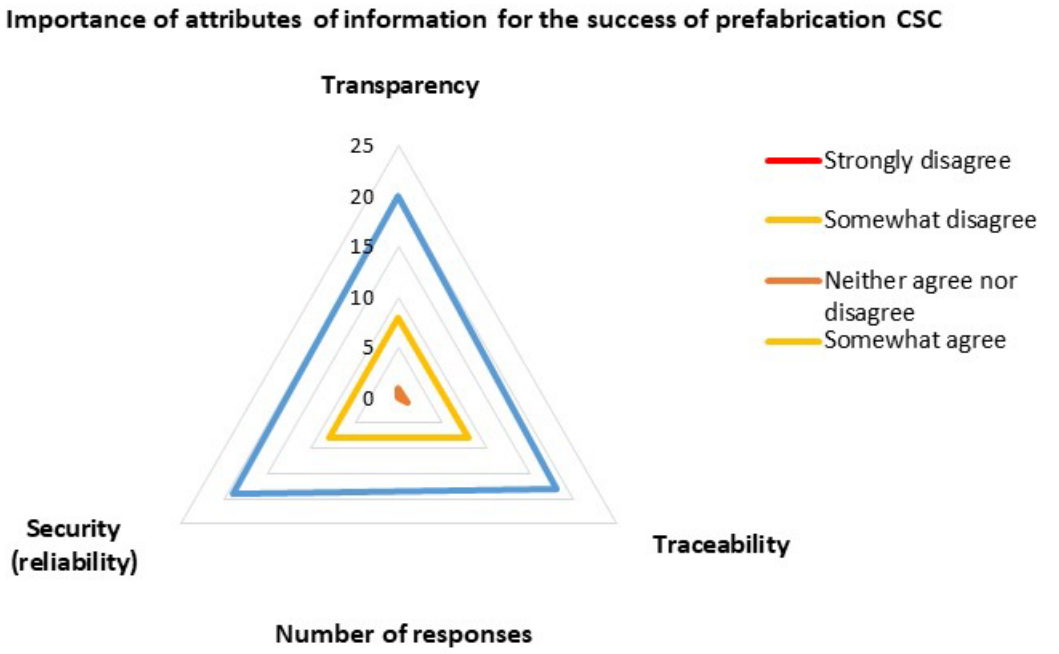

Fig. 2. Important attributes of information

diminish the disruptions to the prefabrication supply chain, information integration should be maintained and controlled constantly (Doran & Giannakis, 2011). Thus, blockchain technology would be a solution for creating integration in the prefabrication supply chain.

In New Zealand, the construction industry has long been intertwined with traditional construction approaches. However, with the rise of newer methods (e.g., prefabrication), industry experts are better discovering the benefits of using technologies. For this study, participants were asked to indicate their level of agreement with the benefits of information integration and blockchain technology. As indicated in Fig. 3, the results show that the breakeven point of the benefits of information integration commensurate with the benefits associated with blockchain technology meets at the level of 31 %.

Many studies have shown the ability of blockchain technology to store a range of information in different formats, such as models, sketches, images, drawings and recordings (Devine, 2015; Chen, Wang & Zhang, 2018). Once these types of information are recorded on the blockchain, information integration is formed, and the prefabrication sector will benefit by reducing fragmentation and improving transparency, traceability and information security.

4. Conclusions

Construction Supply Chain Management is regarded as a network of tasks providing services and values to clients (Mentzer et al., 2001). Most of the social, environmental, and economic shortcomings of traditional construction appear to have been resolved using newer practices, such as prefabrication. However, in this subsector of the construction industry, information integration, which is a major driver of supply chain integration, has not been paid attention to, resulting in a low level of trust amongst stakeholders (Shahzad et al., 2015). Information is transmitted securely amongst the stakeholders within an integrated supply system without any unwanted alterations. Also, It helps the prefabrication supply chain to benefit from the visibility and transparency attached to information integration platforms.

Blockchain technology, being an advanced information integration tool, represents a potential solution for dispelling inherent issues of supply chain systems by ensuring security, transparency, and traceability. Adopting this technology in the prefabrication industry of New Zealand can help obtain a more streamlined and efficient supply chain integration.

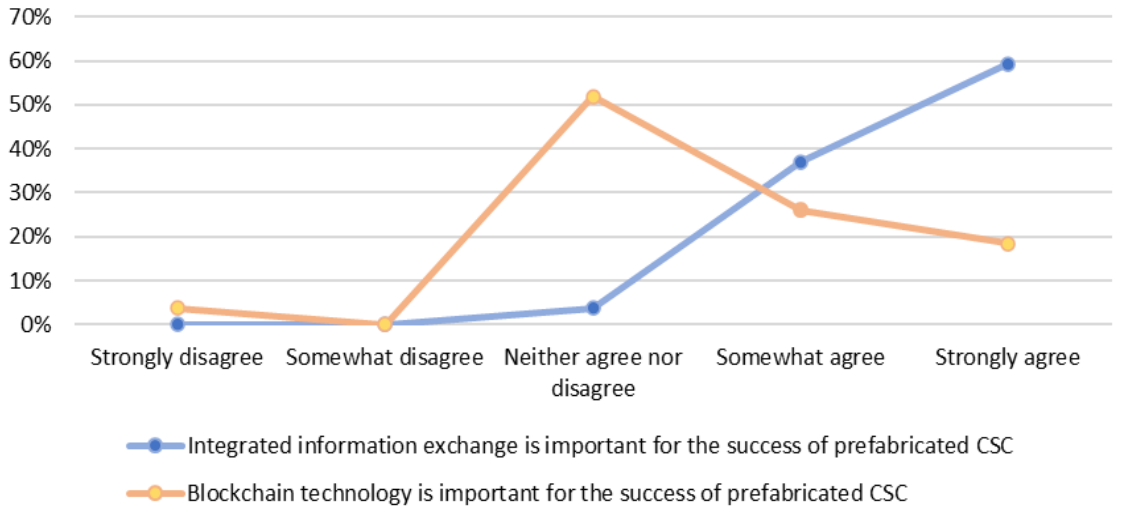

Fig. 3. Significance of using blockchain technology

This study explores the stakeholders' engagement in different stages of prefabrication projects and ascertains the benefits of using blockchain technology in New Zealand's prefabrication supply chain. Firstly, 12 construction phases and nine groups of stakeholders were identified through a pilot interviewing of industry professionals. Then, the disadvantages associated with lack of information integration and the importance of using blockchain technology as an information integration mechanism were explored by adopting a questionnaire survey for collecting a wider industry experts' opinion. Amongst the total of stakeholders and 12 project phases, two stakeholders and three phases were recognised as focal points in the supply chain network. The results show that using blockchain technology can enhance the integration of prefabrication projects by creating trust amongst the organisations working directly or indirectly in their supply systems. This technology also helps stakeholders with their business interactions and generates a transparent collaboration amongst prefabrication projects partners.

One limitation of this study is that the data was collected from the experts within a certain period. Also, all participants had not practically utilised blockchain technology as a tool in their professional experiences. In all cases, the technical definitions used in this study should have been explained to them clearly and upfront. The results of this study could be discussed by other studies which have provided frameworks for the uptake of the prefabrication supply chain. Blockchain technology will gradually become more accepted and more mature, which will enhance stakeholders' viewpoints on blockchain and other advanced IT systems.

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Factors affecting project performance in emerging construction firms: a moderated mediation model

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ABSTRACT
This research study explores the relationship between customer focus and the performance of construction projects undertaken by small companies. Additionally, process management in these companies has been studied as a mediator in explaining the relationship between customer focus and project performance. A moderated mediation model has been proposed to investigate the role of strategic planning and its effects on project outcomes. Data was gathered from 326 staff members working at different levels of management in some of Pakistan's emerging construction companies owned by young entrepreneurs. The study's findings revealed a positive relationship between customer focus and project performance mediated by process management. Moderation analysis indicates a significant relationship between process management and project performance when moderated by strategic planning. Constraints to the study have been identified, and suggestions for future research have been offered.

KEY WORDS
emerging construction firms, customer focus, process management, strategic planning, project performance

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Introduction

The need for innovation and continuous improvement has increased global competition between companies. Continuous improvement has become a challenge, conforming to exceptional quality standards and exceeding the needs and expectations of internal and external customers, specifically in developed countries (Yazdani et al., 2016). Many proposed initiatives encourage businesses and guide them in improving and enhancing their competitive-

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ness, process improvement, quality productions and services, cost reductions, and customer retention (Dreyfus et al., 2004; Imran et al., 2018).

Initially, quality initiatives were extensively used in the manufacturing industry and then in the services sector, but they are comparatively new in the construction industry. These have shown a significant influence on company performance in the past (Heravi & Faeghi, 2014). In the construction industry, different projects are undertaken with different professional teams fulfilling requirements and managing complexity and uncertainties daily. Quality management initiatives allow the construction sector to deal with these challenges by employing strategies that help them manage all of the interrelated components, methods, personnel, and tasks. It is essential in the construction industry in both emerging and developed companies to assure project completion on time, within authorised budgets, by increasing productivity and effectiveness to avoid and reduce losses. Research studies have been conducted to demonstrate the importance of quality management initiatives for small and medium-sized businesses (SMEs), which are considered the backbone of the economy (Mamman et al., 2019). Some other examples are TQM implementation in SMEs in Iran (Mehrabioun Mohammadi et al., 2021), India (Toke & Kalpande, 2021), Oman (Karyamsetty, 2021), and Kuwait (Sawaean & Ali, 2020). These studies have confirmed the importance of total quality management elements in enhancing the performance of any SMEs.

Recently, Pakistan has been observing a trend among young people to initiate and run their businesses, such as small construction companies having less than 20 employees. These small organisations are primarily characterised as project-based organisations. Many research studies primarily focus on manufacturing SMEs, and there is a lack of research on emerging and small project-based organisations in Pakistan. Some recent local cases explored different dimensions of total quality management, including hospital performance (Maqbool, 2019), export performance (Imran et al., 2018), financial and non-financial performance (Shafqat et al., 2021). However, studies that focus on organisational processes, customers and project performance in emerging small construction companies are still deficient, which is identified as a research gap likely to be filled by this research.

This study aims to explore the impact of process management and customer focus initiatives and their impact on project performance in emerging and small construction companies in Pakistan. The key objective is to investigate the research idea as a moderated mediation model where the mediating role of process management and the moderating role of strategic planning is studied to understand their impact on project performance. The research outcome is likely to bring a better understanding of process management and customer focus initiatives in small companies in terms of construction project performance. Management of small construction companies will be able to tailor processes when engaging in management activities for improving project performance within construction firms.

The paper is structured as follows. The literature review of the study is covered in the first section. The research methodology is covered in the second section, after which the analysis and results are presented in the third part. The discussion on findings is presented in the fourth section, after which the paper is concluded with directions for future research.

1. Literature review

1.1. Customer focus and project performance

Customer focus must be a part of a quality programme's overall implementation and scheduling (Mar Fuentes-Fuentes et al., 2004; Ooi et al., 2012). Maintaining a close and strong connection with customers is one aspect of customer focus (Flynn et al., 1994). To identify customer expectations, a company must produce goods and services that meet or surpass their needs (Sadikoglu & Olcay, 2014; Westphal et al., 1997). In previous literature, customer focus has been discussed extensively as a motivator for innovation (Abrunhosa & Moura E Sá, 2008). It motivates companies to be creative and meet customer expectations by introducing new products or services. More specifically, from a business perspective, innovation offers an opportunity to strengthen ties with customers by helping to meet their current needs before they order new products (Mehra & Ranganathan, 2008; Williams & Naumann, 2011; Littunen, 2021; Andrijauskiene & Dumciuviene, 2018; Kocmanová, 2012). In becoming innovative, a company supports its ability to create and maintain an edge over its competitors by adding value to its customers.

The term "project performance" is referred to as "project success". It measures project success or performance to determine how well the project accom-

plished its goals (Zaman et al., 2019). Early research evaluated project performance using such criteria as efficiency, influence on the team, influence on customers, and business success (Chang et al., 2013). Based on these criteria, several indicators were adopted, including meeting schedules, costs, quality necessities, team satisfaction, and market share (Al-Subaie et al., 2021; Arditi et al., 1997; Liu & Yetton, 2007; Mane & Patil, 2015; Pachura & Hairul, 2018). Time, cost and quality are the most important performance measurement indicators.

Quality management companies are devoted to providing excellent service to the company's external clients. They must first understand the expectations and needs of their customers before providing the products or services that will meet those needs. Supported successful customer-focused activities allow customising production to match customer requirements, expectations, and complaints. As a result, firms are more likely to deliver high-quality, reliable products and services on schedule while also improving efficiency and productivity. Satisfied customers buy more from a company boosting sales, expanding its market share and improving the overall performance. Small businesses must have a policy of addressing client needs through customer-focused activities. It is envisaged that QM policy and practice will aid this endeavour (Al-Gasawneh et al., 2021; Toke & Kalpande, 2021). According to previous research, prioritising the needs of the customer has a positive impact on operational performance (Ahire et al., 1996; Tarí & Claver, 2008), innovation performance (Kim et al., 2012), inventory management performance (Phan et al., 2011), customer satisfaction (Forza & Filippini, 1998; Phan et al., 2011; Tarí & Claver, 2008) and the overall firm's performance (Joiner, 2007). Therefore, the following hypothesis was formulated:

Hypothesis 1: Customer focus will have a significant and positive effect on project performance.

1.2. Mediating role of process management between customer focus and project performance

Process management is an approach of interconnected processes that focuses on three elements: "(1) mapping processes, (2) process enhancement, and (3) adhering to documented organisational processes" (Ahire & Dreyfus, 2000; Benner, 2001). For example, to minimise technical failures, excellent process management necessitates appropriately describing and documenting operational procedures, as well as explicit guidance for machine operation and setup implanted at all workstations (Flynn et al., 1994). Firms that attain higher degrees of process management emphasise the measures targeting efficacy, quickness, and expenses, as well as waste reduction, which includes process management encompassing project development (Adler et al., 1995; Czajkowska & Kadłubek, 2015; Edelenbos & Teisman, 2008; Nobelius & Trygg, 2002). These factors might significantly influence project performance, particularly in the construction business and especially in emerging and small construction firms. Process management is also linked to service delivery (Prajogo & Sohal, 2006). It is the decisive factor in how customers perceive the product's quality and, as a result, what degree of delight and satisfaction they experience and what feedback they give. Perception is evaluated based on concrete factors, such as trustworthiness, security, empathy, and responsiveness (Parasuraman et al., 1985; Suárez et al., 2014). Therefore, the following hypothesis was formulated:

Hypothesis 2: Process management will mediate the link between customer focus and project performance.

1.3. Moderating role of strategic planning between process management and project performance

"Strategic planning is based on the process of decision making, and it determines the direction of the organisation and its future outlook, as well as the way to achieving that future" (Oschman, 2017). For total quality management to function successfully, higher leadership must acknowledge strategic planning as a fundamental part of the firm to encourage their workforce to strive for perfection in what they do to achieve long-term excellence, which is critical for lucrative business growth in the long term (Movahedi & Koupaei, 2011; Suárez et al., 2014). Firms achieve a competitive edge if they can produce an effective planning process, which enables visibility and organisational interaction, stimulating dedication, teamwork, and collaborative innovation (Hoang et al., 2010; McLean et al., 2017). Some elements play a significant role in motivating the planning process aimed at creating concrete goals and devoting resources to the critical items, planning processes of departments and process or operation management strategy (Gates, 2010). Strategic planning plays a vital role in process management to accomplish desired

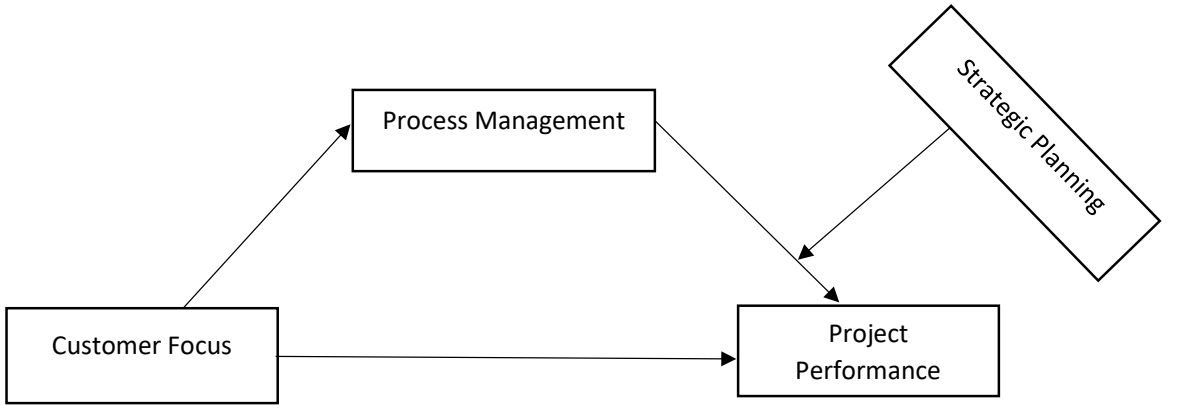

Fig. 1. Proposed research model

organisational performance. It is required for emerging construction firms to achieve a dynamic fit with climatic factors and unpredictability by working actively with resource allocation to mitigate risks and moving senior management's emphasis to uncertainty. So, an initiative would positively influence process management and corporate performance, resulting in indirect gains in the long and medium run. Therefore, the following hypothesis was formulated:

Hypothesis 3: Strategic planning will moderate the link between process management and project performance.

The model (Fig. 1) is developed based on the literature review and subsequent development of the research hypotheses; the customer focus will have a significant and positive effect on project performance; process management will mediate the link between the customer focus and project performance; and strategic planning will moderate the link between process management and project performance.

2. Research methods

2.1. Research focus: emerging construction organisations in Pakistan

This research focused on management employees of emerging construction firms. This target group was chosen for the following reasons: first, these firms are project-intensive, and second, the construction project's success is the responsibility of the management staff. They are in charge of all aspects of the project, including planning, execution, monitoring, control, and closure. Management staff ensure that deadlines, financial plans and quality standards are met.

2.2. Sample and procedure

The study's target group was management staff running emerging construction firms across major cities of Pakistan. A convenience sampling technique was used. Seven hundred questionnaires were distributed, and 360 were returned. However, only 326 filled out questionnaires could be used and comprised the final sample size.

Consequently, the response rate was 51 %. Respondents were asked to indicate their job title, demographics (gender, age, work experience, position, and the total number of employees in their organisation) and share opinions on customer focus, strategic planning, process management, and project performance. Each survey was accompanied by a cover letter that explained the purpose of the study. All participants gave their informed consent.

The participation was entirely voluntary, and confidentiality and anonymity were guaranteed. Regarding the size of studied organisations, about 70 % of the respondents indicated working in an organisation with up to 20 employees, i.e., small enterprises. Table 1 presents information about the respondents.

2.3. Measures

All variables were measured using a 5-point Likert scale ("1=strongly disagree, 2=disagree, 3=neither agree nor disagree, 4=agree, 5=strongly agree"). Customer focus was measured using a 7-item scale (Jong et al., 2019). One sample item of

Tab. 1. Demographic information

	Participants (N =326)	Percentage
1. Gender		
Male	300	92 %
Female	26	8 %
2. Age		
25–35 years	261	80 %
36–45 years	39	12 %
45 & above	26	8 %
3. Position		
Lower level	104	32 %
Middle level	140	43 %
Top level	82	25 %
4. Experience		
0–5 years	267	82 %
6 & above	59	18 %

this scale is "The organisation frequently is in close contact with its customers". The Cronbach's alpha reliability of this scale was 0.75. Strategic planning was measured using a 5-item scale (Lau et al., 2004).

One sample item of this scale is "Our organisation has a comprehensive structured planning process which regularly sets and reviews short and long-term goals". The Cronbach's alpha reliability of this scale was 0.70. Process management was measured using a 7-item scale (Flynn et al., 1994; Lau et al., 2004).

One sample item of this scale is "Our organisation practices daily operation work processes report system". The Cronbach's alpha reliability of this scale was 0.71. Project performance was measured using a 4-item scale (Stankovic et al., 2013). One sample item of this scale is "The project was successful in terms of timeliness of project completion". The Cronbach's alpha reliability of this scale was 0.85.

3. Research results

The analysis was done with SPSS software, and hypotheses testing was done using Model 14 (relevant to our research model) as implemented in the "PROCESS macro" provided by Andrew F. Hayes (Hayes, 2018).

3.1. Hypotheses tests

The values of mean, standard deviation and correlation are presented in Table 2.

In statistics, both moderation and mediation can occur in the same model. Moderated mediation is also called conditional indirect effects. The moderated mediation analysis was performed using PROCESS model 14 (Tables 3, 4, 5 & Fig. 2) to investigate the link between customer focus, process manage-

Tab. 2. Descriptive statistics and correlations

Constructs	Mean	SD	1	2	3	4
Customer focus	3.397	0.522	1			
Process management	3.456	0.448	0.744**	1		
Strategic planning	3.478	0.454	0.791**	0.569**	1	
Project performance	3.428	0.699	0.472**	0.492**	0.373**	1

Note N=326, p < 0.05*, < 0.01**

Tab. 3. Moderated mediation (model 14-results part a)

	Outcome (project performance)					
	Coefficient	SE	t	p	LLCI	ULCI
Customer_ Focus	0.290	0.130	2.09	0.037	0.017	0.563
Process_ Mgt	0.466	0.099	4.730	0.000	0.272	0.660
Strategic_ Plan	-0.051	0.106	-0.475	0.635	-0.260	0.159
Interaction (Process*Strategic)	0.262	0.090	2.909	0.004	0.085	0.439

Tab. 4. Moderated mediation (model 14-results part b)

Test(s) of highest order unconditional interaction(s)					
	R2-chng	F	df1	df2	p
Interaction (Process*Strategic)	0.019	8.463	1.000	321.000	0.004

ment, strategic planning and project performance. The link between customer focus and project performance was statistically significant and positive [Coefficient = 0.290, $p < 0.05$], H1 was supported.

The interaction of process management and strategic planning on project performance was found to be statistically significant and positive (Coefficient = 0.262, LLCI & ULCI ≠ 0, $p < 0.05$), see Table 3. Table 4 shows the test of highest order unconditional interactions. The R2 change term specifies whether or not a moderating effect exists. Because we have an R2 change value of (0.019), which is more than zero; so, in this case moderating effect exists. These results identify strategic planning as a positive moderator of the link between process management and project performance, H3 was supported.

The moderated mediation effect is depicted in Fig. 2 and Table 5. This graph shows process management on the X-axis and the mean values of project performance on the Y-axis. It shows three different levels of the moderator (strategic planning). Based on the graph, strategic planning tends to strengthen the link between process management and project performance. The mediating effect of process management on project performance is maximised when using strategic planning as a moderator. The slope where the level of strategic planning is high (+1SD) = 0.522), the mediating effect (Effect=0.468) of process management on project performance becomes very high and significant. This means strategic planning moderates the link between process management and project performance so that this link becomes

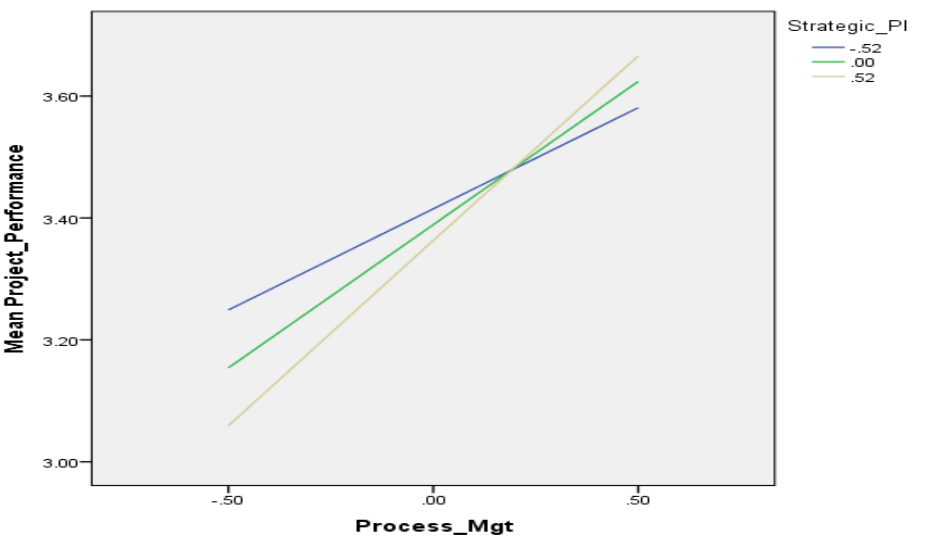

Fig. 2. Moderation effect at different levels

Tab. 5. Moderated mediation (model 14-results part c)

Direct effect of customer focus on project performance					
Effect	**SE**	**t**	**p**	**LLCI**	**ULCI**
2.90	0.139	2.093	0.037	0.017	0.563
Conditional indirect effects of customer focus on project performance					
INDIRECT EFFECT: Customer_ Focus -> Process_ Mgt -> Project performance					
Levels (Strategic_ Plan)	**Effect**	**Boot_ SE**	**Boot_ LLCI**	**Boot_ ULCI**	
-0.522	0.256	0.088	0.054	0.403	
0.000	0.362	0.081	0.188	0.504	
0.522	0.468	0.086	0.294	0.629	
Index of moderated mediation					
	Index	**Boot_ SE**	**Boot_ LLCI**	**Boot_ ULCI**	
Strategic_ Plan	0.203	0.060	0.095	0.333	

The result of index of moderated mediation showed statistical significance of moderated mediation (index =0.203, bootLLCI = 0.095 & bootULCI = 0.333). Thus, hypotheses 1, 2, & 3 were supported.

stronger when strategic planning is high. Two further slopes at different levels of strategic planning are also depicted in the graph. The slope at the mean level of strategic planning shows a significant mediation effect (Effect=0.362) of process management on project performance. Similarly, the slope of strategic planning (low (-1SD) = -0.522) below the mean (Effect= 0.256) also demonstrates a significant mediation effect of process management on project performance.

Thus, the link between customer focus and project performance through process management was statistically significant and positive (Table 5 and Fig. 2). The direct effect of customer focus on project performance: effect = 2.90, $p < 0.05$. The indirect effects at different levels showed corresponding results. At low level, indirect effect =0.256, $p < 0.05$. At middle level, indirect effect =0.362, $p < 0.05$. At high level, indirect effect = 0.468, $p < 0.05$, so H2 was supported.

The result of index of moderated mediation showed statistical significance of moderated mediation (index =0.203, bootLLCI = 0.095 & bootULCI = 0.333). Thus, hypotheses 1, 2, & 3 were supported.

4. Discussion

This section presents the discussion on research findings on the tested hypotheses. The first key finding shows that customer focus has a significant and positive impact on project performance in the context of emerging construction firms (H1). This result suggests that customer satisfaction, external communication and information management are significant ingredients of customer focus. This finding is consistent with previous studies, where communication with customers, data management and customer satisfaction were essential principle indicators of project performance in emerging construction firms as all these principles are important parts of the engine driving the project's ability to deliver superior consumer values and superior business performance (Hassan & Waiganjo, 2016; Mehra & Ranganathan, 2008; Muiruri et al., 2021; Pambreni et al., 2019; Williams & Naumann, 2011).

Clients are essential assets for any business, and efforts to understand the complexities that affect their behaviour and positive responses would benefit both customers and performance (Al-Gasawneh et al., 2021). The study revealed that quality management initiatives are used in emerging and small construction companies in Pakistan, particularly focusing on customers; the major advantage of QM to businesses is "increased customer satisfaction". Customer focus activities improve the satisfaction of customers. Furthermore, satisfied clients are often loyal over time, resulting in increased sales and the improved financial, non-financial and entire performance of an organisation (Ahmad et al., 2019; Albuhisi & Abdallah, 2018). The finding also explains that the customer-related activities implemented in emerging

construction firms enhance the provided services and obtain customer satisfaction. Customer focus refers to an organisation's commitment to meeting customer expectations, as a result, improved overall organisational performance (Aburayya et al., 2020; Ali, 2017). The importance of customer focus is seen as critical to the company's long-term performance and growth (Baidoun et al., 2018).

This study also indicates the link mediated by process management between customer focus and project performance in the context of emerging construction firms (H2). This outcome is consistent with earlier studies, where stable production, reduced process variation, and efficiently working distribution were indicated as technical aspects of process management for better business performance (Psomas & Jaca, 2016; Zhang et al., 2020). Consequently, these technical aspects matter greatly when trying to enhance the performance of any business. This study found that to obtain an enhancement in the end product, technical aspects should be considered in the emerging and small construction firms. Few studies examine the mediating effect of process management on the link between customer-oriented activities and performance.

The technical aspects reflect how organisations plan their management of internal resources and external parties to support effective and efficient process operations (Calvo-Mora et al., 2015; Gadenne & Sharma, 2009; Oakland, 2011; Vanichchinchai & Igel, 2011). The aim of the production function is the accomplishment of optimum operational efficacy. Efficacy is generally assessed through performance & productivity. Practically, this purpose is supplemented with additional objectives and more particular performance measurements which explain the difficulties of the firm's processes and/or operations.

These measures include customer satisfaction, reduction of defects and expenses, and, most importantly, flexibility in operations-related activities (Feng et al., 2008; Ferdinandus, 2020; Fotopoulos & Psomas, 2010). In simple words, customer-focused activities are designed to enhance the end products with customer satisfaction. The results of "customer-related activities will then be shifted to technical aspects of process management to be implemented and reflected in the entire performance of the project".

Another important finding of this study shows that strategic planning significantly moderates the link between process management and project performance in the context of emerging construction companies of Pakistan, and the moderated mediation index was also statistically significant (H3).

Thus, this finding proved that strategic planning was the way for creating a path for emerging and small business functions by assessing the current and future goals. It is the mechanism by which a business analyses its mission, makes decisions and strategies about allocating internal resources, establishing business models, and processes for better overall performance (AlQershi, 2021). Strategic planning is frequently used for the improvement of organisational performance.

Strategic planning provides hope of uniting the organisation around a clearly defined set of missions and goals (Bryson et al., 2018; Stoeglehner et al., 2011). Strategic planning plays a vital role in process management for achieving the desired performance, specifically in project-based organisations.

Planning improves manager awareness of strengths, weaknesses, threats, opportunities, enhances the understanding of processes, managing of internal resources, materials, increases productivity, enhances profitability, and strengthens the company's position in the market. Most importantly, organisational performance improves when strategic plans are implemented successfully (Aldehayyat & Al Khattab, 2012; Mustafee et al., 2013).

Setting process and operation objectives, devising and executing plans, monitoring performance, or controlling the plan's progress are all aspects of strategic planning that are important for the overall performance (Aquilani et al., 2017; Özgüner, 2015). In simple words, planning is necessary for effective and efficient use of resources during the execution phase for achieving desired project performance in emerging construction firms.

This study supported all research hypotheses. Customer focus, process management and strategic planning were considered essential quality initiatives in emerging construction firms for better project performance.

Conclusions

The role of quality management in construction projects has evolved into means of gaining a competitive edge worldwide. The construction sector is viewed as having a significant impact on economic growth and poverty reduction. Popular quality initiatives in emerging construction firms focus on customers, process management and strategic planning.

These three elements are interlinked. The processes depend on customer feedback. Their execution requires strategic planning for better project performance. This study supported all hypotheses. Customer focus has a significant effect on project performance. Process management significantly mediates the relationship between customer focus and project performance. Strategic planning significantly moderates the relationship between process management and project performance in the context of Pakistan's emerging firms run by young people.

This research contributes to the literature on quality aspects and construction project performance differently. First, it contributes to theory by examining the hypothesised link between researched variables, suggesting that prioritised customer needs significantly impact the success of building projects. Second, process management incorporated as a potential mediator in this paper extended the previous study of customer focus and project performance. Third, the strategic planning operationalised in this research to affect the interaction between process management and the project through a moderated mediation technique adds to the scarce literature and enriches the understanding. The research found that strategic planning serves as a driver for individuals and firms, resulting in process management, which leads to success. As a result, the greater the planning, the better the process management. Lastly, the contribution to the literature is made by quantitatively assessing the links between customer focus, process management, strategic planning, and project performance, given the Pakistani environment of this study.

This study demonstrated the effect of "quality initiatives" on project performance. The outcomes revealed that only three total quality management elements significantly correlated with performance in construction projects. Therefore, it is understandable for owners, managers and supervisors that the implementation of quality initiatives (customer focus, process management, and strategic planning) enhanced project performance. The implication is that emerging construction firms should focus on those quality practices, including customer focus, process management, and strategic planning for improvement in the performance of construction projects. The research has valuable practical implications for Pakistan's government that should encourage emerging construction firms to seek a quality system and enhance their project performance, improving Pakistan's economy.

The research has certain limitations. First, emerging construction enterprises were selected for the investigation. This research could be repeated in other industries in the future. Second, the study was limited to Pakistani construction firms only. It is suggested to extend the research to different areas. Other relevant moderated mediation mechanisms could be at work to describe the link between the customer focus and project performance. Future research may look into the mediating role of communication and the moderating influence of enterprise size and employee experience to better understand the link.

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Adaptation of Polish regions to the challenges and opportunities of the Belt and Road Initiative

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ABSTRACT
The Belt and Road Initiative (BRI) is an international project focused on creating a network of infrastructure and strengthening trade links, primarily between China and Europe. Transport of goods within the BRI is conducted through one maritime and six rail economic corridors, one of which (New Eurasian Land Bridge) crosses the territory of Poland. This article covers issues related to the impact of the BRI on the regions of the participating countries and aims to determine the position of Podlaskie voivodeship compared to other Polish voivodeships in the BRI. To achieve this aim, a multi-stage study was conducted, including the design of a set of quantitative factors determining the position of voivodeships in the BRI, evaluation of the importance of the factors during the expert study, collection and normalisation of quantitative data, and comparative analysis of the factors. Research results show that, given the adopted methodology, the Podlaskie voivodeship is ranked 11th out of 16 Polish voivodeships in terms of its position in the BRI. This article's findings contribute to the discussion on development opportunities in the Podlaskie region in the BRI context. They also motivate comprehensive research on the strategy for the widest possible inclusion of Podlaskie in the BRI's activities and provide an important stimulus for the region's development.

KEY WORDS
New Silk Road, Belt and Road Initiative (BRI), Podlaskie voivodeship

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Introduction

The Belt and Road Initiative (BRI) is an international project that will be celebrating its 10th anniversary in 2023. It was initiated by the People's Republic of China (PRC) President Xi Jinping in 2013. In September 2013, during a visit to Nazarbayev University in Astana, Kazakhstan, President Xi delivered a speech in which he proposed the creation of the "Silk Road Economic Belt". A month later, in October 2013, during a speech at the Indonesian

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Parliament in Jakarta, he expanded this concept with a parallel initiative of the "21st-Century Maritime Silk Road". The two projects have been merged under "One Belt and One Road" and later renamed "Belt and Road Initiative". Later, the infrastructural scope of BRI was extended to include the initiative of the Northern Sea Route (also called the Polar Silk Road), a maritime route linking China and Europe via the Arctic Ocean (Tillman et al., 2018, p. 348).

Even though the BRI is widely present in today's global economy and involves an increasingly larger part of the world in its physical and economic scope, it still lacks a precise definition. It is frequently perceived as an emerging network of infrastructure links to strengthen trade connections between China and Europe (Bartosiewicz & Szterlik, 2020, p. 7). But in a wider context, this project can be seen as an open platform for cooperation between the participating countries. Despite its vague scope, the BRI has undeniably become a project of global economic importance, with the potential to have a real impact on the economic situation of the member states. Investments under the BRI often help involved countries improve their infrastructure and increase trade and connectivity among themselves and the world. According to PwC, investments gathered under the BRI can help meet some infrastructure needs in the developing part of Asia (Wijeratne et al., 2017, p. 12).

The BRI has been attracting considerable academic interest since the beginning. Given its vast political and economic implications (such as estimated financial scale, the number of countries and actors involved or its geographic scope), the scholarly attention is not surprising. However, the interdisciplinary multiplicity of aspects related to the BRI and the complexity of the subject causes problems in conducting related research. According to Blanchard (2021, p. 237), to provide analyses of substantial value for academics, businesspeople, and policymakers, BRI researchers should consider making several adjustments.

One of these adjustments should focus on a more in-depth BRI analysis in specific regions or countries instead of looking at the BRI in its entirety, as the subject is too comprehensive (Blanchard, 2021, p. 240). This article unintentionally follows this advice, as it covers issues related to the BRI's impact on regions of participating countries. The research aims to determine the BRI position of Podlaskie voivodeship compared to other Polish voivodeships. To achieve this objective, the authors conducted a multi-stage quantitative study.

The paper is structured as follows. The first chapter presents the results of a literature review on the BRI's launch and development and its regional influences based on a case study of a particular member country. It also includes a discussion on Poland's place in the project. The second chapter describes the research methodology that has been adopted. The third chapter presents research results related to Polish voivodeships' ranking in the context of the BRI. The fourth chapter includes an in-depth analysis and discussion of the obtained results. In conclusion, the authors explain the study's limitations and indicate the directions for further research.

1. Literature review

1.1. Project's genesis, scope and development over the years

The first mentions of the will to recreate the ancient Silk Road date back to 1994. During the visit to Central Asia countries, China's Prime Minister Li Peng proposed to further develop and stabilise Sino-Central Asian relations, economic cooperation and non-inferential ties through collaboration along a "New Silk Road" (Ali, 2020, p. 74–75). However, it was not until 19 years later that Xi Jinping's administration formally inaugurated efforts to create a modern version of the Silk Road. It was his government that conceptualised "Two Centenary Goals" for Chinese society. The first goal was aimed at transforming China into a "moderately prosperous society of a higher level to the benefit of well over one billion people" and was to be achieved by 1 July 2021, the centenary of the founding of the Chinese Communist Party (CCP). However, from a global point of view, it is the second objective — "Great rejuvenation of the Chinese people" — that deserves special attention (Góralczyk, 2016, p. 290–291). According to the Chinese government, this will be the construction of a "prosperous, powerful, democratic, civilised and harmonious socialist modernised country", set to be accomplished by 1 October 2049, the centenary of the founding of the PRC (Lu, 2016, p. 80). The first objective is directed at the domestic policy of the country, while the second is a strong allusion to the increasingly assertive and world-open external policy pursued by contemporary China. The Belt and Road Initiative can be perceived as the element of this second goal, as this project involves vast foreign cooperation.

In their pursuit to define the project most thoroughly, the researchers created several different terms to describe the BRI. The academic literature provides terms ranging from more general, such as "connectivity venture" (Blanchard, 2021, p. 236), "geostrategic project" (Góralczyk, 2016, p. 293), or "development programme" (Erschbamer et al., 2020, p. 3), to more specific, such as "logistics endeavour" (Nazarko & Kuźmicz, 2017, p. 497) or "transport network" (Wagener et al., 2020, p. 198). Researchers hold similarly divergent views on the territorial scope of the project. In the initial phase of the project's development, the identification of BRI member states was fairly easy and possible through authoritative documents and public statements. However, it became more difficult over time as the project expanded to more geographic realms, including the Arctic or Latin America (Blanchard, 2021, p. 239). The most common assumption is that there are around 70 BRI member states with territories located along the seven defined BRI routes, one maritime and six land (OECD, 2018, p. 12). One of the limitations of this approach is the fact that the line between an infrastructure project funded by China and the BRI project is often unclear (Teo et al., 2019, p. 3), and as the project is expanding, the BRI "brand" is often being applied to many other China-financed projects (Hughes et al., 2020, p. 584), which to some researchers equals the country's participation in the BRI, but in some instances that may not be the case. As far as the material scope of the project is concerned, researchers are slightly more unanimous. Teo et al. (2019, p. 9) proposed a typology of the BRI infrastructure including four categories: transport (road, rail, airports, seaports, rail terminals), energy (pipelines, power lines, dams, coal, wind, solar, mines), communication (fibre-optic cables, receiving stations) and economic (Special Economic Zones, development incentives, financial mechanisms).

According to Blanchard (2021, p. 239), "soft" infrastructure, such as bilateral investment treaties or free trade agreements, also constitutes part of the BRI. This opacity of the BRI may be understood as one of its key characteristics. Narins and Agnew (2020, p. 829) suggested that the project's vagueness is intentional because it makes the BRI a flexible container for necessary but unforeseeable future adaptations. However, regardless of the difficult-to-define geographical and subject matter scope, the BRI is undoubtedly a project that covers a significant part of the world with its reach and impact.

One of the declared foundations of the BRI emphasised by the Chinese side is the formula "win–win cooperation", meaning the cooperation that benefits all parties involved (Nobis, 2016, p. 8). On the one hand, this concept appears to convince the world decision-makers, as, over the years, many countries have expressed their willingness to participate in the BRI. On the other hand, the controversy over China's increasing presence and influence in member countries, including accusations of the BRI being a "debt trap" and the example of "new colonialism" (He, 2020, p. 139), must also be addressed. The resolution on this issue remains a matter of each researcher's own conclusions, as to date, there has been no comprehensive study identifying, classifying and measuring the benefits and costs of the BRI for both China and member states. The existing literature contains two lines of argument: the first focuses on collaboration (cooperation, co-creation, joint growth), and the second — on self-interest, highlighting China's one-sided goals to grow and prosper (Thürer et al., 2020, p. 8). For example, Nawrot (2018, p. 276) stated that Chinese investments should be widely accepted in Europe, as they may stimulate market growth, and Yu argued that the potential benefits coming from the BRI would be mutual (2017, p. 365). On the other hand, Ma (2017, p. 152) pointed out that China wanted to use the BRI to increase the openness of other countries' markets to its investments and products, but at the same time close its own market to foreigners. According to Nazarko et al. (2017, p. 1213), China is going to benefit the most from the BRI, given their export surplus and ever-growing trade imbalance. Blanchard listed the following factors as potential benefits of participation in the BRI: increased economic growth, better infrastructure, job creation, poverty alleviation and regional economic integration. Potential costs include higher trade deficits, the loss of domestic and foreign policy independence, increased pollution, environmental degradation and social dislocation (Blanchard, 2021, p. 243).

There is also no academic consensus on China's true rationales behind the project's establishment. A whole lot of potential reasons for China to launch such a project have been expressed in academic literature, including (i) seeking political support and legitimacy internationally (Ma, 2017, p. 152), (ii) reducing internal excess production capacities (Holslag, 2017, p. 49; Jones & Zeng, 2020, p. 1422), (iii) accelerating development and the ensuring stability of western provinces (Chaisse & Matsushita,

2018, p. 169; Nazarko et al., 2016, p. 3), (iv) ensuring reliable access to other countries natural resources (He, 2020, p. 142; Holslag, 2017, p. 51), or even (v) stimulating China's import to satisfy Chinese upper-class consumers (Alon et al., 2018, p. 369). Although these rationales remain uncertain, there seems to be an agreement that the BRI already has a tangible effect on the member countries' economies and global economy, as reflected in various statistics. The World Bank analysts claim that BRI projects could help alleviate extreme poverty for up to 7.6 million people (earning less than USD 1.90 per day) and moderate poverty for 32 million people (earning less than USD 3.20 per day) in BRI and in non-BRI economies. This may be possible by increasing trade, complementary trade facilitation reforms and preferential reduction of tariffs (The World Bank, 2019, p. 5, 59, 70). It is estimated that the development of infrastructure within the BRI may reduce delivery times by 1.2 to 3 % globally (Choroś-Mrozowska, 2019a, p. 15), and by up to 12 % for countries located along the economic corridors (The World Bank, 2019, p. 5). Of course, it must be considered that these forecasts were made before the outbreak of the global pandemic, so the presented figures have become outdated to some extent. However, they still provide information on the potential strength and scale of the BRI's impact in the context of the global economy.

1.2. Impact factors of the BRI on the regions of the member states

The BRI is undeniably a project that covers a large part of the world, despite the exact territorial scope of the project being ambiguous. Even though BRI's transport corridors, which are the main territorial axes of the project, have been outlined only in Europe, Asia and Africa so far, it is easy to overestimate the project's real coverage. Some researchers go so far as to consider China's cooperation with Latin America as a part of the BRI (He, 2020; Toro-Fernandez & Tijmes-Ihl, 2021). However, this expansion of the BRI scope can be considered rhetorical for the time being. For the purpose of this paper, it is considered that so far, the BRI mostly focuses on two continents: Asia and Europe, with the key regions being Central Asia, South-East Asia, Middle East and Central and Eastern Europe (Garlick, 2020, p. 4). The identified regions can be considered as the first level of cooperation within the BRI. The second level encompasses bilateral relations between China and the project's member countries. The third cooperation level centres on the most important regions of selected countries. The first level of cooperation is meant to facilitate regional economic integration and takes place through such platforms as Shanghai Cooperation Organisation, "16+1" format or China–Arab States Cooperation Forum (Yu, 2017, p. 356). The second level of cooperation, expressed through bilateral relations, is implemented through agreements signed by heads of state, while the third level is mostly done through investments targeting specific business outcomes. Thus, the more limited the scope of cooperation within the BRI, the less this cooperation takes place on the basis of ideas and more on the basis of specific projects. It is through the projects and their results that the opportunities for regional development and the benefits for the member countries of the BRI can be considered.

Investments within the scope of the BRI are mainly focused on the network of transport corridors, covering the construction or modernisation of transport infrastructure (road, rail, air and sea). For many member states, especially those with a low level of development, the possibility of receiving economic support from China means a chance to escape the low or middle-income trap (Choroś-Mrozowska, 2019a, p. 14). These countries have major deficiencies in transport-related infrastructure, which limit their productivity, increase the cost of doing business and reduce their attractiveness to outside investors. However, the costs involved in filling these gaps are usually beyond the budget capabilities of developing countries. In this situation, China, as a new source of capital, ideas and know-how, may contribute to bringing a member state's previously unprofitable industrial capacity into operation (Vangeli, 2020, p. 24). This renewed industrial capacity, in combination with other capital investments as well as greenfield projects, has the potential to influence the economic landscape of participating regions and countries. The population structure of such places is often characterised by a high proportion of young people struggling with underdeveloped labour markets and high unemployment. The development of infrastructure, trade and industry can give BRI member regions and states the opportunity to realise their potential and embark on a path of growth, including the creation of countless jobs.

The infrastructural projects being developed within the BRI are a bold display of China's influence and capabilities. At the same time, the long-term

effects of the sudden explosion of Chinese construction projects in developing countries are not yet entirely clear. Even though the potential for economic development resulting from participation in the BRI is evident, there is still space for organisational improvement. According to Thees (2020, p. 2), the most prominent issues related to BRI projects remain: the unclear local effects, a lack of transparency and fears around Chinese dominance. These aforementioned local effects include environmental concerns, as there have been cases where investors have not carried out environmental impact studies in relation to launched projects (Wang & Resare, 2021). Among the risks cited in this context, there are also concerns of social and religious background about working with Chinese workers and companies, increased financial dependence on China, or the risk of losing control over strategic assets, one of them being the country's energy sector (Rahman, 2020, p. 7). Vakulchuk and Overland noted that another potential risk associated with the rapid, uncontrolled growth of BRI-related investment in the region is bringing up a possibility to reinforce bad governance and corruption and provoke profit-seeking behaviour and competition between different interest groups (Vakulchuk & Overland, 2019, p. 119).

The decision to join the BRI must be preceded by a thorough analysis of the potential benefits and costs for every country. Serbia can serve as an example of how the BRI can influence, positively and negatively, the development of member countries and regions. In March 2017, the European Union's (EU) foreign policy chief Federica Mogherini described the Balkans as "the chessboard where the big power game can be played" (Makocki, 2017) and Serbia fits into this metaphor quite well. According to Dimitrijevic (2017, p. 68), the Serbian foreign policy strategy is designed on four pillars, namely the EU, Russia, the United States and China. Russia was once considered Serbia's most important economic partner, but now China seems to be taking its place. Since 2009, there has been a strategic partnership between these two countries, expanded in 2013 and raised to the high level of comprehensive strategic partnership in 2016 (Obradović, 2018, p. 197). As one of the poorer countries in Europe, with an unstable economy, high levels of unemployment and corruption and major deficiencies in key infrastructure, Serbia is rather receptive to external stimuli for development, one of them being Chinese loans and investment. As for the Chinese side, the investors see the advantages of Serbia's geographical location in a "transit zone" between east and west, and between north and south Europe. This is reflected in the range of investments underway, including a high-speed railway, the Land-Sea Express Route, designed to link the Chinese-owned port in Piraeus, Greece, with Budapest, through Skopje and Belgrade (Barisitz, 2020, p. 63). Other prominent examples of the Chinese investment activity include the purchase of the Serbian steel mill in Smederevo and Mining and Smelting Combine Bor (RTB Bor) (Bugarčić et al., 2020, p. 24). Although nowadays Chinese investments are mainly merger and acquisition oriented (Choroś-Mrozowska, 2019b, p. 49; Ma, 2017, p. 151), some greenfield investments are also present in Serbia, some examples being the Shandong Linglong tire factory, the Minth Automotive Europe and Xingyu Automotive Lighting Systems factories, or the industrial park in Borca (Paszak, 2020).

These projects can undoubtedly have a positive impact on the momentum of Serbia's development. For example, the transfer of the nearly bankrupt Smederevo steel mill and RTB Bor into the hands of Chinese companies has saved roughly 5 000 jobs each in their respective regions (Surk, 2017). In the Podunavlje District, which is one of the less developed and poorer districts of Central Serbia, the Smederevo steel mill is an important employer for the local population, so the Chinese investment has had a real impact on the economic situation of the region's inhabitants. Telekom Srbija's growing cooperation with Huawei in the construction of 5G networks, as well as in the development of urban monitoring in Belgrade (Pantovic, 2020), can positively affect the quality of life of citizens. The close cooperation between the two countries also resulted in Serbia receiving substantial aid from China in the form of medical equipment and vaccines against COVID-19. On the other hand, it is also important to consider possible disadvantages related to BRI projects in Serbia. Chinese industrial investments are said to be burdened with negative environmental impact, resulting from investors' failure to carry out environmental and social impact assessments, as well as from repeatedly exceeding permitted emissions of harmful elements, including sulphur dioxide and arsenic (Wang & Resare, 2021; Pantovic, 2020). As for the Land-Sea Express Route, The European Commission (EC) started investigating the project for possible breach of the European competition laws related to public tenders for large transport projects (Obradović, 2018, p. 197). The EC investigation has involved only Hungary (as a member state), but Ser-

bia was urged to strengthen standards of legal compliance and warned that distancing itself from EU guidelines may threaten the success of the accession process (Wang & Resare, 2021). In addition, the loans taken out for investments, usually for 20–30 years and at interest rates of 2.0–2.5 %, will burden Serbia's budget for many more generations. Although some scholars describe the BRI investment in Serbia as a huge opportunity (Dimitrijević, 2017, p. 77), necessary for the accomplishment of the development goals (Bugarčić et al., 2020, p. 23), others focus more on the negative side effects, such as national stability and security dilemmas (Mišev et al., 2018, p. 241). Therefore, the evaluation of the Chinese presence in Serbia remains unsettled.

1.3. Poland's place and role in the BRI so far

The international affairs between Poland and China, renewed in 1991, have for many years been characterised by a mutual desire to maintain good relations and enhance economic cooperation (Bartosiewicz & Szterlik, 2018, p. 8). The milestones of this relationship have been the meetings of the heads of state of the two countries, which have taken place over the years and have resulted in signing multiple cooperation agreements. The most significant events include issuing the joint communiqué in 1997, which stated that the two states had established cooperation in the fields of economy, trade and technology (Wizyta oficjalna…, 1997), and signing a joint statement on the establishment of strategic partnership relations in 2011 (Polsko-chińskie…, 2011). Apart from looking at the bilateral relations between the states, one should also consider the milestone of Poland joining the EU in 2004. Since then, Poland has also been a side to all EU–China relations. The EU has been China's largest economic partner for years, and since 2020, China has replaced the United States as the EU's largest economic partner (China-EU…, 2021). However, Poland, as a member state, does not have the authority to decide on behalf of the EU on the dynamics of EU–China relations.

The third dimension of Sino–Polish relations is the 16+1 platform. This platform was initiated in 2011 by China with a group of sixteen countries from the Central Eastern Europe (CEE) region, including Poland. Since 2012, several 16+1 summits have been held (the first in Warsaw), during which plans for specific investments in the CEE area were negotiated, and agreements on their implementation were signed (Bartosiewicz & Szterlik, 2018, p. 9). The appropriateness of a format such as 16+1 can be seen, given the difference in the size of the Chinese economy compared to the economies of the CEE area. Even Poland, being one of the biggest CEE states, can be compared to some Chinese provinces in terms of size and is twice smaller than some of them in terms of GDP (Kamiński, 2019, p. 233). However, among the criticisms voiced against this platform, researchers point to the lack of tangible results of its functioning and the implementation of a small part of the plans created so far (Góralczyk, 2017, p. 157).

As it can be noticed, in the case of two out of three dimensions of Sino-Polish cooperation (EU and 16+1 membership), the rate and the momentum of relations' development is relatively limited. The bilateral relations provide the greatest opportunity for Sino-Polish cooperation. Poland officially accessed the BRI in 2015, when a cooperation agreement between the countries was signed during President Andrzej Duda's visit to the PRC, concerning, among other things, the cooperation within the BRI (Tomaszewska & Pohl, 2019, p. 168). But the actual cooperation started in 2013 when the first regular rail link between the Polish city of Łódź and the Chinese city of Chengdu was launched (Choroś-Mrozowska, 2019b, p. 42). Since that time, relations between Poland and China have deepened to some extent, including the establishment of partnerships between cities and regions (Kamiński, 2019, p. 232), increased Chinese foreign investment in Poland (Kostecka-Tomaszewska & Czerewacz-Filipowicz, 2019, p. 482), and growing cooperation in fields of science and education (Nazarko & Kuźmicz, 2017, p. 501).

However, in terms of BRI's main component, which is infrastructural development, no significant progress has been made, and in recent years, Polish authorities have not taken any steps towards greater involvement in the BRI. The Polish government does not seem to have a consistently implemented long-term strategy of foreign policy development towards China, while its position towards the BRI is described as "reactionary" (Mrożek, 2018). However, another option for deepening the relationship within the BRI could be the cooperation between member state regions and Chinese provinces, which are very active in the project. The equivalent of Chinese provinces in Poland is 16 local government units called voivodeships. Although they have limited constitutional powers, as Poland is a unitary state, they have some competences of their own and can develop

cooperation with foreign regions (Ustawa z dnia 5 czerwca…, 1998).

In determining Polish regions that have the best predisposition to engage in the BRI, the location of Poland should be considered on the map of Eurasia and the map of BRI economic corridors. Poland's eastern border marks the external border of the EU and the Eurasian Economic Union (EAEU), which is an integration group comprising Russia, Kazakhstan, Belarus, Armenia and Kyrgyzstan. Through the territory of Poland runs the New Eurasian Land Bridge (NELB), which is one of three BRI land corridors reaching Europe, running through Kazakhstan, Russia and Belarus. In comparison to the other two corridors (the Northern Corridor running through the Siberian Railway and the Central Corridor running through Central Asia), it is the shortest connection with the best condition of infrastructure and, therefore, it is the most frequently used (Jakóbowski et al., 2018, p. 41). Thanks to the customs union between Russia, Belarus and Kazakhstan within the EAEU, the NELB involves only two customs boundaries (Czerewacz-Filipowicz, 2019, p. 32), which makes it the most economically viable option. At the Kazakh–Chinese and Belarusian–Polish borders, the transported goods have to undergo customs procedures as well as reloading, due to the changing width of the railway gauge, which in China and Poland is 1435 mm, while in the territory of the former USSR, it is 1520 mm. Further advantages of Poland's location are several major European transport routes intersecting on the country's territory, namely, two out of nine Trans-European Transport Network (TEN-T) corridors, the Amber Rail Freight Corridor (Bartosiewicz & Szterlik, 2022, p. 5), and corridors Via Carpatia, Via Baltica and Rail Baltica. Also, Poland has access to the Baltic sea, which creates opportunities for intermodal transport. All these location features are of great importance from the point of view of further distribution of goods in Europe.

Some Polish regions seem eager to benefit from the advantages of Poland's location and are establishing and deepening relations with their eastern counterparts independently. Particularly those located in central and eastern Poland are predisposed to develop their transport offer in the context of the BRI and benefit from the provision of logistics services and infrastructure or customs handling of goods. The Łódzkie voivodeship, located in central Poland, is an example of cooperation established and maintained since the beginning of the BRI. Coordinated actions of private business, local authorities and academia led to tangible results, e.g., opening the first regular railway connection with China in 2013, launching several new transhipment terminals, opening a permanent office in Chengdu or establishing the Department of East Asian Studies at the University of Łódź (Kamiński, 2019, p. 238). In the case of the Lubelskie voivodeship, located in eastern Poland, a success factor was the fact that the Terespol/Brest border crossing and the associated transhipment area of Małaszewicze, are located in the region. In 2020 the Małaszewicze terminal handled more than 90% of the volume of goods reaching Europe via the New Eurasian Land Bridge. However, the capacity of the transhipment area is no longer sufficient. Trains coming from China often have to wait up to several days before being reloaded, and an increasing part of the transit is being redirected via other routes, including Kaliningrad Oblast, Lithuania, Slovakia or Hungary (Antonowicz, 2019, p. 157). Increased involvement of other eastern regions of Poland may provide a solution to this problem. In this context, the potential of the Podlaskie voivodeship, located in north-eastern Poland, is worth noting. Podlaskie has four border crossings with Belarus that could be expanded and used to handle BRI rail routes (Kostecka-Tomaszewska & Czerewacz-Filipowicz, 2019, p. 478), and one of them is located approx. 50 kilometres north from the Terespol crossing. According to Ejdys (2017, p. 185), some indicators have already attested to Podlaskie's potential and readiness to engage in the BRI, including numerous economic, educational and scientific factors. Whereas the voivodeship authorities draw attention to the investment and infrastructural potential of the region, pointing to access to important transport routes, the existing reloading capacity, the large offer of investment areas and the high quality of human resources (Podlaskie. Naturalna droga…, 2020). Also, it should be noted that no direct competition exists between different Polish regions in the context of the BRI because the growing demand for transhipments calls for a further supplement of the reloading capacity.

2. Methodology

The research part of this study is aimed at determining the position of individual voivodeships in the BRI in general and the position of the Podlaskie voivodeship in comparison to others in particular. For this purpose, the first stage of research designed

a set of 14 quantitative factors determining the position of the voivodeship in the project. The next step was conducting the survey in which a group of academic, business and local government experts determined the importance of said factors. The comparison of the factors helped to assess the voivodeships and rank them in terms of the achieved results in the third stage of the research. The last step was the analysis of the results achieved by individual voivodeships, which enabled identification of possible areas of intervention for the Podlaskie local government and recommendation of measures to be taken in these areas.

Three groups of factors considered in the first stage of the research were "state and administration", "the business sector", and "academia". This classification was based on the triple helix model, developed in 1994 by Etzkowitz and Leydesdorff as a concept promoting the extension of the industry-government relationship to university–industry–government interaction. The triple helix model may be used to support the development of innovation and regional economic growth and to promote entrepreneurship by understanding the dynamics of interaction between the three institutional spheres (Cai & Etzkowitz, 2020, p. 8). The important role of universities in the creation of innovation in a knowledge-based society, and the overlapping of roles and functions held by the individual parties, are aspects of this model worth emphasising (Nazarko et al., 2013, p. 66). In terms of the research on the position of the Polish voivodeships in the BRI, it was concluded that the triple helix model was an appropriate background for the specification of factors determining the level of involvement and potential of voivodeships, as the chance for a region to participate in the Initiative was possible only through the synergy of the three dimensions: local authorities, business and science (Nazarko et al., 2016, p. 5). The presented classification of factors is also consistent with the main dimensions for cooperation within the BRI, which are policy coordination, financial integration, facilities connectivity, unimpeded trade, and people-to-people bonds (Baker McKenzie, 2017, p. 2). The first two dimensions are omitted here as they are hardly influenced by local government units, but the other three are represented by consecutive groups of factors. The aspect of infrastructural connections is considered in group 1, "state and administration", the dimension of undisturbed trade is addressed in group 2, "the business sector", while the dimension of people-to-people exchange is represented by the factors in group 3, "academia".

Table 1 lists a set of 14 quantitative factors. The first group includes aspects related to the infrastructural situation of the voivodeships as well as their geographical and geopolitical location. The factors in question referred to the transport and transhipment potential of voivodeships. For example, factor 3 refers to the reloading capacity of the voivodeship, illustrating a population that lives within 500 km of the voivodeship's capital, which corresponds to the

Tab. 1. Factors describing the position of Polish voivodeships in the BRI

Group of factors	No.	Factor	Unit
State and administration	1	Density of rail network	km/100km^2
	2	Density of road network	km/100km^2
	3	Distributional coverage of the voivodeship	mln people
	4	Access to wide gauge and border crossings	y/n
	5	The distance from seaports by rail	km
	6	The distance from seaports by road	km
The business sector	7	Number of intermodal terminals	num.
	8	Number of railway links with China	num.
	9	Number of Chinese companies in the voivodeship	num.
	10	Voivodeship's tourism potential	km/km^2; num/km^2; % of area; num/km^2
Academia	11	Number of logistics studies graduates	num.
	12	Number of Confucius Institutes and Classes	num.
	13	Number of Chinese exchange students	num.
	14	Number of Sino-Polish research projects	num.

average range of a distribution centre considered to be international. Group 2 contains factors connected with conducting business activities related to the BRI. Issues related directly to logistics activities and to international cooperation at company and people levels were considered. Factor 10 refers to the human-to-human aspect of the BRI and expresses voivodeship's tourism potential, which was expressed using four indicators: the length of tourist routes, the presence of areas with exceptional natural values, the number of tourist accommodation facilities and the number of historical monuments. The last group of factors lists those related to scientific and research cooperation in the BRI context. This group includes both issues related to academic cooperation and exchange and issues related to qualifications and human resources in the context of international cooperation.

The second stage of research on the position of Polish voivodeships in the BRI was expert research. Using the CAWI (Computer Assisted Web Interview) method, a survey questionnaire was sent to 15 intentionally selected representatives of local administration, the private sector and the academic community. Respondents were asked to rate the importance of the listed factors using a 5-point scale, where a rating of one meant that the factor was considered "definitely not important" and five meant "definitely important". By using two questions in the respondent's metric, information was obtained about the respondent's place of work (a local government unit, private company or university) and the nature of their interest in BRI topics (professional, private or professional and private). Five experts from each of the abovementioned groups took part in the survey. Seven of them declared that they are interested in the BRI professionally (for example, by managing a business related to the handling of freight from China, conducting research on the BRI issue, organising BRI-related events), while eight respondents were interested in the BRI both professionally and privately (e.g., by following the news on the BRI in the media and literature or participating in conferences and events related to the BRI).

The third stage of the study involved the collection of quantitative data for individual voivodeships corresponding to the specified factors, as well as the normalisation of these data. In the case of factor 10, "Voivodeship's tourism potential", it was expressed using four indicators: the length of tourist routes, the presence of areas with exceptional natural values, the number of tourist accommodation facilities and the number of historical monuments. The data representing these indicators for individual voivodeships were normalised, while the final value of the factor for a given voivodeship was presented as the average value of the normalised data. In the case of factor 11, "Number of logistics studies graduates", due to deficiencies in statistical data, values for two voivodeships were estimated. In the next step, the quantitative data collected for the voivodeships were normalised, as due to different ranges of data, it was necessary to bring them to a state of comparability. The normalisation procedure was performed using the classical unitisation formula, which was described in more detail by Jarocka (2015).

The fourth stage of the study included the determination of results achieved by individual voivodeships, considering the value of quantitative factors and their importance determined by experts. Comparison of these results made it possible to rank the voivodeships and determine the position of Podlaskie voivodeship.

3. Research results

The first relevant input that had to be considered was the importance of the factors identified by the experts. Table 2 presents the results of the factor importance assessment and selected statistical measures.

Considering the expert assessments, factors in group 1 are characterised by average importance of 3.64, where the most important was factor number 4, while the least important was factor number 5. The importance of the factors in the second group averaged 3.33. The experts assigned the highest importance in this group to factor number 7 and the lowest to factor number 10. For the factors in group 3, the average importance was 3, where factor number 14 was the most important and factor number 13 the least important. The importance ratings of all factors are quite homogeneous and characterised by low (less than 25 %) or average (25 %÷45 %) variability. The lowest variability (17 %) is observed in the case of factor 7, the assessments of which deviate from the arithmetic mean by 0.72, which means that in its assessment, the experts were highly unanimous.

The second relevant input was quantitative data for individual voivodeships corresponding to the specified factors, collected from statistical yearbooks and Internet sources. The process of normalisation was used to bring the data to a consistent range from 0 to 1. Then, the results for individual voivodeships

Tab. 2. Importance of the factors

Group of factors	No.	Factor	Arithmetic average	Standard deviation	Coefficient of variation
State and administration	1	Density of rail network	3.73	0.88	24%
	2	Density of road network	3.87	1.06	27%
	3	Distributional coverage of the voivodeship	3.93	0.70	18%
	4	Access to wide gauge and border crossings	4.00	0.85	21%
	5	The distance from seaports by rail	3.07	0.88	29%
	6	The distance from seaports by road	3.27	0.96	29%
The business sector	7	Number of intermodal terminals	4.33	0.72	17%
	8	Number of railway links with China	3.60	1.06	29%
	9	Number of Chinese companies in the voivodeship	3.07	0.96	31%
	10	Voivodeship's tourism potential	2.33	0.98	42%
Academia	11	Number of logistics studies graduates	3.33	0.90	27%
	12	Number of Confucius Institutes and Classes	2.80	1.01	36%
	13	Number of Chinese exchange students	2.47	0.74	30%
	14	Number of Sino-Polish research projects	3.40	0.74	22%

were calculated as a sum of the quotients of the factor importance and the data corresponding to this factor. Table 3 presents the results of the final calculation.

In the classification of positions in the BRI, Podlaskie was placed in the second half of the set, 11th among 16 Polish voivodeships. Certainly, this is a result that gives room for further work and improvement. To determine which areas represented in the study are potential places of intervention, a further analysis was conducted, including comparing the results of Podlaskie with the average results for the whole country, with the results of the three leaders of the classification, as well as with the results of the voivodeships located in the east of Poland (Fig. 1).

Podlaskie achieved relatively good results in comparison with average results (a), which is indicated by the fact that only in the case of factor 3 the result achieved by Podlaskie is significantly below the average. As far as other factors are concerned, Podlaskie scored above average for factors 4 and 12, close to average for factors 6 and 7, and slightly below average for the remaining 9. In comparison with the leaders of the voivodeship classification (b), Podlaskie achieves a better result only in the case of factor 4. In the case of the remaining factors, strong domination of the leaders is visible. It is worth noting that of these three provinces, one is a capital region, one is located in the industrial and mining basin of the country, and

Tab. 3. Classification of voivodeships according to their position in the BRI

Ranking	Voivodeship	Result	Ranking	Voivodeship	Result
1	Mazowieckie	28.33	9	Kujawsko-Pomorskie	12.71
2	Śląskie	28.16	10	Warmińsko-Mazurskie	11.58
3	Pomorskie	21.19	11	Podlaskie	11.42
4	Wielkopolskie	21.02	12	Lubuskie	10.17
5	Dolnośląskie	18.37	13	Opolskie	9.62
6	Łódzkie	18.69	14	Świętokrzyskie	9.43
7	Małopolskie	17.56	15	Podkarpackie	7.28
8	Lubelskie	12.90	16	Zachodniopomorskie	7.03

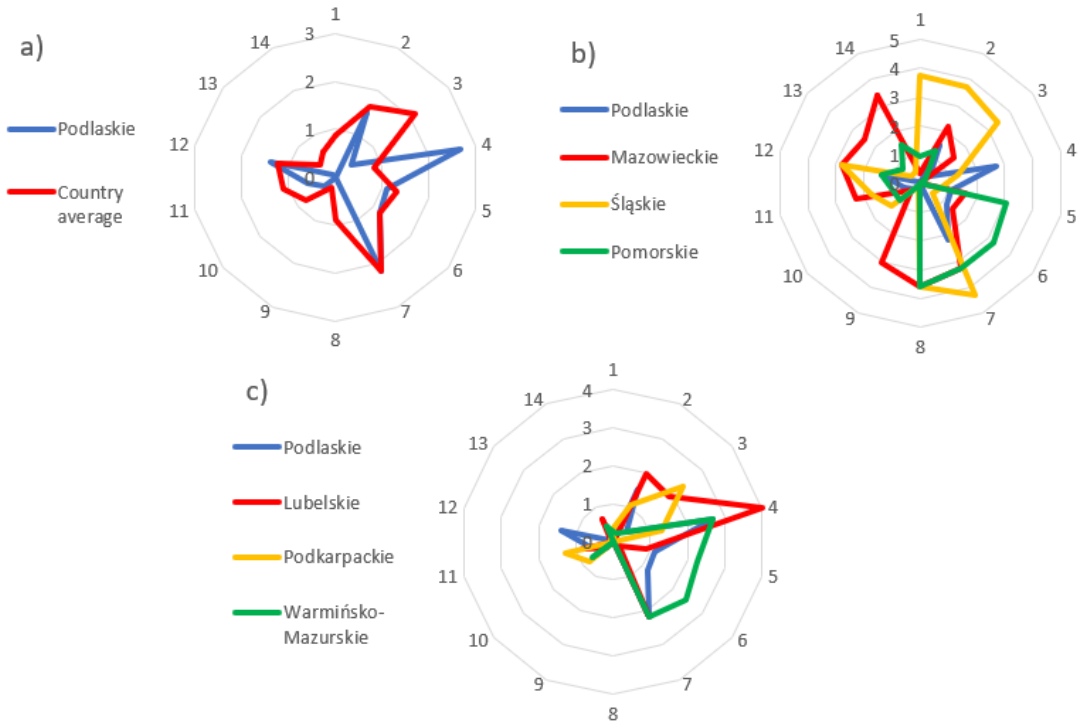

Fig. 1. Results of Podlaskie voivodeship compared to a) average results, b) best results, c) results for Eastern Poland

one is a maritime region with the largest seaport in the country. In comparison with other voivodeships located in Eastern Poland (c), Podlaskie achieves similar results, being the leader in the case of factor 12 and reaching similar results in the case of several others.

The presented analysis certainly does not fully cover the possibility of comparing the results achieved by the Podlaskie voivodeship in the BRI with the results achieved by other Polish voivodeships. However, it provides a relatively comprehensive comparison. The analysis carried out so far allows identifying the current state of affairs and drawing general conclusions but identifying particular fields for strengthening Podlaskie's position in the BRI and defining more detailed recommendations for improvement requires further consideration. Table 4 presents the results achieved by Podlaskie voivodeship in the case of particular factors, compared with their importance and with three subsequent benchmark levels: average results for Eastern Poland, the whole country and the leaders of the list. Four factors were omitted because

Tab. 4. Classification of possible intervention areas

No.	Factor	Importance	Podlaskie	Eastern Poland	Average for country	Best results
1	Density of rail network	3.73	0.00	0.16	0.87	3.73
8	Number of railway links with China	3.60	0.00	0.00	0.90	3.60
14	Number of Sino-Polish research projects	3.40	0.00	0.27	0.59	3.40
11	Number of logistics studies graduates	3.33	0.60	0.67	1.11	3.33
9	Number of Chinese companies in the voivodeship	3.07	0.00	0.00	0.22	3.07
10	Voivodeship's tourism potential	2.33	0.28	0.50	0.78	2.12
2	Density of road network	3.87	1.51	1.20	1.65	3.87
13	Number of Chinese exchange students	2.47	0.07	0.06	0.41	2.47
7	Number of intermodal terminals	4.33	2.17	1.62	2.17	4.33
12	Number of Confucius Institutes and Classes	2.80	1.40	0.35	1.23	2.80

their level for a given voivodeship results from permanent conditions and is not subject to improvement. The remaining ten factors could represent potential areas of intervention for local government in synergy with the private sector and academia. As for the method to determine the priority of these potential areas of improvement, it assumes a three-stage approach. Firstly, attention should be brought to matters in which Podlaskie achieves results below the average of eastern voivodeships. Upon achieving the improvement there, the next step would be to include factors in the case of which Podlaskie's result is lower than the average result of the country. Last but not least, there are two areas in which Podlaskie's result is lower than the maximum and can be improved. Within these three stages of action, the factors were ranked in order of their importance determined in the expert study.

4. Discussion of the results

The selected and prioritised areas of intervention provide a background for planning and recommending specific actions that can be taken to improve Podlaskie's position in the context of the Belt and Road Initiative. For the purposes of this study, recommendations for actions will be presented in relation to the local government. However, these will certainly not be actions whose implementation will be influenced solely by the selected stakeholder. According to the aforementioned triple helix model, regional development and economic growth are conditioned by the dynamics of interaction between three institutional spheres (government, industry and academia). An important element of this model is the overlapping of roles held by the different parties, so the recommended actions will consider cooperation between all parties, which will certainly constitute a key aspect of achieving positive results of the introduced changes.

The mission of the local government is to perform tasks that are not reserved by law to the central administration. The basic tasks of the voivodeship's local government include, but are not limited to, creating conditions for economic development, promoting the advantages and development opportunities, supporting the development of science, and maintaining and developing infrastructure important to the voivodeship (Ustawa z dnia 5 czerwca…, 1998). The local government has a certain degree of independence, manages the voivodeship's property and budget, and has the possibility to obtain EU funds. However, as an authoritative entity, it must manage financial resources transparently, using long-term plans. Therefore, the proposed recommendations must be compatible with already planned activities. The Development Strategy for Podlaskie Voivodeship 2030 (hereinafter — the Strategy) can be a determinant of the long-term objectives of the voivodeship. It considers various perspectives of the region's development: economic, human capital and international partnership (Strategia…, 2020).

The areas of intervention represented by factors 1, 2 and 7 concern the infrastructural sphere and describe the voivodeship's connectivity and logistical attractiveness. Strategic plans concerning the development of transport infrastructure are included under the operational goal 2.3 of the Strategy, entitled "High-quality space". The logistics potential of the voivodeship is represented by its location at the intersection of important international transport routes and the functioning of three modern intermodal terminals with a total capacity of 300 000 TEU. However, to fully utilise this potential, it is necessary to develop the infrastructure network in the voivodeship by building new and modernising existing railway and road routes, which is necessary due to the relatively low density of the railway (lower than the average on the eastern wall) and road network (lower than the national average). Local governments can obtain funds for these purposes from EU programmes, such as Infrastructure and Environment, or government programmes, such as the Government Road Development Fund. Local governments should also promote the use of border crossings on the border with Belarus. Two out of four border crossings operating in the region are already operational to a limited extent, but their reloading potential is much greater, and the operation of the remaining two crossings is hindered by administrative and infrastructural problems, which the local government could certainly help to solve.

The areas of intervention represented by factors 8 and 9 concern the business sphere of international cooperation with China and describe the business and investment attractiveness of the voivodeship. Strategic activities related to this area are included in the Strategy under the operational goal 3.3, entitled "International and trans-regional partnerships". Breaking the stereotype of the low investment attractiveness of Podlaskie will require building an attractive offer directed to investors. To increase the business attractiveness of the voivodeship and to

attract Chinese investors and exporters to the region, it is important to use the existing resources (geographical location, strong scientific background, development potential) and to create new opportunities through cooperation with other regions of the country and the EU. A developing region, open to innovation, with skilled workers, a strong logistics base and developed infrastructure, can become an attractive place for foreign investors. It is necessary to support initiatives that contribute to the positive image of the region in terms of innovation (such as the Białystok Science and Technology Park). The local government may support industries that constitute smart specialisations of the region, i.e., competences of the region that may contribute to its transformation and restructuring (Strategia…, 2020, p. 64), which in the case of Podlaskie include the agri-food sector or the metal and machinery industry. Supporting these key industries for the development of the region (e.g., through assistance in obtaining subsidies or joint implementation of promotional campaigns) may strengthen their export potential and attract Chinese interest both in terms of investing in the region and importing regional products.

The areas of intervention represented by factors 14, 11 and 12 concern the scientific sphere and describe the voivodeship's attractiveness in terms of teaching and research. Strategic activities related to this area are included in the Strategy under the operational goals 1.2 and 2.1, entitled "System of open innovation" and "Competent inhabitants". The goal defined by the local authorities is to develop a model of dynamic national and international cooperation between universities and scientific centres, which would foster a high level of education and research and benefit the region's economy. This can be achieved by increasing the activity of local universities in international projects and competitions (such as SHENG1 or Polish–Chinese bilateral competitions), and by matching the undertaken projects with the needs of industry and searching for new directions of the voivodeship development, such as nanotechnology (Nazarko et al., 2013).

The activities of the local government in supporting the development of the region in this aspect could include support in obtaining funding for the development of scientific and research centres and for increasing the competences of students through internships and international cooperation. Such cooperation with China is already underway, e.g., the Summer School of Logistics in China or the functioning of the Confucian Class at the Białystok University of Technology, but there are certainly many more opportunities.

The areas of intervention represented by factors 10 and 13 concern the area of attractiveness and image of the region and describe the general interest of Chinese tourists and students in the voivodeship. Strategic actions related to this area are included in the Strategy under operational objective 3.4, "Hospitable region". Local authorities, through promotional activities, build a brand of the region as a comfortable and clean place, attractive both for settlement and recreation, with a high potential of human resources and innovation, but also attractive and culturally diverse, safe and clean (Podlaskie. Naturalna droga…, 2020). However, promotional activities must also be supported by some operational measures. Local government support in this area should cover all the spheres mentioned so far: infrastructure, international business cooperation and science. Institutional, organisational, and financial support for all initiatives aimed at making Podlaskie voivodeship an attractive place to study (e.g., through assistance provided to universities in financing foreign exchange programmes for Chinese students and researchers), work, or visit, combined with promotional activities, can certainly strengthen both the position and image of the Podlaskie voivodeship in the Belt and Road Initiative.

Conclusions

Studying the position of Polish regions in the Belt and Road Initiative proved to be a relatively difficult research challenge. In the context of a project of such global influence, it may seem more natural to compare the positions of individual countries in it. However, in the case of comparing individual regions of a member country, setting up the criteria for comparison proved to be a challenge (especially specifying factors that would both be characteristic for the regions and actually describe aspects that influence the region's position in the international project).

In the case of an international project like the BRI, where the main strategic decisions are made at the governmental level, it is impossible to consider the participation of the regions of the member states in the project without considering the participation of the whole country. In the case of Poland, the government's actions and approach to the BRI have been so far characterised by moderate optimism and keeping distance from deeper involvement, making it dif-

ficult for individual voivodeships to actively join the project and increase their participation and importance. The current organisational, legislative, tax and customs conditions related to the handling of imported goods in Poland make their clearance, control and reloading relatively difficult on the territory of Poland compared to Western European countries. Polish entrepreneurs undertake individual and collective actions to adjust the existing regulations to good western practices. However, the insufficiency of political will at the national level makes such actions challenging.

The authors are aware of the non-representative and fragmentary nature of the study. Therefore, the developed set of recommendations that the local government can undertake in selected areas does not constitute a definitive list. However, these actions have a chance to bring the expected results if they are combined with the development of consistent objectives and plans at the level of central and local government, the private sector and the academic community, and with mutual support for each other's activities. Openness to international cooperation and the opportunities that the Belt and Road Initiative brings for businesses and the country are crucial in this respect. Only if these opportunities are recognised in time will Poland be able to realise its potential to participate in this project and see the benefits of such participation.

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Appendix 1. Figures for voivodeships before normalisation

		VOIVODESHIP															
FACTOR NUMBER	UNIT OF MEASUREMENT	DOLNOŚLĄSKIE	KUJAWSKO-POMORSKIE	LUBELSKIE	LUBUSKIE	ŁÓDZKIE	MAŁOPOLSKIE	MAZOWIECKIE	OPOLSKIE	PODKARPACKIE	PODLASKIE	POMORSKIE	ŚLĄSKIE	ŚWIĘTOKRZYSKIE	WARMIŃSKO-MAZURSKIE	WIELKOPOLSKIE	ZACHODNIOPOMORSKIE
1	km/100km^2	8.8	6.7	3.6	6.5	5.9	6.7	4.8	8.3	4.8	3.6	6.6	15.8	5.1	4.4	6.3	5.1
2	km/100km^2	123.1	155.9	148.1	111.9	142.9	208.8	154.5	110.1	119.6	132.8	124.6	203.9	150.7	91.7	137.9	84.7
3	mln people	93.5	74.1	75.6	98.1	83.6	86.1	70.6	93.8	80.2	59.5	57.4	92.6	82.7	59.3	86.4	54.7
4	y/n	0	0	3	0	0	0	0	0	1	2	0	1	1	2	0	0
5	km	456	162	498	446	370	608	335	533	705	449	0	539	523	180	309	364
6	km	493	178	600	464	348	592	359	549	637	407	0	531	480	167	321	363
7	num.	3	0	2	1	4	2	3	0	0	2	3	4	0	2	4	2
8	num.	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0
9	num.	70	14	18	33	33	55	2570	11	18	17	40	125	11	14	119	24
10	km/km^2	34.5	32.7	16.8	45.4	14.1	57.5	18.2	16.3	13	21.7	17.9	52.3	24.9	11.7	16.9	34.3
	num/km^2	5.2	2.3	1.9	2.2	1.8	10.2	1.8	1.8	3.7	1.4	9	5.7	2.1	2.2	2.3	7
	% of area	18.6	32.2	22.7	37.4	19.5	53	29.7	27.6	44.9	31.6	32.8	22.1	64.9	46.7	29.6	21.8
	num/km^2	44	20	17	33	16	41	22	36	29	12	20	35	16	27	27	19
11	num.	2321	698	1024	339	2147	750	2829	547	1541	746	1216	2132	693	0	4081	800
12	num.	2	1	0	0	0	2	2	1	0	1	1	2	0	0	2	0
13	num.	87	101	15	0	111	100	521	43	21	14	161	81	10	0	115	7
14	num.	5	0	3	0	1	5	16	0	0	0	7	2	0	2	3	0

Appendix 2. Figures for voivodeships after normalisation

	VOIVODESHIP															
FACTOR NUMBER	DOLNOŚLĄSKIE	KUJAWSKO-POMORSKIE	LUBELSKIE	LUBUSKIE	ŁÓDZKIE	MAŁOPOLSKIE	MAZOWIECKIE	OPOLSKIE	PODKARPACKIE	PODLASKIE	POMORSKIE	ŚLĄSKIE	ŚWIĘTOKRZYSKIE	WARMIŃSKO-MAZURSKIE	WIELKOPOLSKIE	ZACHODNIOPOMORSKIE
1	0.43	0.25	0.00	0.24	0.19	0.25	0.10	0.39	0.10	0.00	0.25	1.00	0.12	0.07	0.22	0.12
2	0.31	0.57	0.51	0.22	0.47	1.00	0.56	0.20	0.28	0.39	0.32	0.96	0.53	0.06	0.43	0.00
3	0.89	0.45	0.48	1.00	0.67	0.72	0.37	0.90	0.59	0.11	0.06	0.87	0.65	0.11	0.73	0.00
4	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	0.67	0.00	0.33	0.33	0.67	0.00	0.00
5	0.35	0.77	0.29	0.37	0.48	0.14	0.52	0.24	0.00	0.36	1.00	0.24	0.26	0.74	0.56	0.48
6	0.23	0.72	0.06	0.27	0.45	0.07	0.44	0.14	0.00	0.36	1.00	0.17	0.25	0.74	0.50	0.43
7	0.75	0.00	0.5	0.25	1.00	0.50	0.75	0.00	0.00	0.50	0.75	1.00	0.00	0.50	1.00	0.50
8	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00
9	0.02	0.00	0.00	0.01	0.01	0.02	1.00	0.00	0.00	0.00	0.01	0.04	0.00	0.00	0.04	0.01
10	0.48	0.28	0.10	0.47	0.06	0.91	0.18	0.27	0.35	0.12	0.39	0.54	0.37	0.29	0.23	0.35
11	0.57	0.17	0.25	0.08	0.53	0.18	0.69	0.13	0.38	0.18	0.30	0.52	0.16	0.00	1.00	0.20
12	1.00	0.50	0.00	0.00	0.00	1.00	1.00	0.50	0.00	0.50	0.50	1.00	0.00	0.00	1.00	0.00
13	0.17	0.19	0.03	0.00	0.21	0.19	1.00	0.08	0.04	0.03	0.31	0.16	0.02	0.00	0.22	0.01
14	0.31	0.00	0.19	0.00	0.06	0.31	1.00	0.00	0.00	0.00	0.44	0.13	0.00	0.13	0.19	0.00

Appendix 3. Sources of data for particular quantitative factors

No.	FACTOR	SOURCE
1	Density of rail network	https://utk.gov.pl
2	Density of road network	https://stat.gov.pl
3	Distributional coverage of the voivodeship	https://www.osw.waw.pl
4	Access to wide gauge and border crossings	https://www.freemaptools.com
5	The distance from seaports by rail	https://www.pkpcargo.com
6	The distance from seaports by road	https://www.google.com/maps
7	Number of intermodal terminals	https://stat.gov.pl
8	Number of railway links with China	https://www.shiphub.pl
9	Number of Chinese companies in the voivodeship	https://www.coig.com.pl
10	Voivodeship's tourism potential	https://stat.gov.pl; https://bdl.stat.gov.pl
11	Number of logistics studies graduates	https://stat.gov.pl
12	Number of Confucius Institutes and Classes	https://www.digmandarin.com
13	Number of Chinese exchange students	https://radon.nauka.gov.pl
14	Number of Sino-Polish research projects	https://www.ncn.gov.pl; https://archiwum.ncbr.gov.pl